Oregon State University

COLLEGE OF ENGINEERING | School of Civil and Construction Engineering

Reducing Unwanted Cracking: Shrinkage and Shrinkage Cracking

Jason Weiss, Edwards Distinguished Professor, Oregon State University

Things Shrink

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On its own shrinkage is not a big issue

However, if the displacement is fixed, there will be stress

Todays Outline

- Origins of deformation
- Types of shrinkage
- Stress due to restraint and the degree of restraint
- Moisture gradients
- Evaluating cracking resistance
- The use of computational modeling
- Approaches to minimize shrinkage – Mechanisms are key: minimize paste, SRA, int. curing, expansive agents, fibers

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Origins of Deformation

Photo 215481085 © Olga Sabirjanova | Dreamstime.com

Thermal Expansion and Contraction

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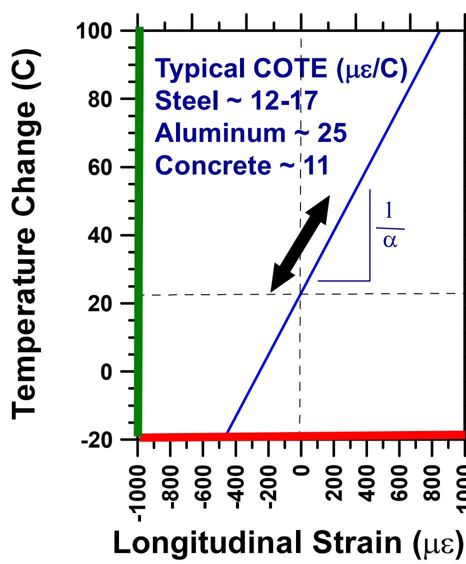
Temperature Deformations

- Stimulus - Temperature Change
- Response – Length Change
- This happens in nearly all materials (in concrete moisture dependence exists)
- Frequently reversible

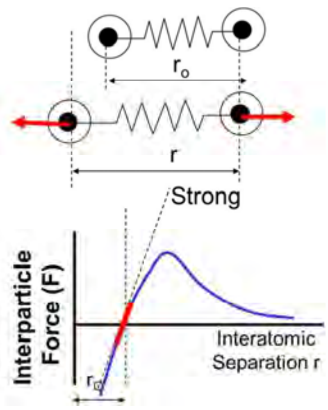
$$\delta_{TEMP} = \alpha \cdot L \cdot \Delta T$$

$$\varepsilon_{TEMP} = \alpha \cdot \Delta T$$



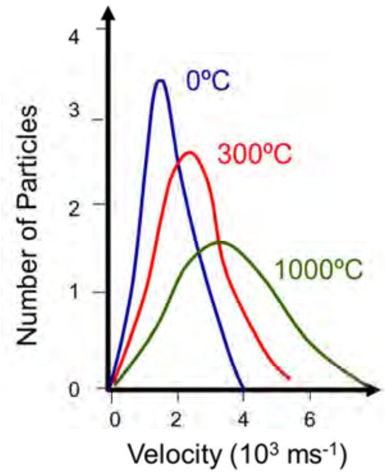
Weiss, CE 231, 2001

Expansion/Contraction Joints



- **Internal vibration** motion due to the storage of energy
- Many properties depend on the thermal properties of a material
- **Robert Brown** – studied plant pollen under a microscope, pollen jiggled randomly

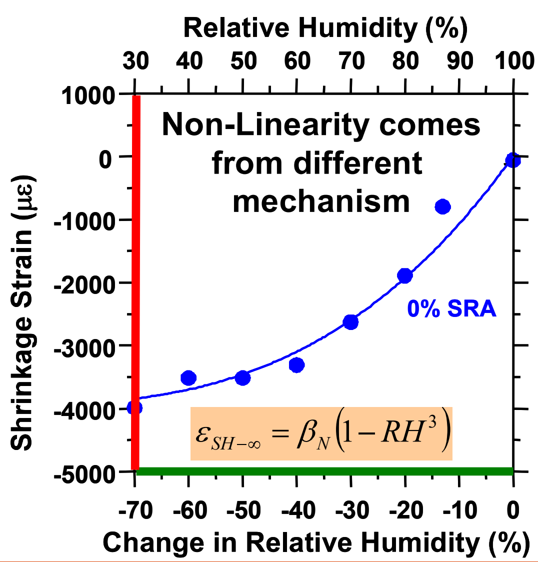
- **Brownian motion (1828) -** molecules in some liquids and gases he was studying had a special motion or movement



Weiss, CE 231, 2001

Shrinkage Due to Moisture Loss

- Stimulus is Change in Moisture (Drying External or Internal) and Chemical Reaction
- Response is the Change in Length (Volume)



Weiss 2005

Origins of Non-Linearity

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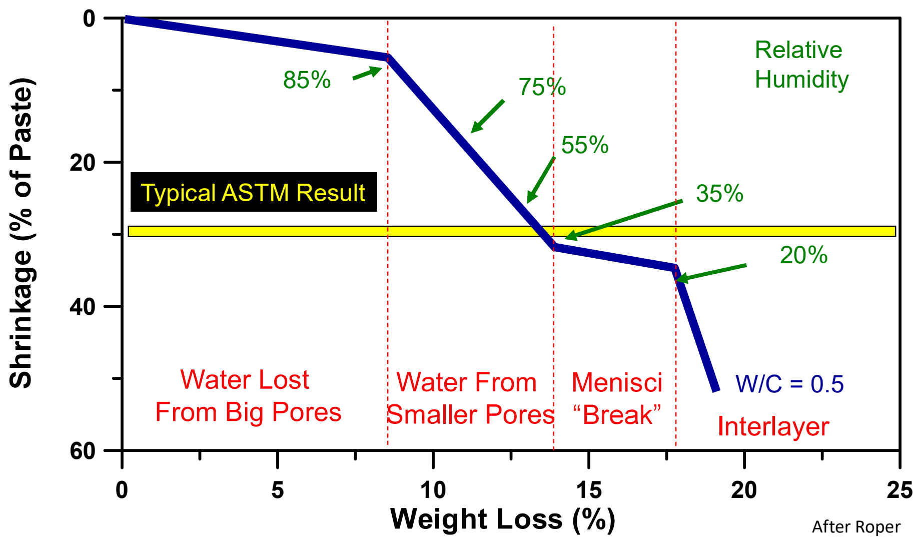
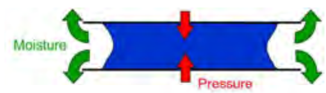
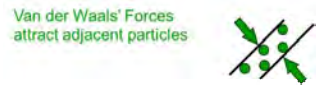


After Roper

- Capillary Stress > 40-60% RH



- Disjoining Pressure >50% RH



- Surface Tension < 40% RH

Capillary Stress

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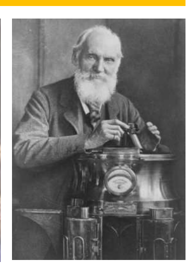
- Some insights on the factors influencing shrinkage

$$p_{cap} = -\frac{2\gamma \cdot \cos\theta}{r}$$

Thomas Young (1773 – 1829)

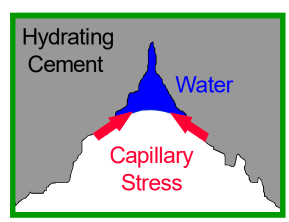
Carl F. Gauss (1777 - 1855)

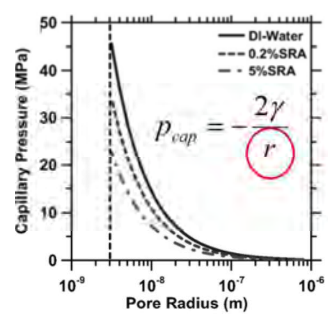
Marquis de Laplace (1749 - 1827)



Lord Kelvin (1824 - 1907)

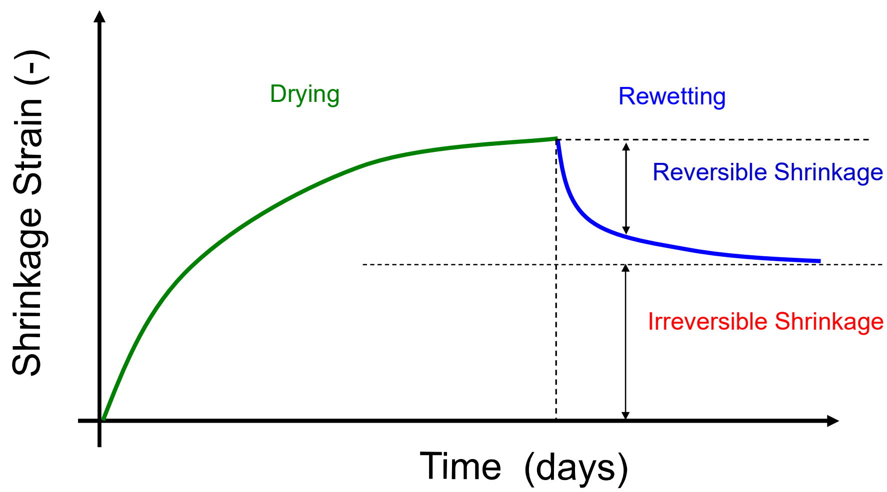
$$\ln\left(\frac{p}{p_0}\right) = \ln(RH) = -\frac{2\gamma \cdot \cos\theta \cdot V_W}{r \cdot RT} = p_{cap}\frac{V_W}{RT}$$





Sant et al. 2008

Irreversibility



Todays Outline

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Types of Shrinkage

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- Drying Shrinkage – Generally Reserved for Hardened Concrete (Strictly Just Due to Water Loss, Evaporation or Suction)
- Autogenous Shrinkage – Shrinkage without Temperature Change or Moisture Loss (Chemical and Self-Desiccation Shrinkage During Hydration)
- Carbonation Shrinkage – When Hydrated Cement Paste Reacts with Carbon Dioxide
- Thermal Shrinkage – Change in Length Due to Temperature Change
- Plastic Shrinkage – Occurs in Fresh Concrete while the Concrete is Still Plastic

Drying Shrinkage (ACI 116)

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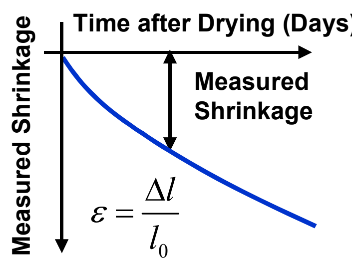
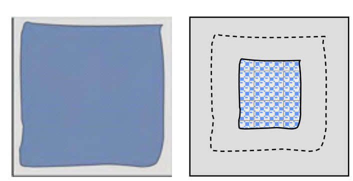
- **Shrinkage:** Decrease in either length or volume. May be restricted to the effects of moisture content or chemical changes.
- **Drying Shrinkage:** Shrinkage that is caused by drying. (Size dependence)
- **ASTM C 157 (23C, 50% RH)**



Three Dimensional Phenomena



Weiss, CE 530, 2002

Chemical Shrinkage

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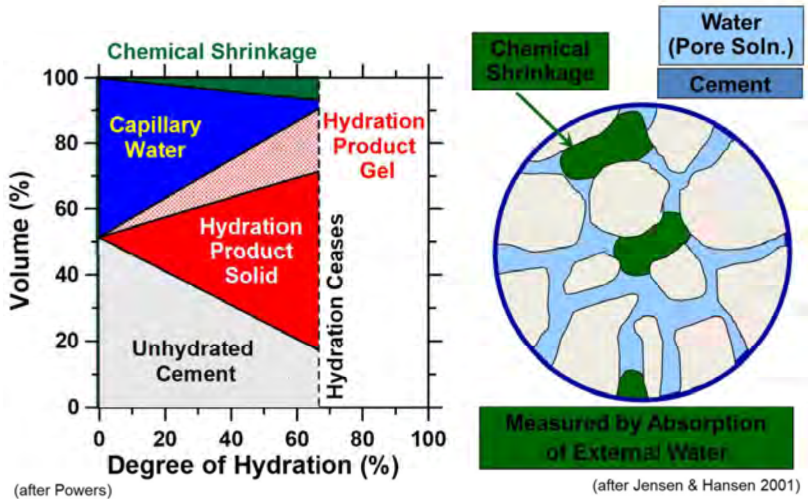
- "the volume reduction associated with the hydration reactions in a cementitious material"
- Powers conceptual model shown ~ 6.4% reduction



Autogenous Shrinkage

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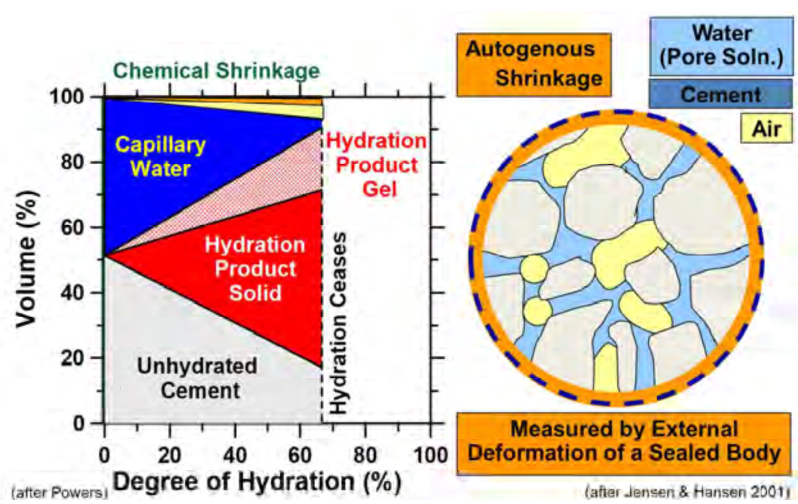
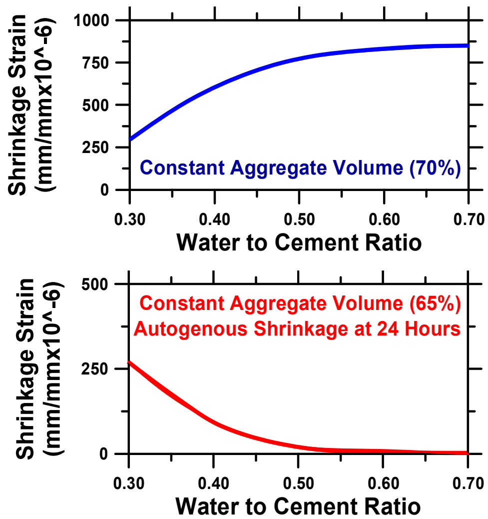
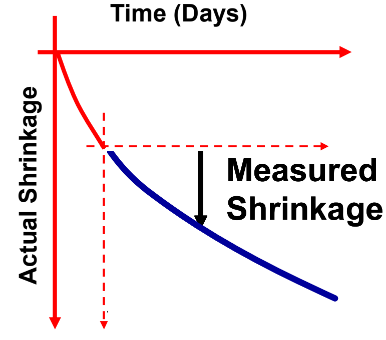
- New shrinkage protocols should be standardized to replace tests that miss critical information
- Several tests have been compared
- Reasonable agreement is observed between different protocols



Measuring Shrinkage Starting Time is Critical

- Typically standard measurements Begin at the Time of Demolding (i.e., 24 Hours)
- Why ?? – This is a Convenient Time for the Technicians to Demold
- More of an Issue in Low W/C Concrete



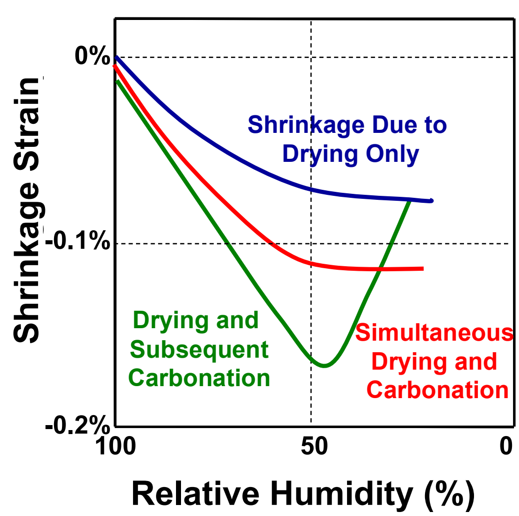


After Aitcin 1999

Weiss, CE 530, 2002

Carbonation

- Paste will React with Carbon Dioxide forming Calcium Carbonate from CH and CSH
- Slow in Normal Conditions But Can Be High if High Concentration of $C0_2$ is Present
- May Change Moisture Distribution



After Mindess, Young and Darwin

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Toward an Understanding of Boundary Conditions

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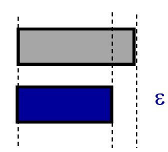
- **Unrestrained (Free) –** A material can shrink or expand freely (without stress development)



Toward an Understanding of Boundary Conditions

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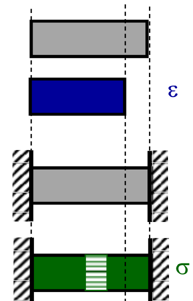
- **Unrestrained (Free) –** A material can shrink or expand freely (without stress development)
- **Complete Restrained -** (also called perfect, 100%) – material can't shrink or expand at all (max. stress development)



Residual Stress Development

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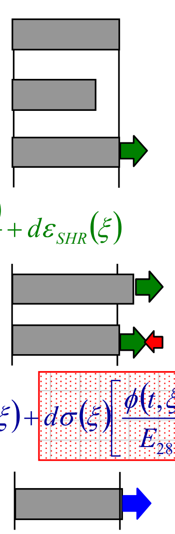
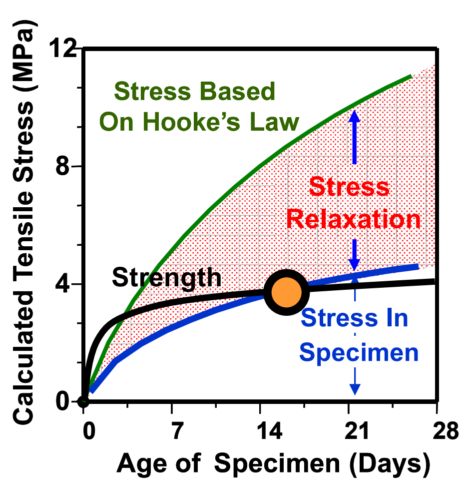


$$d\varepsilon(t,\xi)=\frac{d\sigma(\xi)}{E_\sigma(\xi)}+d\varepsilon_{SHR}(\xi)$$

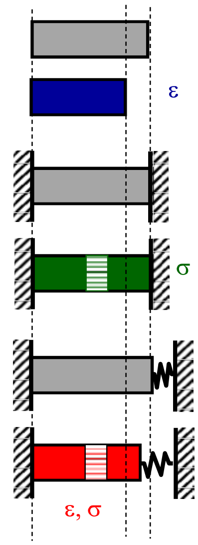
$$d\varepsilon(t,\xi)=\frac{d\sigma(\xi)}{E_\sigma(\xi)}+d\varepsilon_{SHR}(\xi)+d\sigma(\xi)\left[\frac{\phi(t,\xi)}{E_{28}}\right]$$



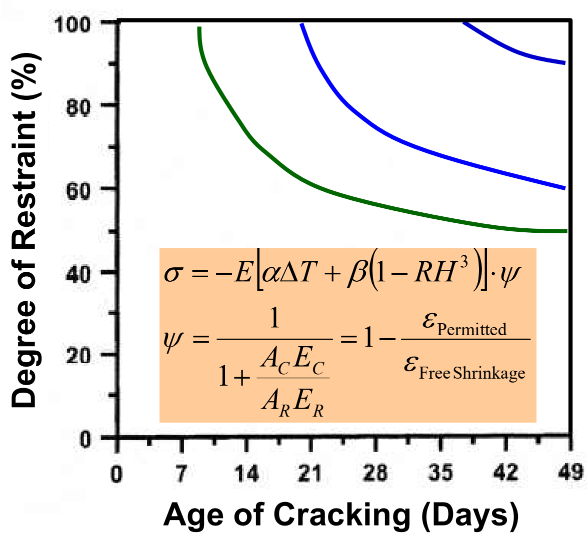
Weiss et al. 1998, JEM

Toward an Understanding of Boundary Conditions

- **Unrestrained (Free) –** A material can shrink or expand freely (without stress development)
- **Complete Restrained -** (also called perfect, 100%) – material can't shrink or expand at all (max. stress development)
- **Partially Restrained –** (a portion of the shrinkage or expansion is prevented)
- **Restraint is "External" to Material**



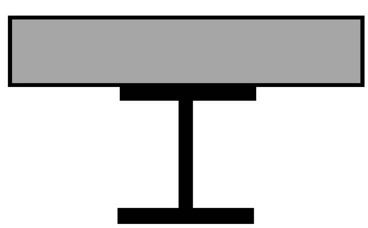
Degree of Restraint on the Age of Cracking



$$\sigma = -E\left[\alpha \Delta T + \beta\left(1 - RH^3\right)\right] \cdot \psi$$

$$\psi = \frac{1}{1 + \frac{A_C E_C}{A_R E_R}} = 1 - \frac{\varepsilon_{\text{Permitted}}}{\varepsilon_{\text{Free Shrinkage}}}$$

- Importance of ψ
- You can see that this relationship is highly non-linear



Weiss 1997

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Transforming RH Pressure into A Stress Profile

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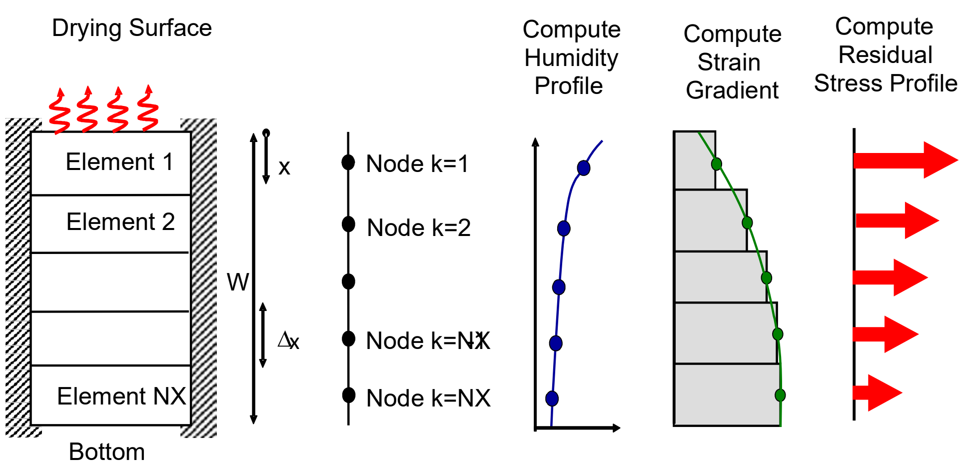
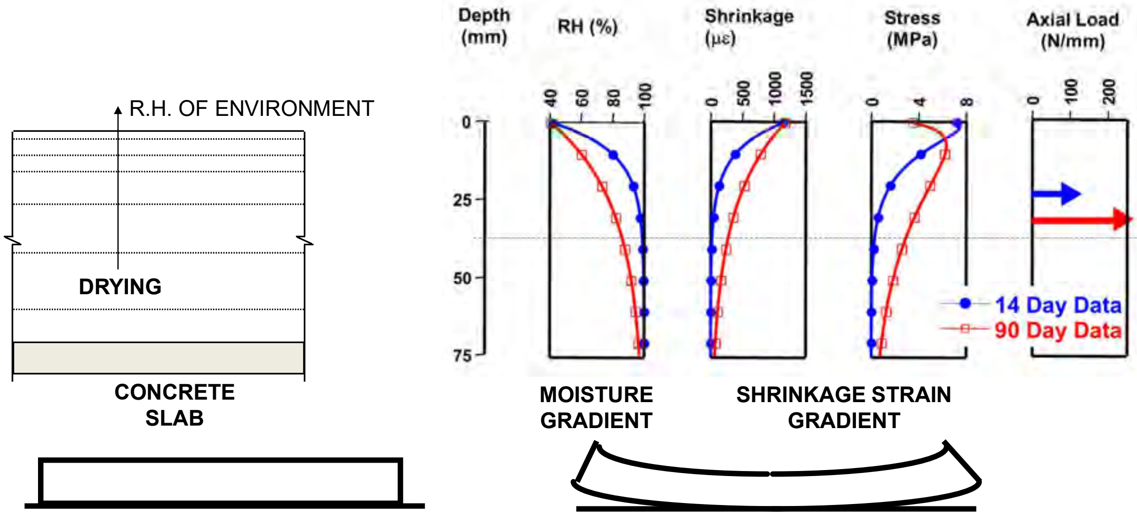


Weiss 1999

Moisture Gradients

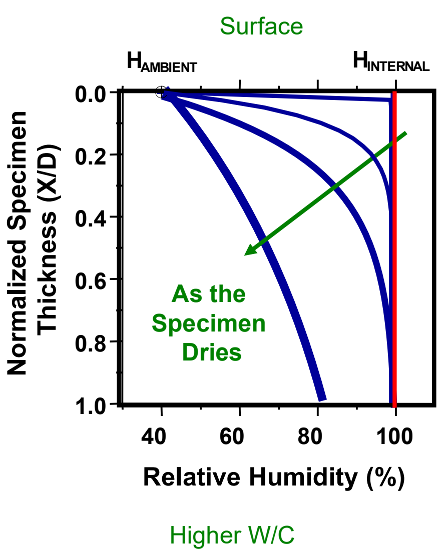


INITIAL SLAB

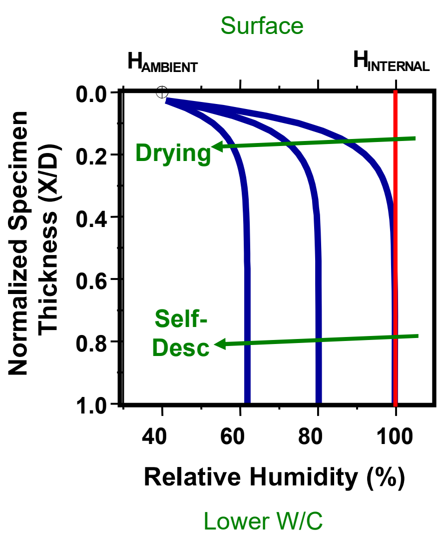
CURLING IN A SLAB

Weiss 1999

The Difference in Shrinkage Across the Specimen in High and Low W/C



Higher W/C

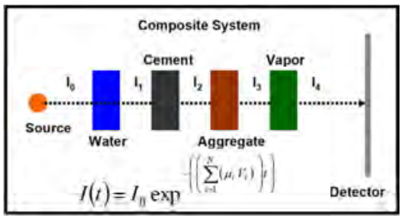


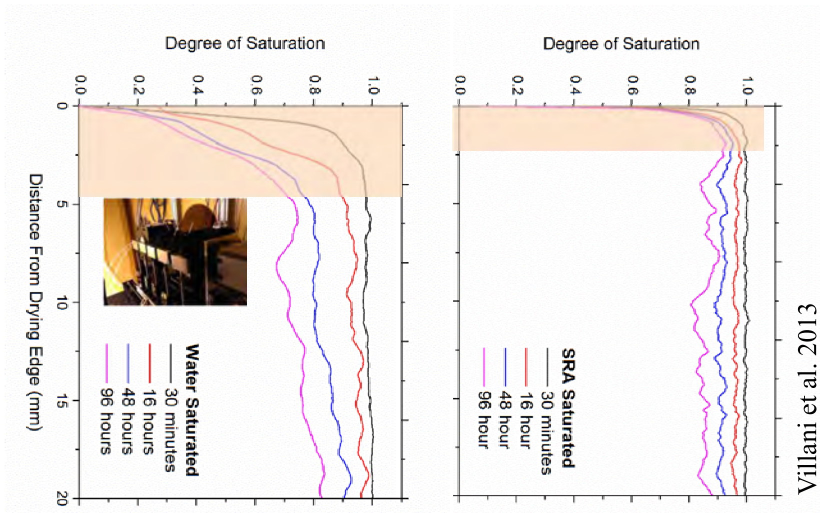
Lower W/C

Weiss et al. 2006

Moisture Profiles (NR)

- Slower drying with SRA (keeps core more saturated, lowers moisture gradients, less curl)





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Simple Tests to Assess Restrained Shrinkage

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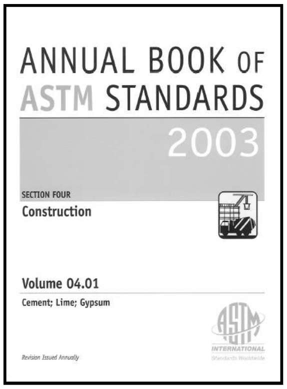
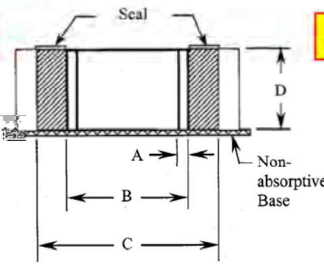
Ring is economic, 'simple to conduct' which lend it to selection & QC/QA



ASTM C 1581-04

Dimensions [mm]	
A	12.5 ± 0.13
B	330 ± 3
C	406 ± 3
D	150 ± 6



$B = 2R_{IC}$ $C = 2R_{OC}$

AASHTO PP 34-99

Dimensions [mm]	
A	12.7 ± 0.4
B	305 ± 5
C	457 ± 5
D	152 ± 5

- DOR is very different (ASTM >> AASHTO)
- How close are you to cracking
- Swamy et al. and Attiogbe et al. (2000) thin wall stress
- Weiss et al. (2000) thick wall stress in rings

Obtaining Residual Stress in From the Restrained Ring Test

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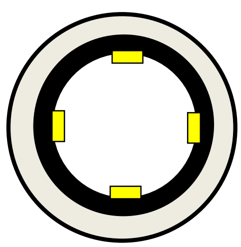
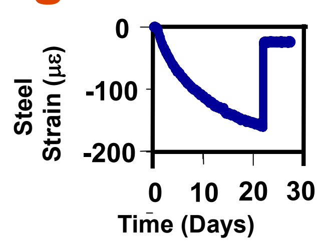
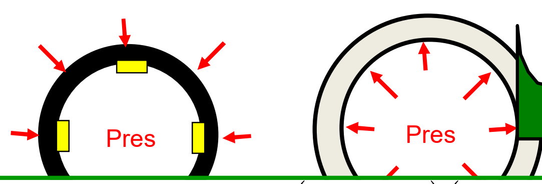
- Using an Instrumented Ring
- Measure Strain that Develops in Steel
- Determine the Pressure Required to Obtain that Strain
- Apply Pressure to Concrete and Obtain Tensile Stress

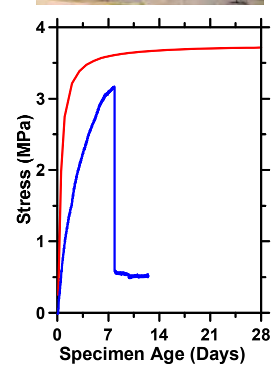


Original Ring



Measured Strain





$$\sigma_{Concrete}(t)\Big|_{r=R_{IC}} = \varepsilon_{Steel}(t)E_S\frac{\left(R_{OS}^2-R_{IS}^2\right)}{2R_{OS}^2}\frac{\left(R_{OC}^2+R_{IC}^2\right)}{\left(R_{OC}^2-R_{IC}^2\right)}$$

Hossain and Weiss, CCC, 2004

Shah and Weiss, 2005

Drying Direction

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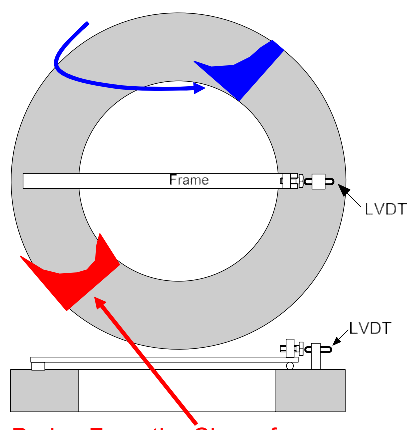
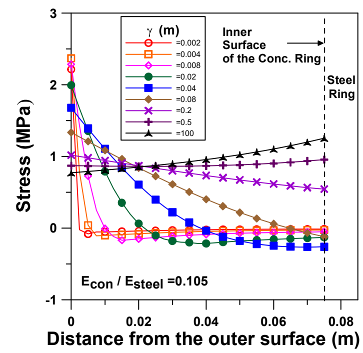
- Circumferential Drying Leads to a Complex, Changing Stress Field
- Drying from the Top and Bottom has a Constant Stress Shape with a Changing Magnitude

Drying From the Top and Bottom
Stress Field is Always ($1/r^2$)



Drying From the Circumference
Complex, Variable Stress Field



- Fick's 2nd Law for moisture distribution
- $\gamma^2 = 2Dt$
- Measure γ electrically

Moon et al. 2006

The Dual Ring Test

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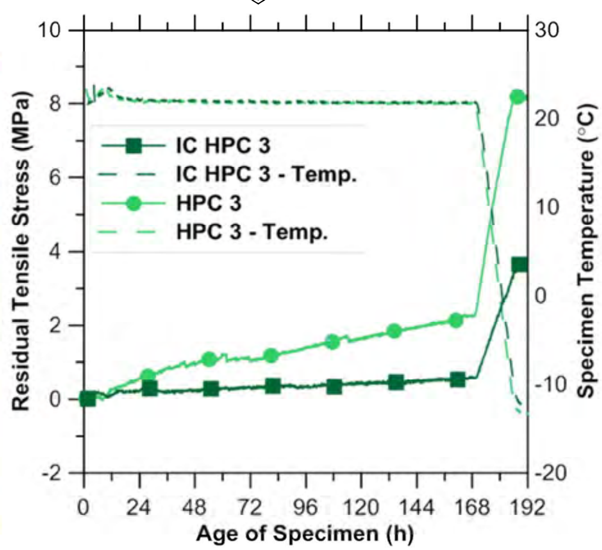
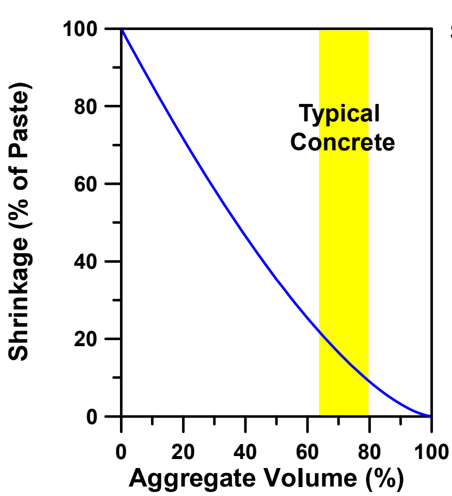


Minimizing Shrinkage and Cracking

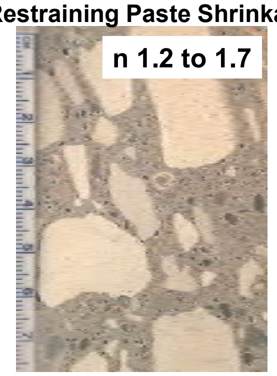
- Approaches to minimize shrinkage and cracking
- Mechanisms are key
  - Minimize cement paste
  - Shrinkage Reducing Admixtures
  - Internal curing
  - Expansive agents
  - Fiber Reinforcement

Photo 79252774 © Bengul Fidan Kaya | Dreamstime.com

Minimize Paste

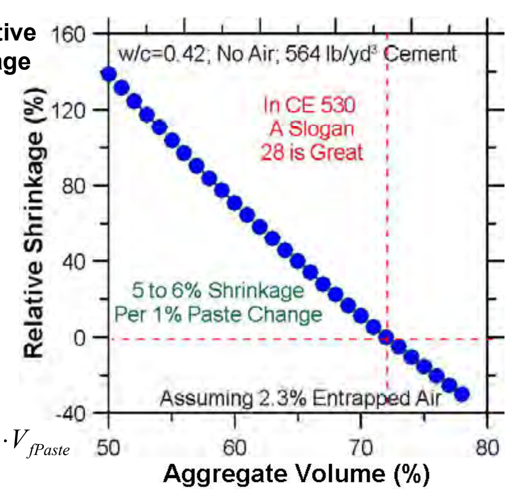


Stiffer Aggregate More Effective In Restraining Paste Shrinkage



$$\varepsilon_{Concrete} = \varepsilon_{Agg} \cdot V_{fAgg} + \varepsilon_{Paste} \cdot V_{fPaste}$$

$$\varepsilon_{Concrete} = \varepsilon_{Paste} \cdot (1 - V_{fAgg})^{n}$$



Weiss, CE 530, 2006

Water Curing & Curing Compounds

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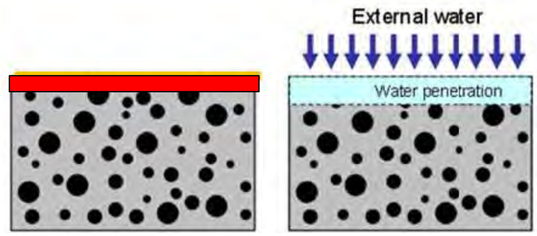
- A fundamental difference exists in typical curing
- Water Ponding, Sprinkling, Burlap: Supply Additional Water
- Curing Membranes: Reduce Loss of Water to the Environment



Shrinkage Reducing Admixtures (SRA)

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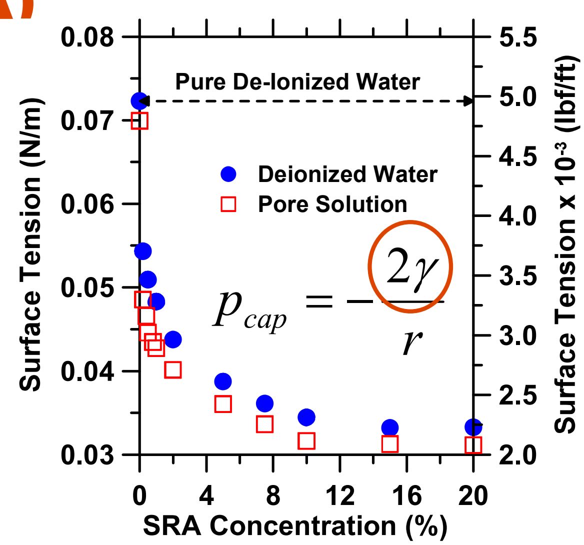
- SRAs reduce surface tension, in doing so they reduce capillary stress and shrinkage
- Surface tensions can reduce to approximately 50% of the original as do shrinkage values
- Reduce gradients



Rajabipour et al. 2006

Internal Curing

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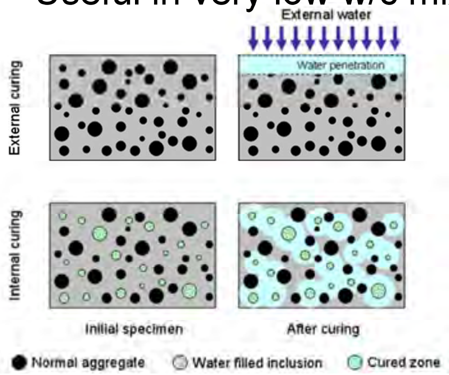
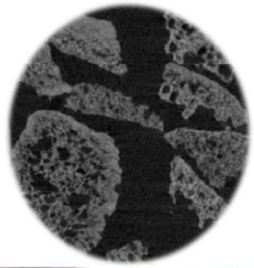
- Use LWA or SAP to provide
- Curing water from within
- Useful in very low w/c mixtures



Castro et al. 2010



Türk, Muench, Lura and Weiss 2009

Streeter et al. 2012

Barrett et al. 2014

DiBella et al. 2010

Internal Curing Commercial Uses

Expansive Agents

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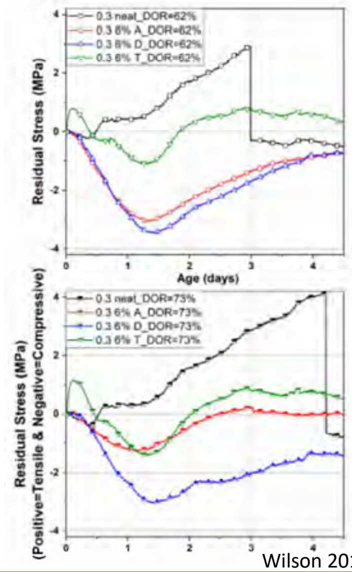
- Expansive agents can be useful
- Generally expansion occurs early
- Requires some restraint to be fully effective (offset drying not reduce it
- Dual rings are useful to evaluate expansive agents
- Different degrees of restraint

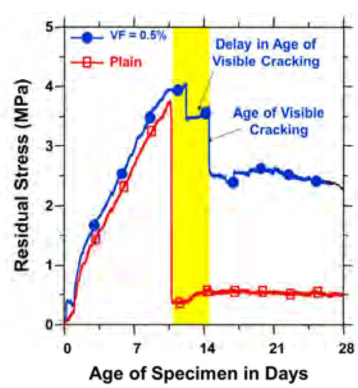


Wilson 2018

Fiber Reinforcement

Oregon State University College of Engineering

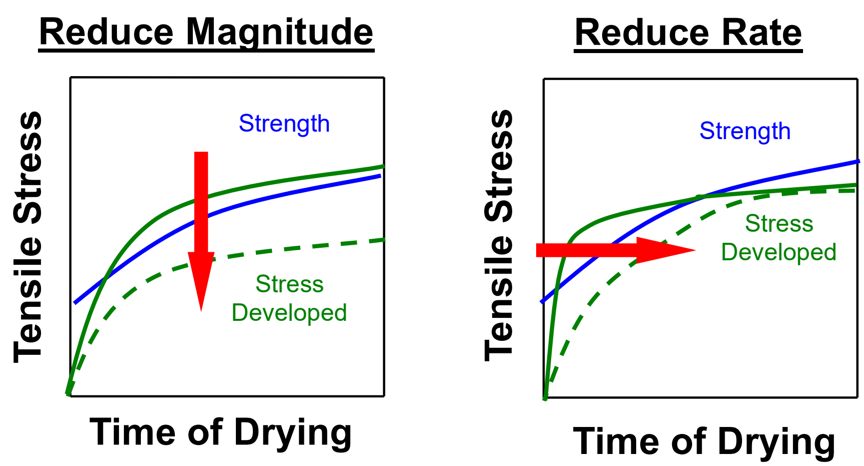
- Fibers in general do not reduce shrinkage
- Fibers do alter plastic shrinkage (fibrillated PP, cellulose) by changing viscosity/settlement and bleed
- Fibers (especially high modulus) bridge cracks and reduce crack width
- Need to be 'careful' in using ring results in field as widths are small and transfer is high due to 'length' of the ring



$$w = 2\pi R_{IC} \psi \varepsilon_{SH} \left(1 - \frac{\varepsilon_{ST}^{AC}}{\varepsilon_{ST}^{BC}}\right)$$

Shah and Weiss, 2005

Reducing Cracking: Rate and Magnitude



- Reducing both the magnitude and rate of shrinkage are important
- HSC or HESC is a great example

Weiss et al. 1999

Conclusions

- Temperature and moisture changes result in length changes
- Restraint of these changes leads to stress (partial, DOR)
- Types of volume change that occur
- Moisture gradients are key for curing and curling
- Test methods to evaluate cracking resistance
- Modeling has come a long way
- Approaches to minimize shrinkage – Mechanisms are key: minimize paste, SRA, int. curing, expansive agents, fibers