Performance of Concretes Made Using Portland Limestone Cement

Prepared by

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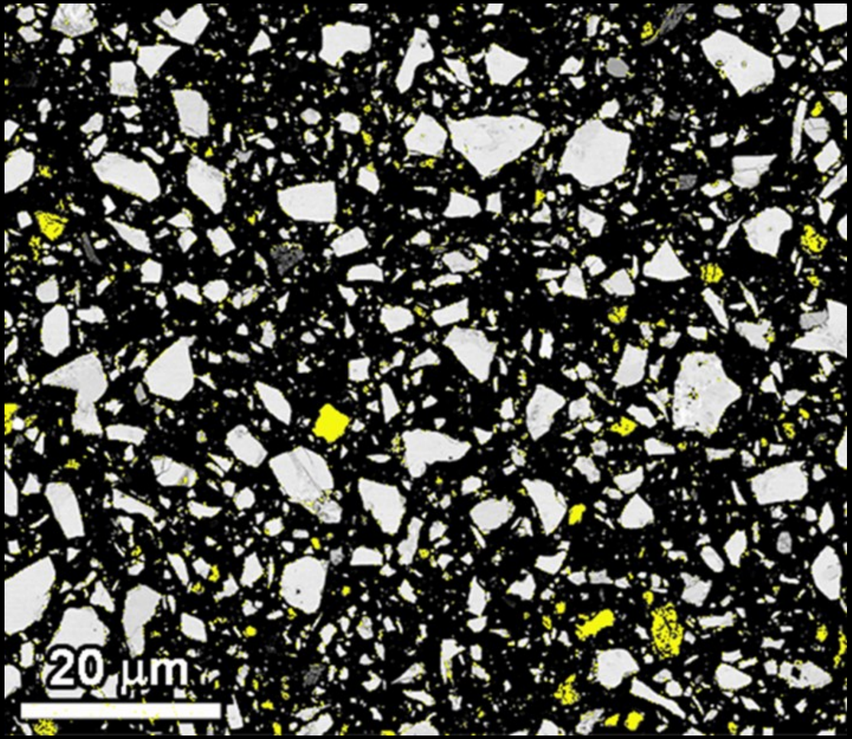
Outline for PLC Talk

- Motivation: Question What, Why, Who, How (Where)
- What are Potential Consequences
- Previous Shrinkage Study
  - Phase I –Clinker #1
  - Phase II – Using Added Limestone
  - Phase III – Clinker #2 (4 Clinker study)
- Current Shrinkage Investigation
  - Three Systems – OPC, PLC, PLC-S
- Summary

Carne – Verdon Gorge Southern France

Portland Limestone Cement
What is it?

- PLC has been added to current cement specifications ASTM C595/AASHTO M240
  - 5 to 15% interground limestone
  - Min. $CaCO_3$ content
  - Physical requirements same as OPC
  - New test requirements MBI and TOC



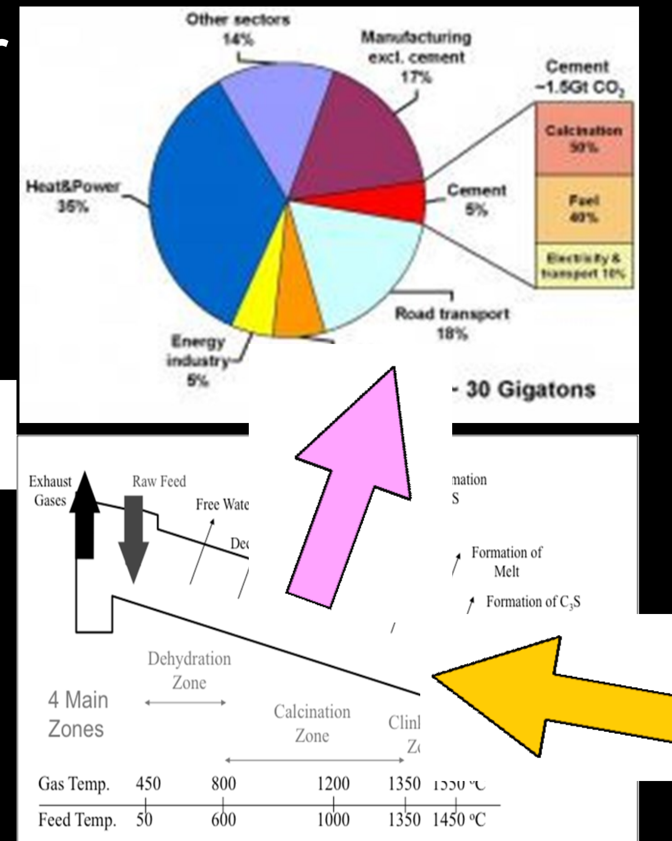
- Type IL blended cements, Type IT ternary cements

PLC – Why Do We Want It? Cement and CO_2 Production

- You will hear cement accounts for 7-8% of global CO_2 (Mehta 1998)
- Where is the CO_2 coming from
  - Calcination (50)
  - Combustion (40)
  - Transportation (10)

$$CaCO_3 \xrightarrow{\text{yields}} CaO + CO_2$$

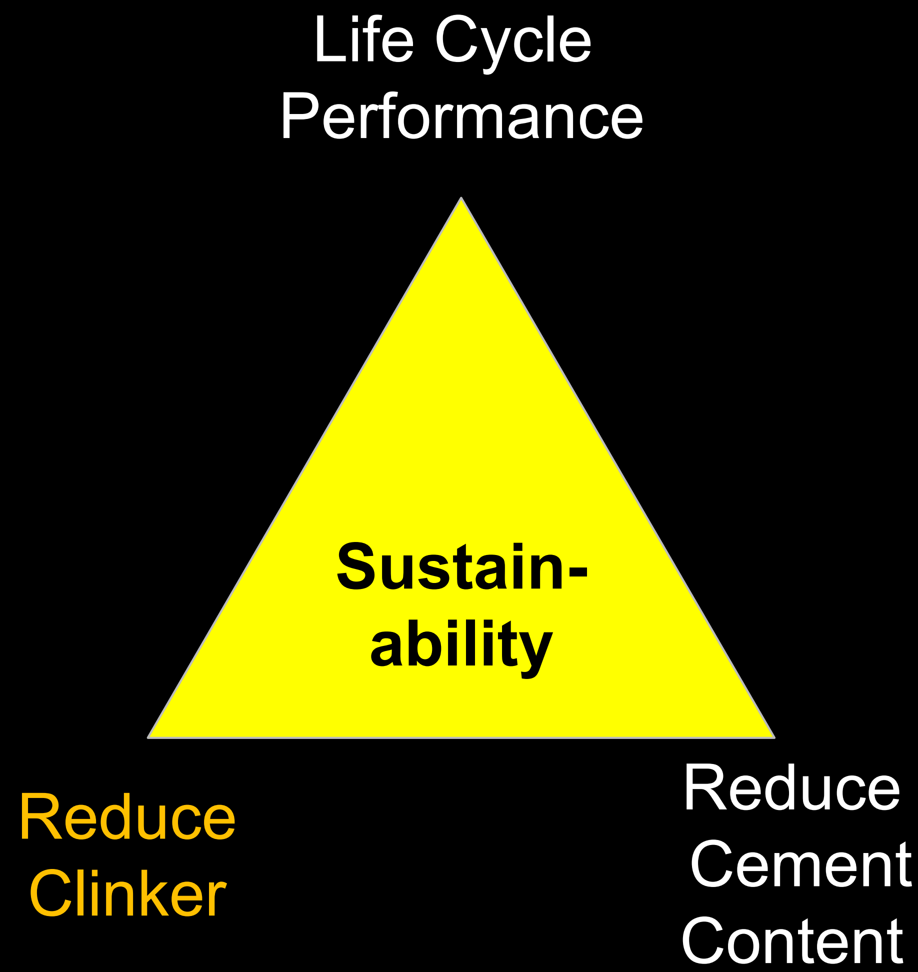
$$C + O_2 \xrightarrow{\text{yields}} CO_2$$



- Concrete has relatively low carbon emission per unit; however widespread use of concrete makes it a major contributor to manmade CO_2 emissions

Portland Limestone Cements
Why do we want it?

- Sustainability
  - less energy is consumed
  - Less CO_2 & greenhouse



Portland Limestone Cement
Who Has Used This Before?

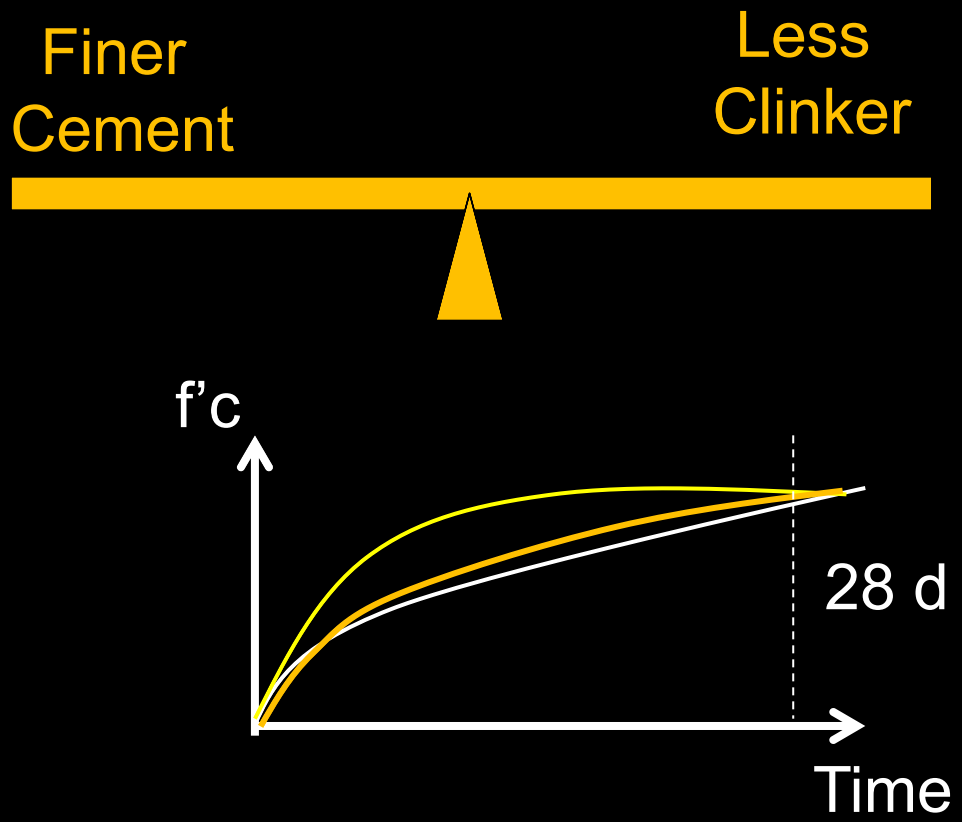
- Technical information on use of limestone of up to 15% (PLC)

<u>Summary of Contents</u>

- environmental benefits
- history of use of cements with limestone
- chemical and physical effects on properties

Portland Limestone Cement
How is it Made … In North America

- Similar performance to OPC is targeted
- PLC is generally ground finer than OPC
  - Overcome dilution
  - Higher fineness may act as a nucleating agent to increase early age strengths
  - Improve packing



- Higher reaction rates may show benefits of blending with other supplementary materials

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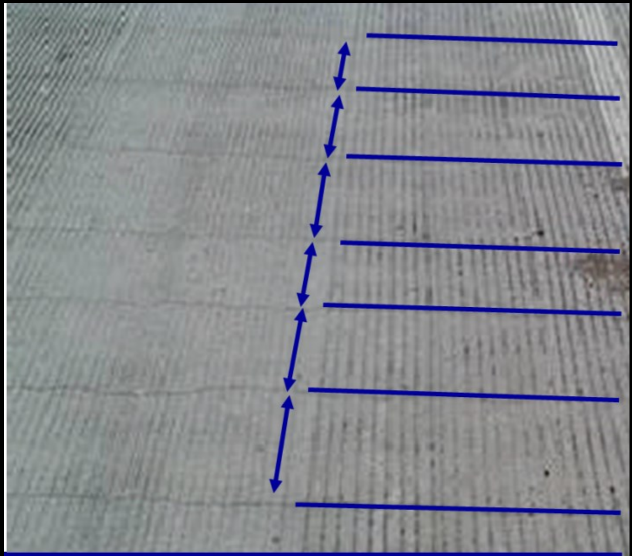
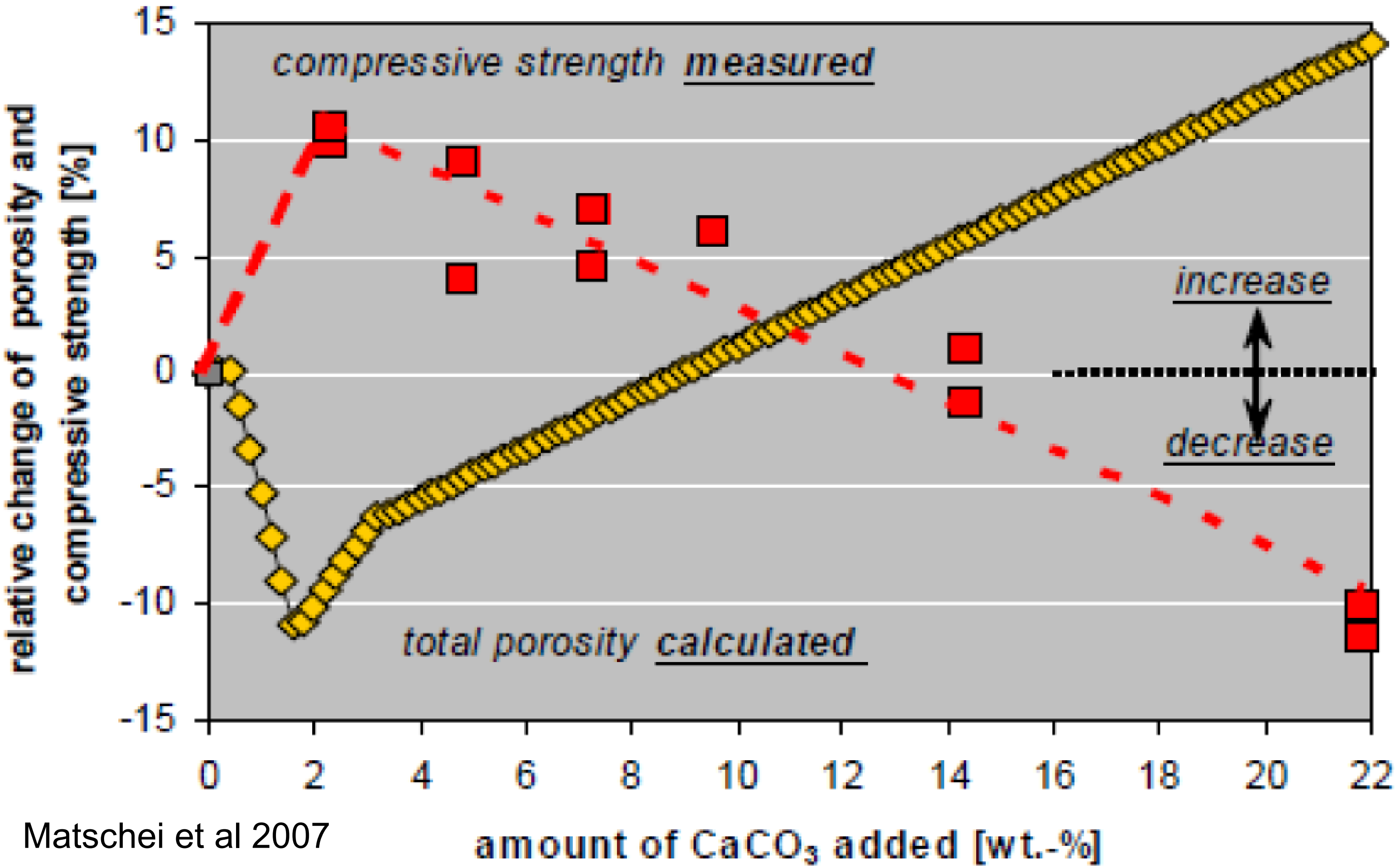


Here we see cracks spaced at 2.5 ft
On the approaches to a bridge

PLC Performance Studies

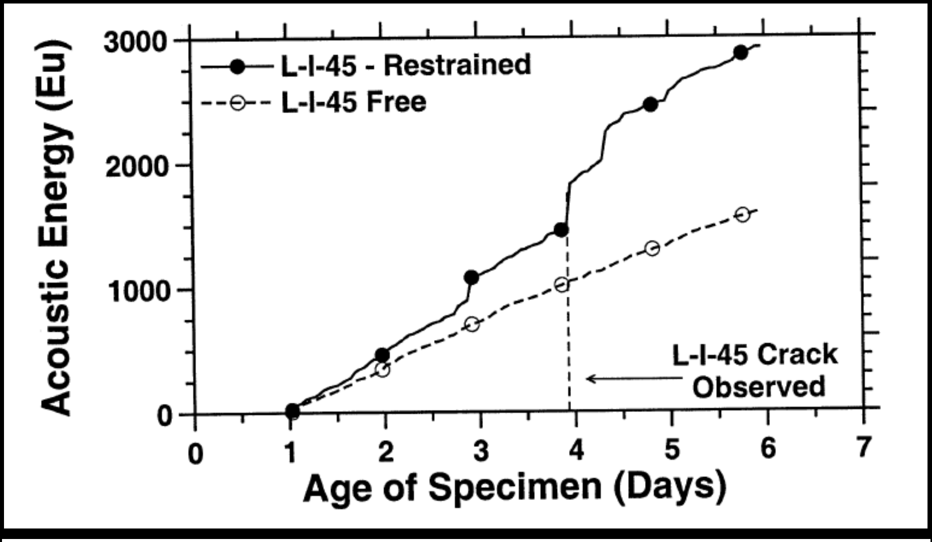


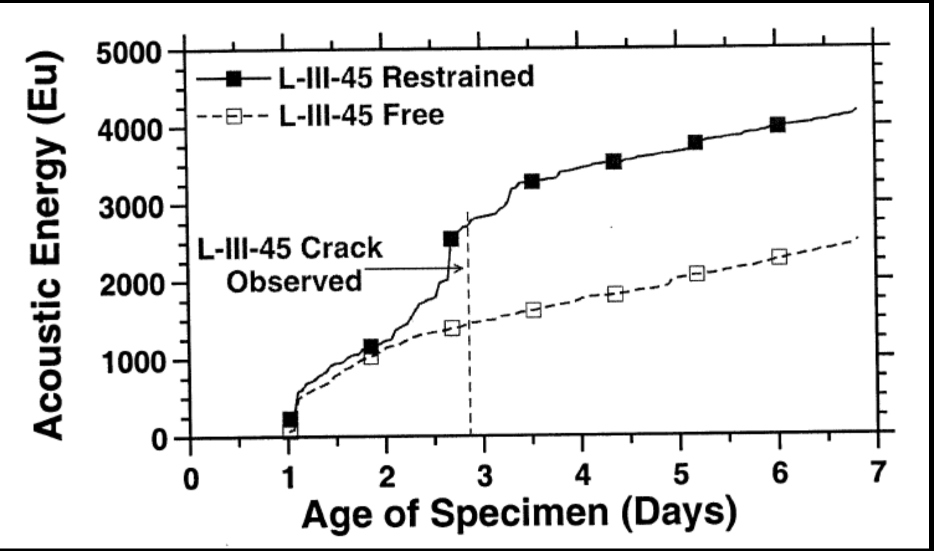
Matschei et al 2007

Fineness and Shrinkage Cracking

- Burrows (1998) – Monogaph
- Bentz, D.P., et al. (2001) ACERS
- Chariton, T., and Weiss, W. J., (2002) ACI SP – Cracking Data shown

- Several reports say finer cements crack earlier
- Blaine fineness often used in these studies however we are not really after surface area
- Rather we are after the space between particles – pore sizes important

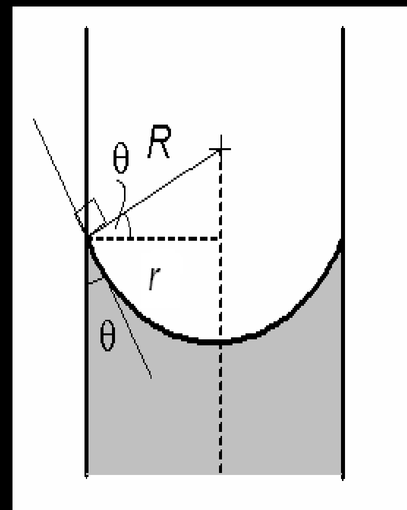




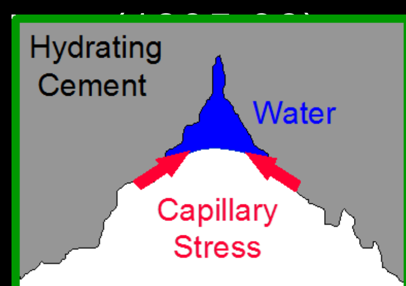
Origins of Shrinkage (Young and Laplace Equation)

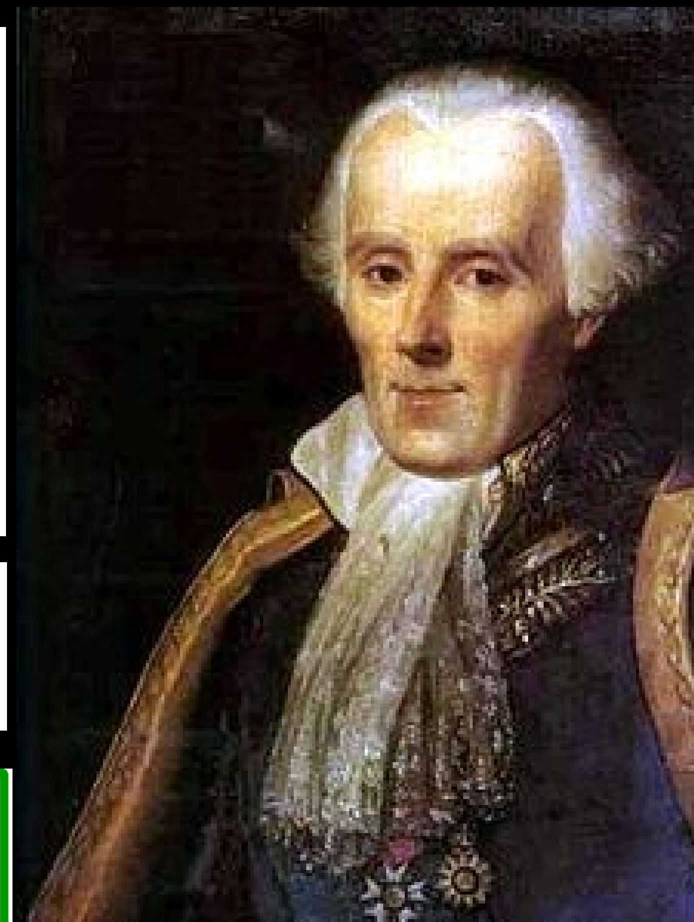
Thomas Young (1773 – 1829)

After Lura et al 2007



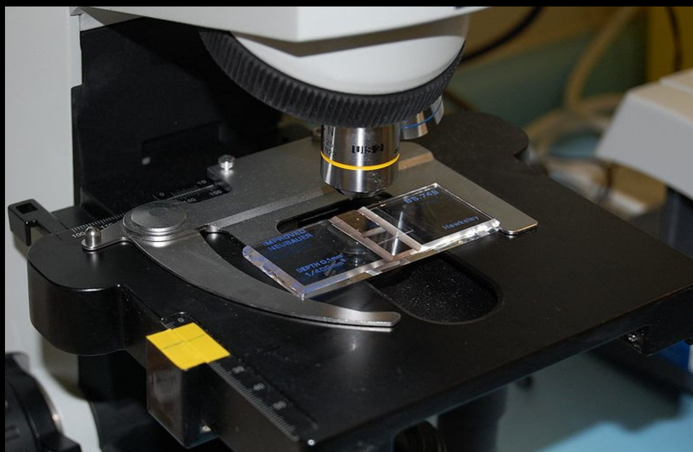
$$\sigma_{cap} = \frac{2\gamma \cos\theta}{r_{pore}}$$





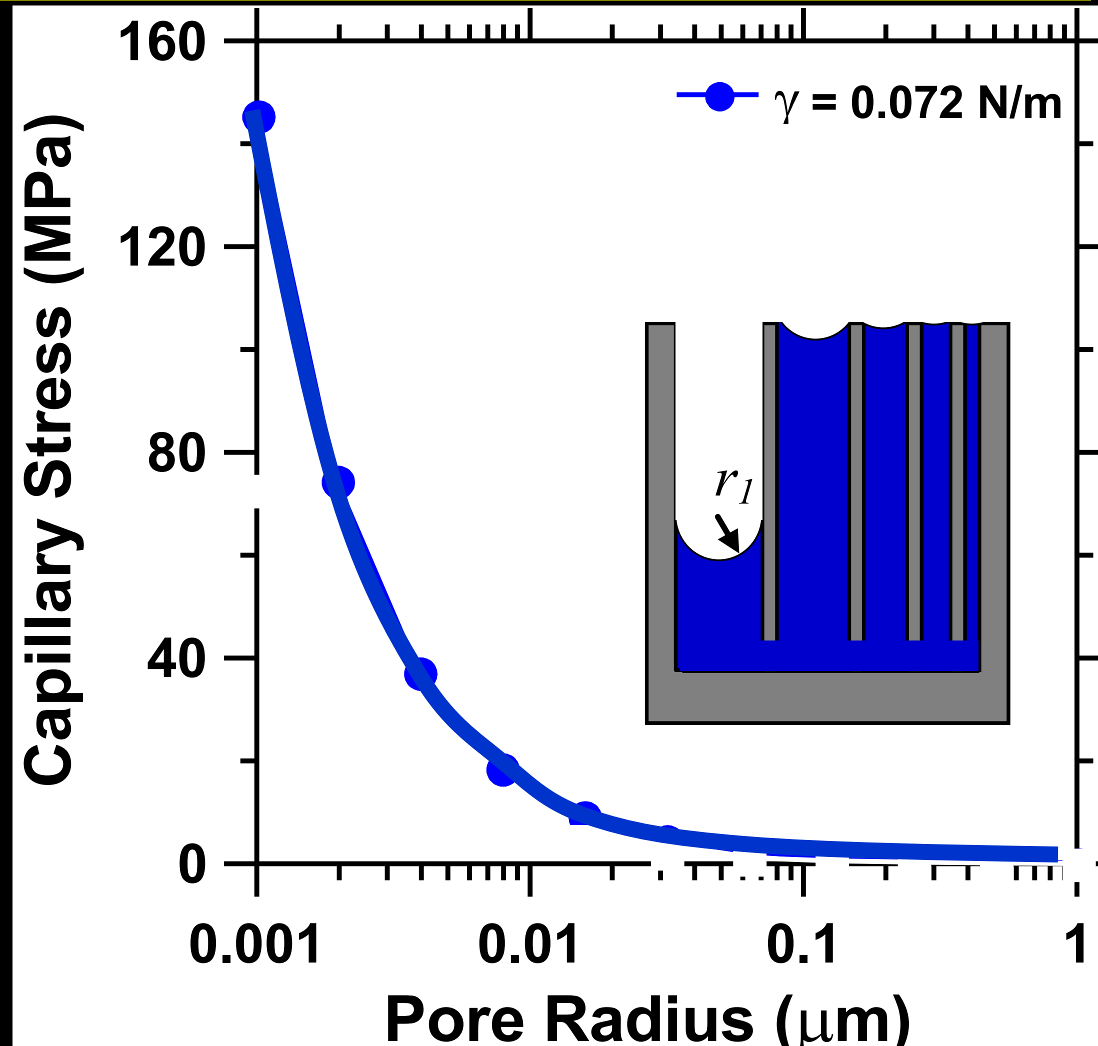
Pierre-Simon, marquis de Laplace (1749 - 1827)

Shrinkage Concepts (Young-Laplace)



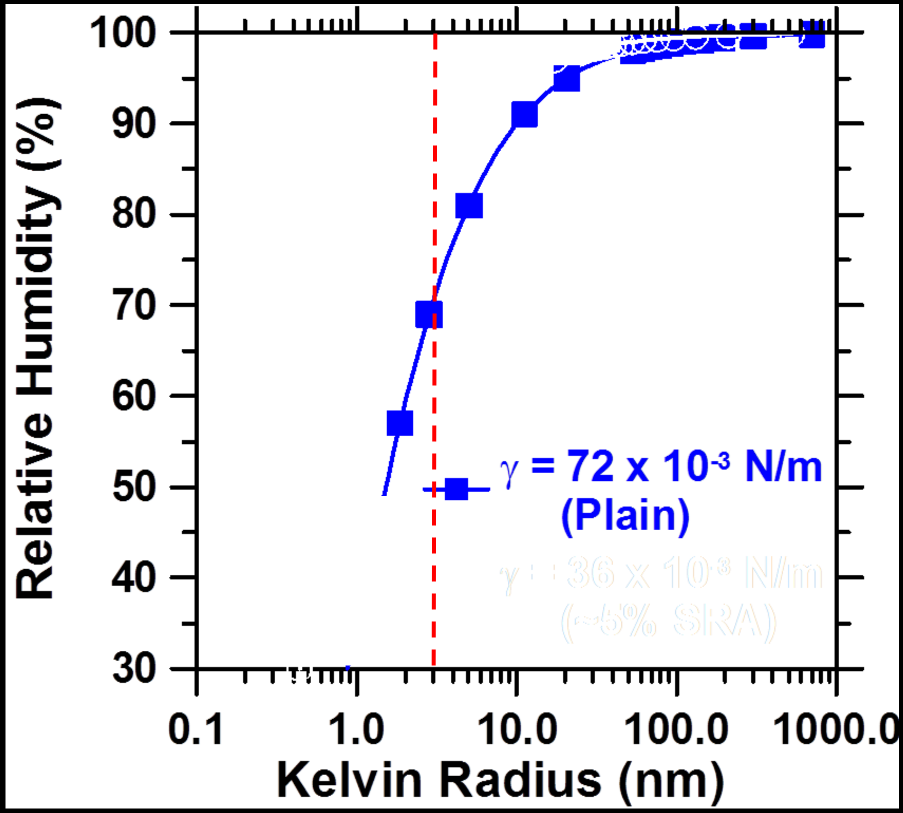
$$\sigma = \frac{2\gamma\cos\theta}{r}$$

capillary stress (σ)
pore geometry (r)
surface tension (γ)



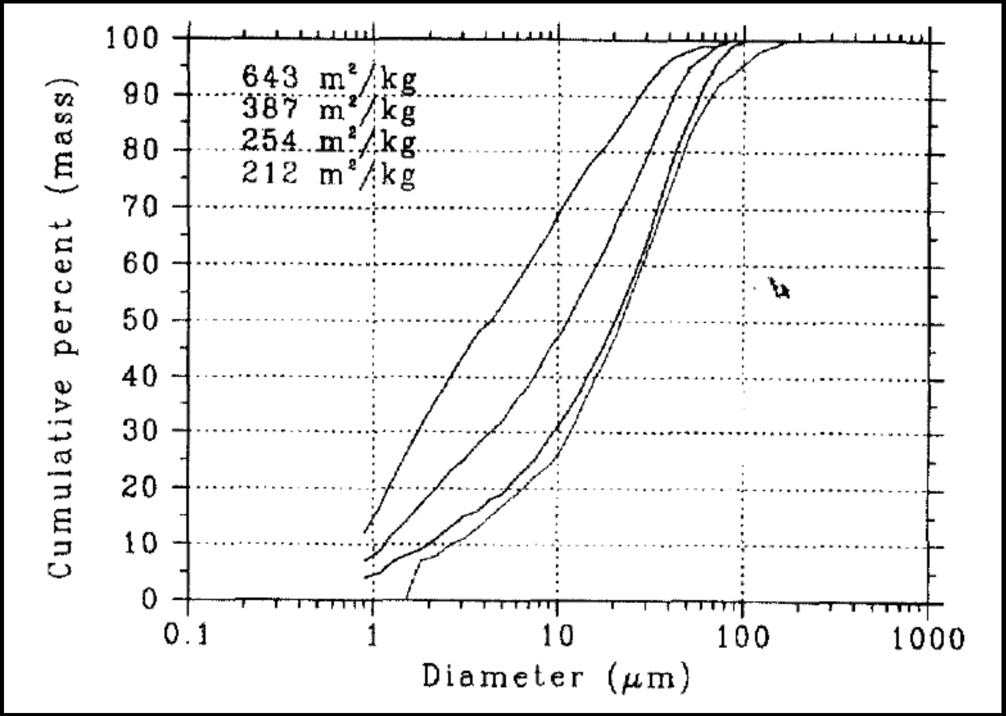
Important Take Aways

- Shrinkage is related to the space between pores that empty
- Some pores are more important
  - pores less than a few nm (other effects)
  - pores greater than 50 nm (low stress)
- Pore size is related to the particle size distribution of the cement



Important Distinction Between Blaine Fineness for PLC and OPC Will Be Made

- Example of a PSD for Cement with different Blaine fineness from Bentz et al. (2001)



- You can notice that the change in Blaine fineness (a measure of permeability) also significantly alters the pore size distribution (shifting the entire curve)

Outline for PLC Talk

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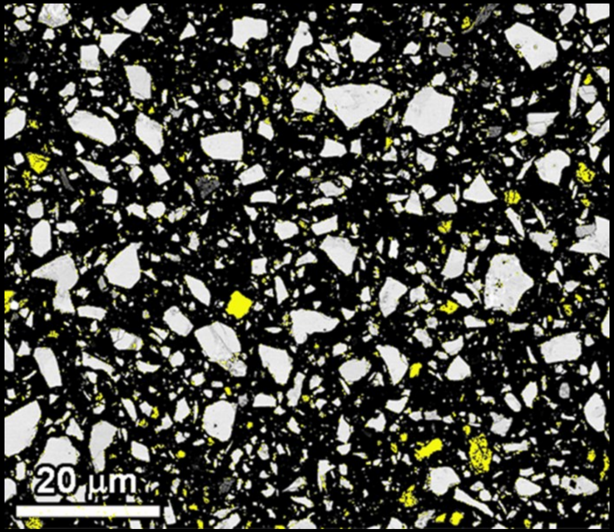
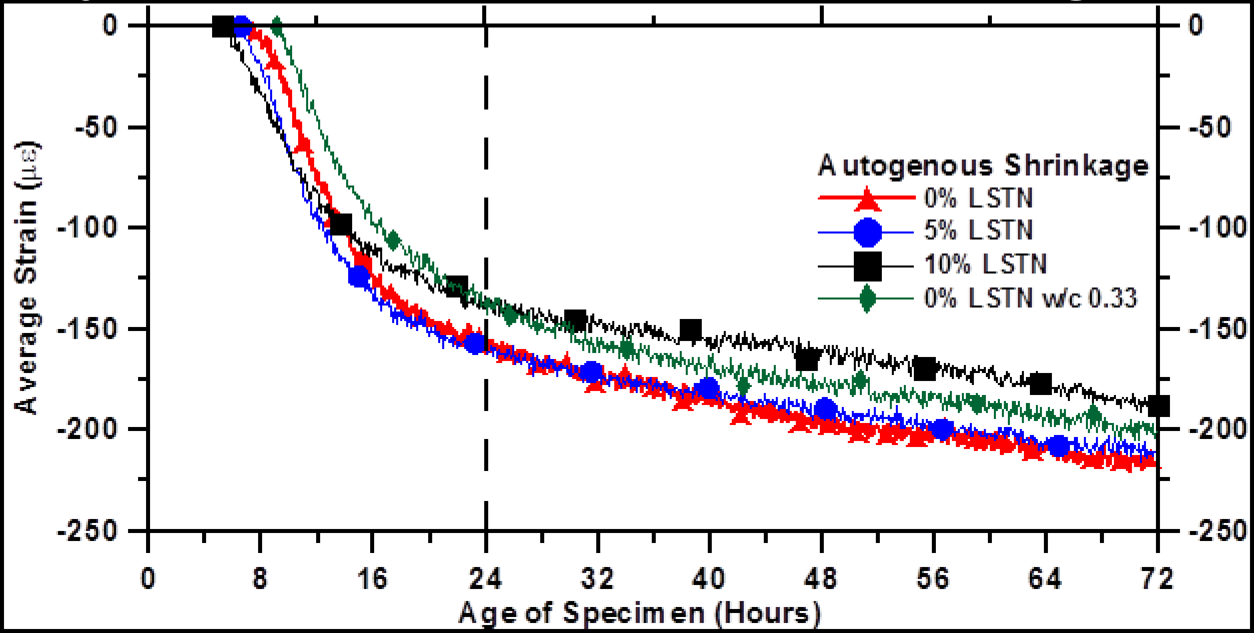


- Current Shrinkage Investigation
  - Three Systems – OPC, PLC, PLC-S
- Summary

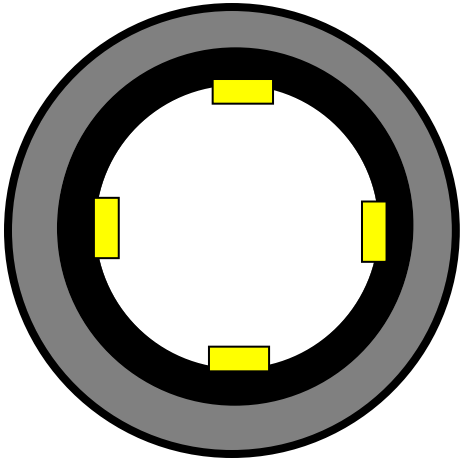
Bucher et al. (2009a) – Phase I Commerically Ground Blends

- 0%, 5%, 10% limestone replacement by mass
- 0% limestone, Type I/II, Blaine fineness 382 m^2/kg
- 5% limestone, Blend of 0% and 10%
- 10% limestone, Type GU, Blaine fine. 461 m^2/kg
- HRWRA
- w/cm = 0.30
- Mortar - 55% aggregate by volume

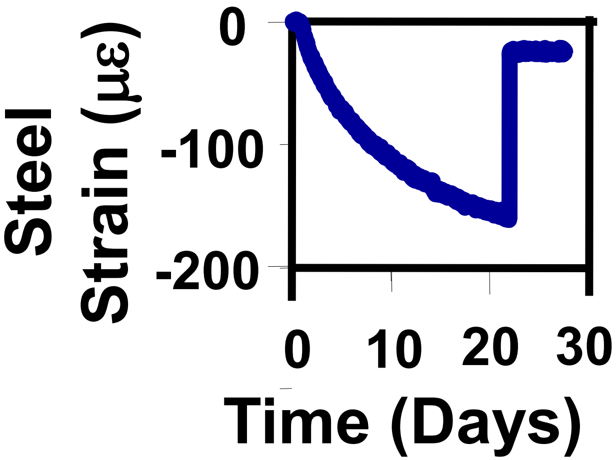


Restrained Ring Test

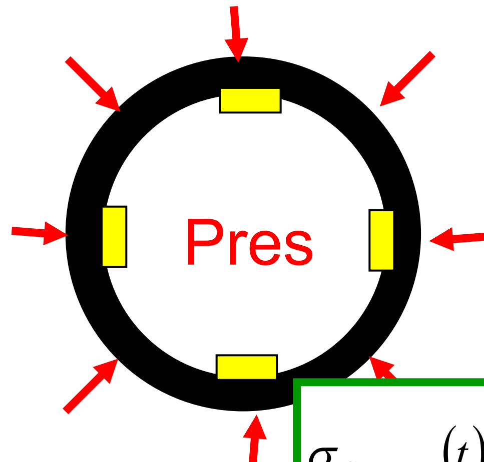
- Using an Instrumented Ring
- Measure Strain that Develops in Steel
- Determine the Pressure Required to Obtain that Strain
- Apply Pressure to Concrete and Obtain Tensile Stress



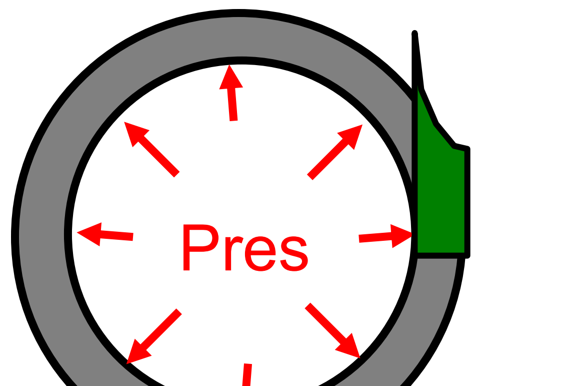
Original Ring



Measured Strain



Determine

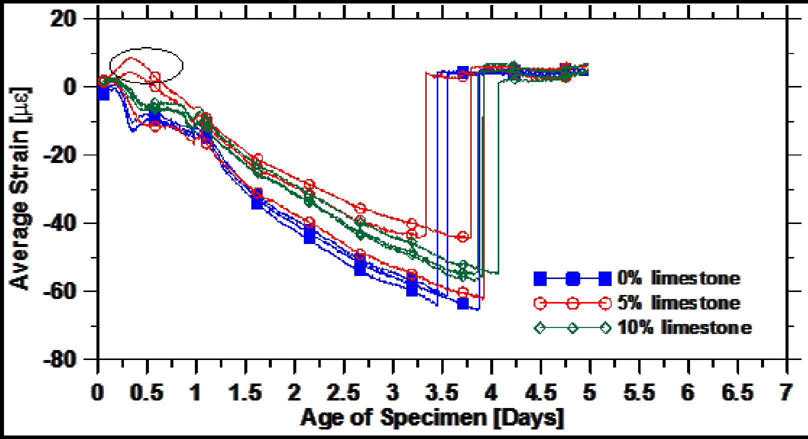


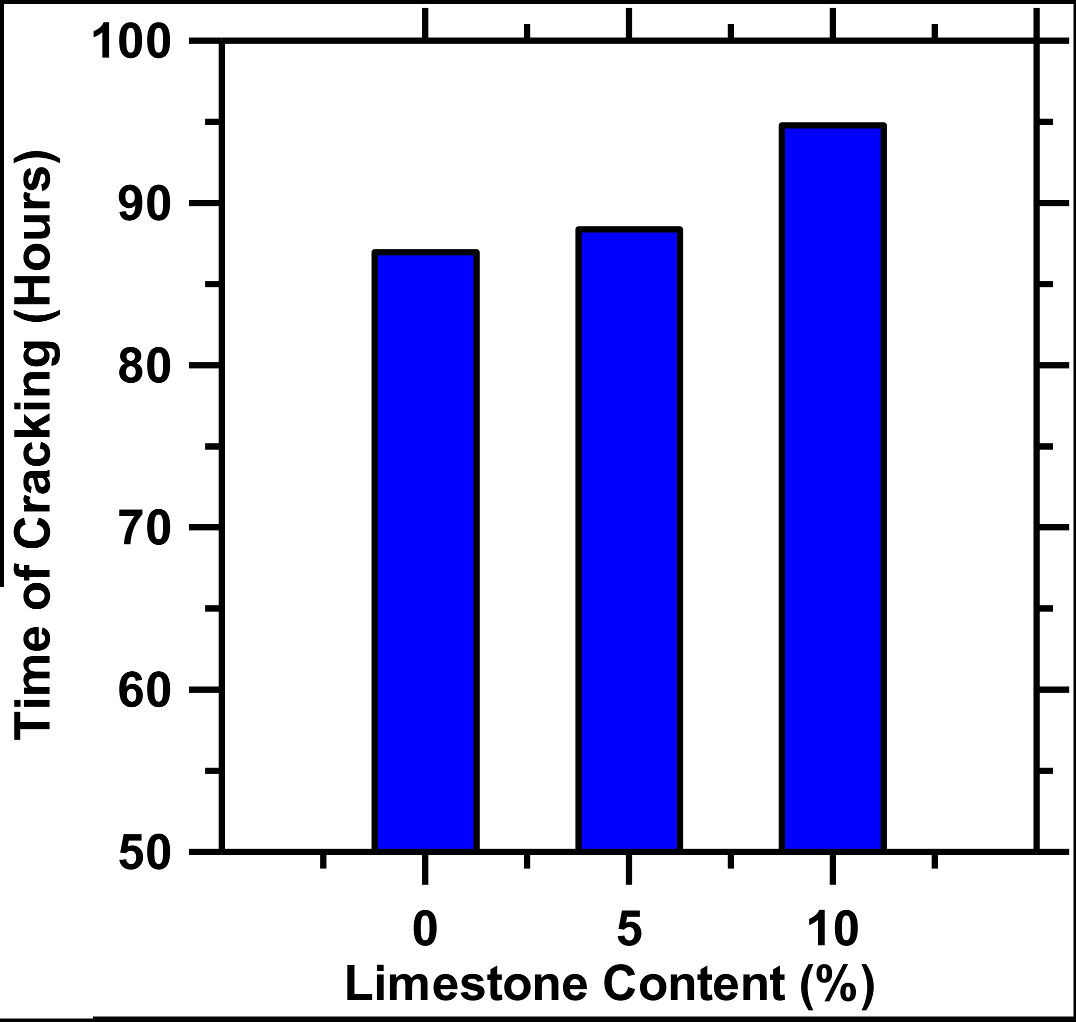
$$\sigma_{Concrete}(t)\big|_{r=R_{IC}} = \varepsilon_{Steel}(t)E_S \frac{\left(R_{OS}^2 - R_{IS}^2\right)}{2R_{OS}^2} \frac{\left(R_{OC}^2 + R_{IC}^2\right)}{\left(R_{OC}^2 - R_{IC}^2\right)}$$

Hossain and Weiss, CCC, 2004

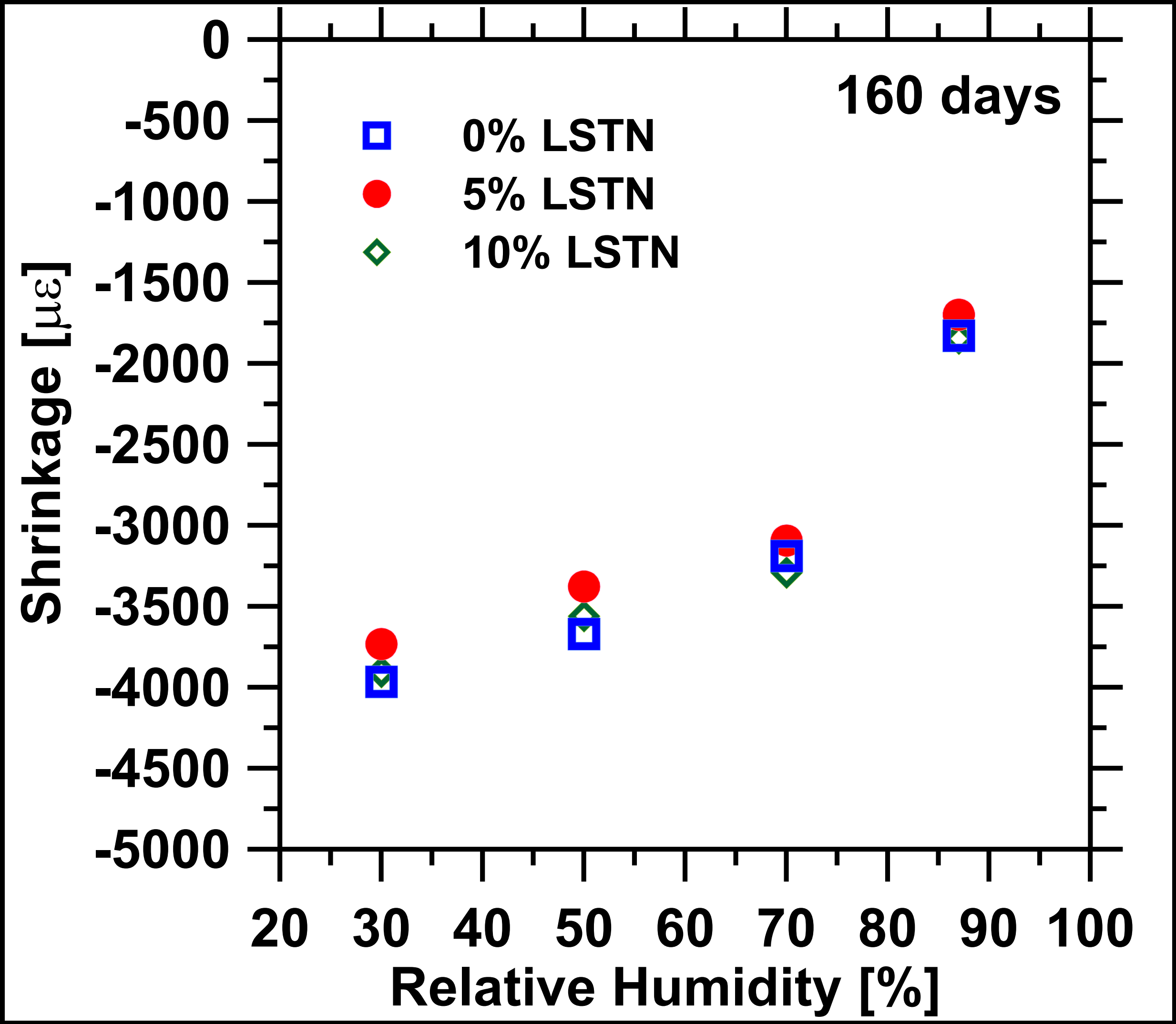
Restrained Ring Results

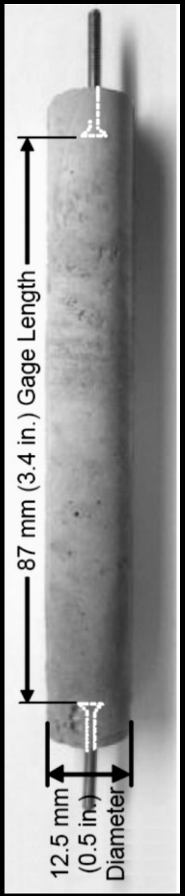
- The delay in time to cracking indicates that cements with limestone are slightly more resistant to cracking than plain cement systems.





Shrinkage in Paste



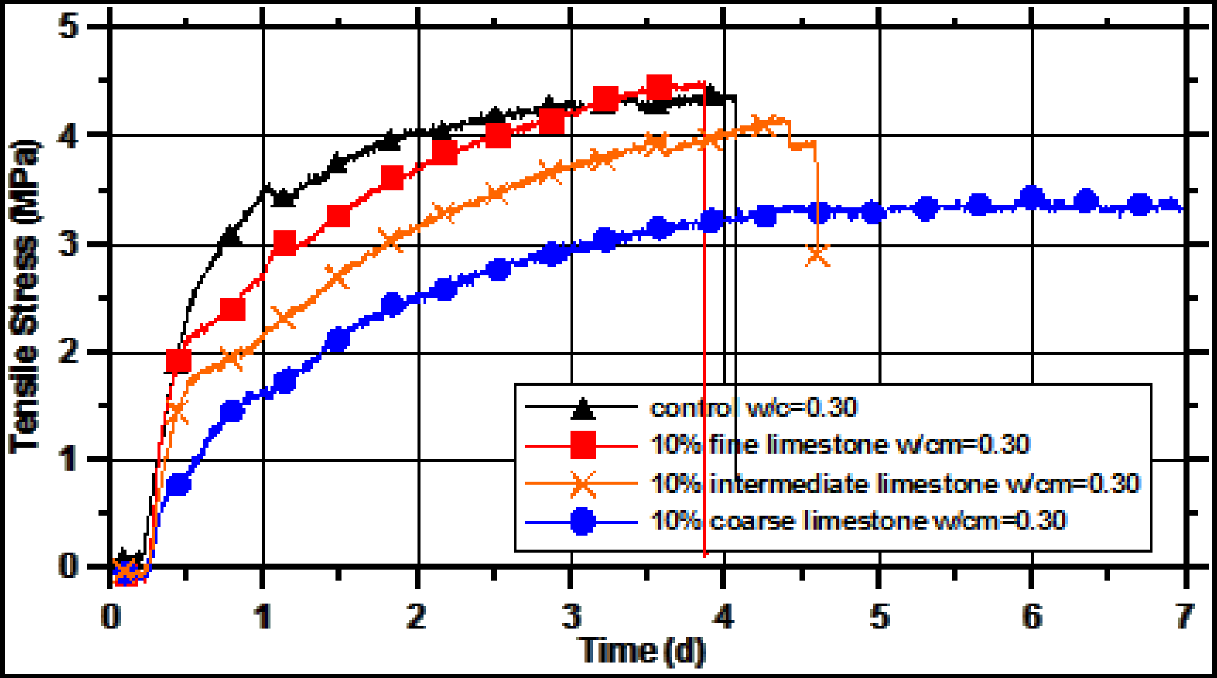


Phase II (Bucher 2009b) Cement with Limestone Replacement (Not Interground)

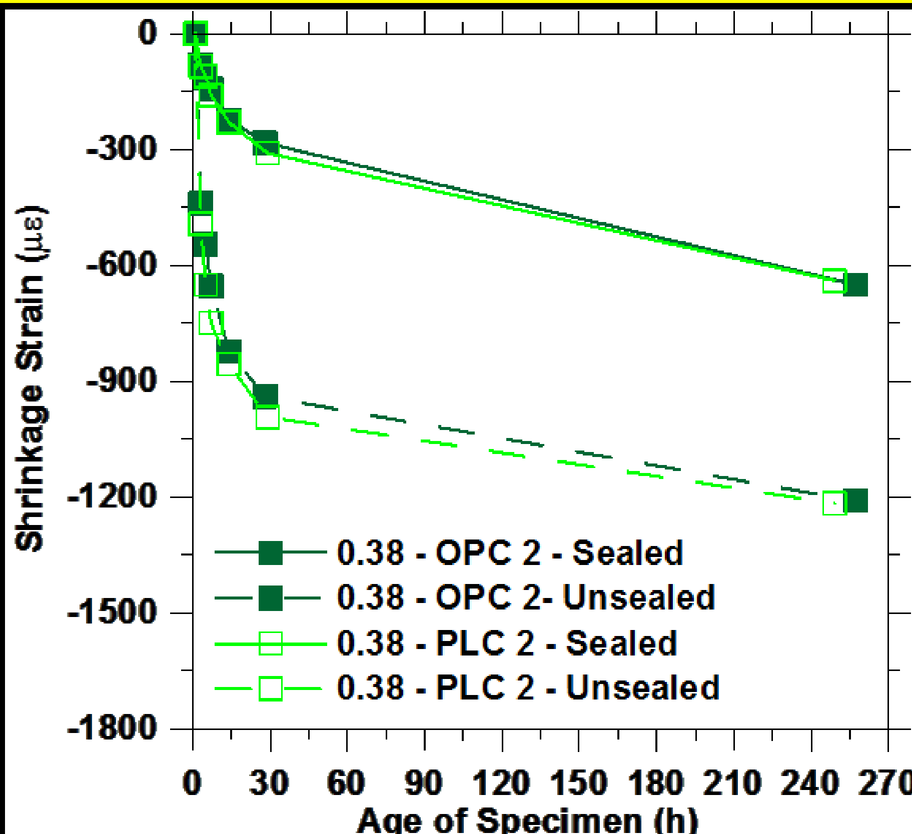
- Bucher et al. (2009) examined how limestone addition of limestone/replacement of cement influenced shrinkage & cracking of mortar.
- 3 sizes of limestone were used to replace 10% of the cement by volume (Unlike Other Phases)
  - small 3 micron
  - medium 17 micron, and
  - large 100 micron
- Note these are not equivalent performance

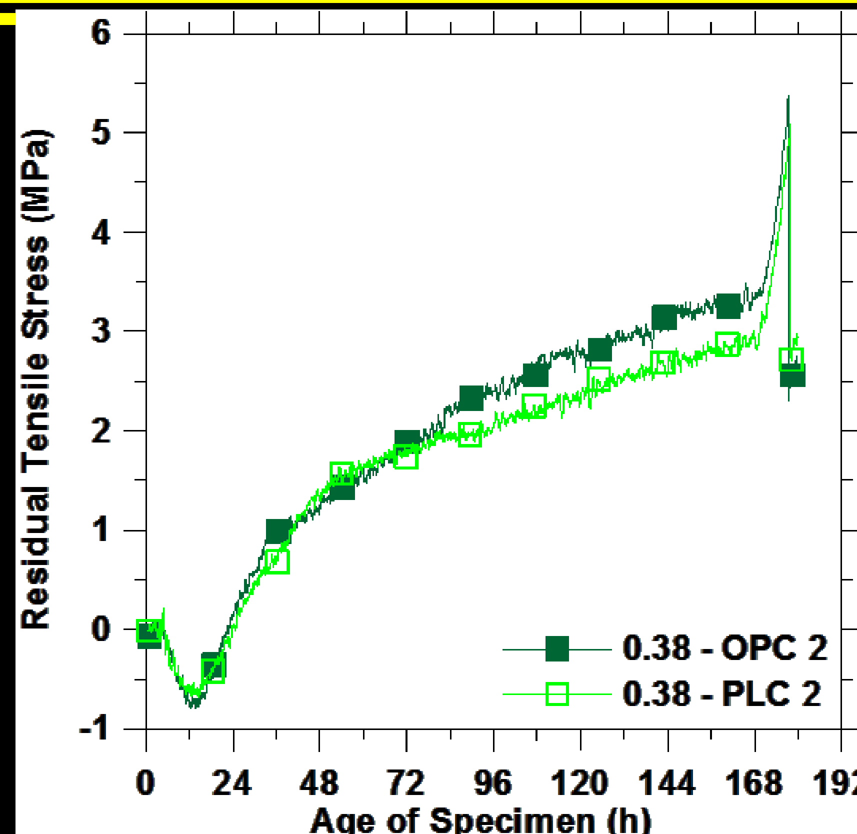
Phase II (Bucher 2009b) Shrinkage and Cracking Studies Cement/Limestone

- Fineness influences stress
- Fine limestone was similar
- Binder was a cement with additional limestone of different particle sizes
- Note these are not equivalent performance



Phase III – An Additional System Investigatged (Barrett et al. 2012)





- Used a commercially interground cement
- No increase in cracking tendancy

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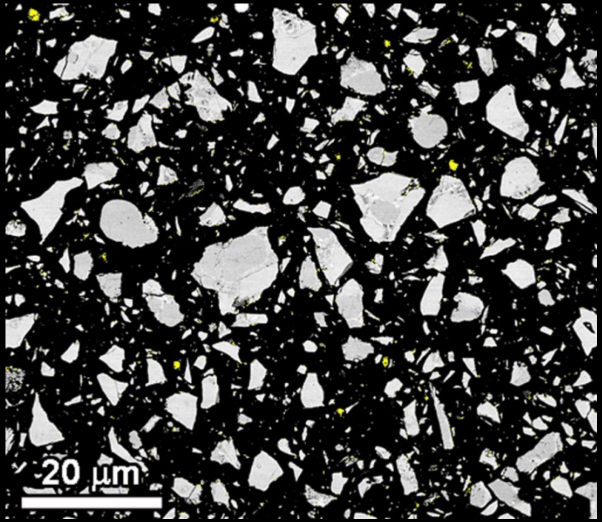
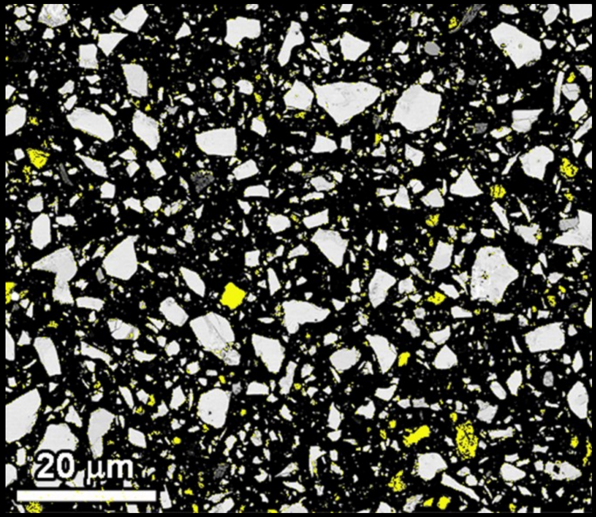
Phase IV - Objectives

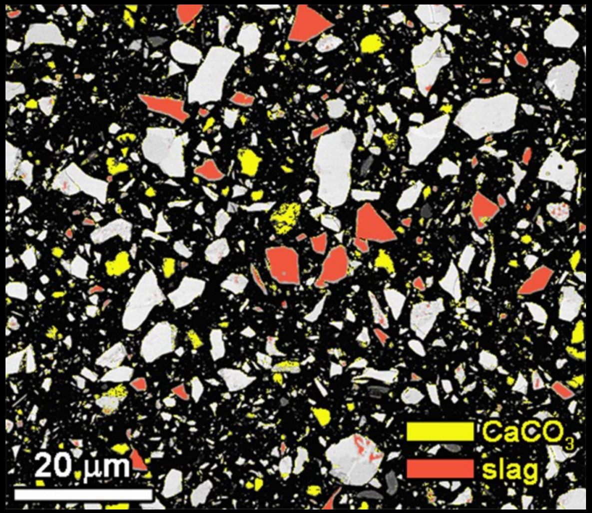
- Shrinkage and cracking potential in 3 systems
- Clinker and limestone interground (industrial)
- w/c = 0.39, mortar with 55% sand volume



OPC
(3.7% L)



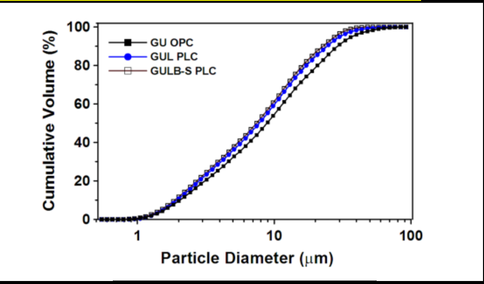
PLC
(11% L)



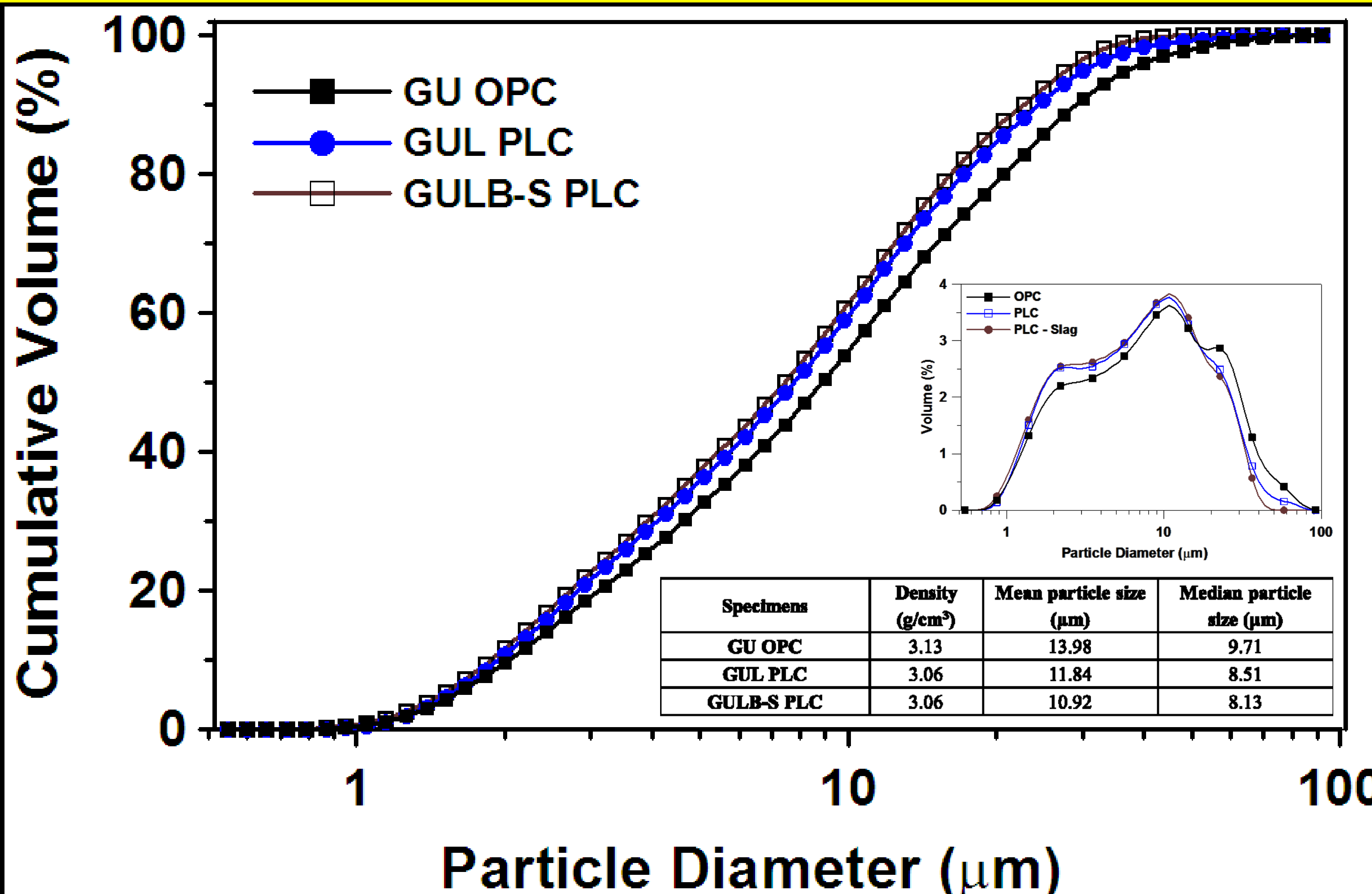
PLC-Slag
(10% L + 12% Slag)

Study Outline

- Task 1: Particle Size and Pore Size Distribution

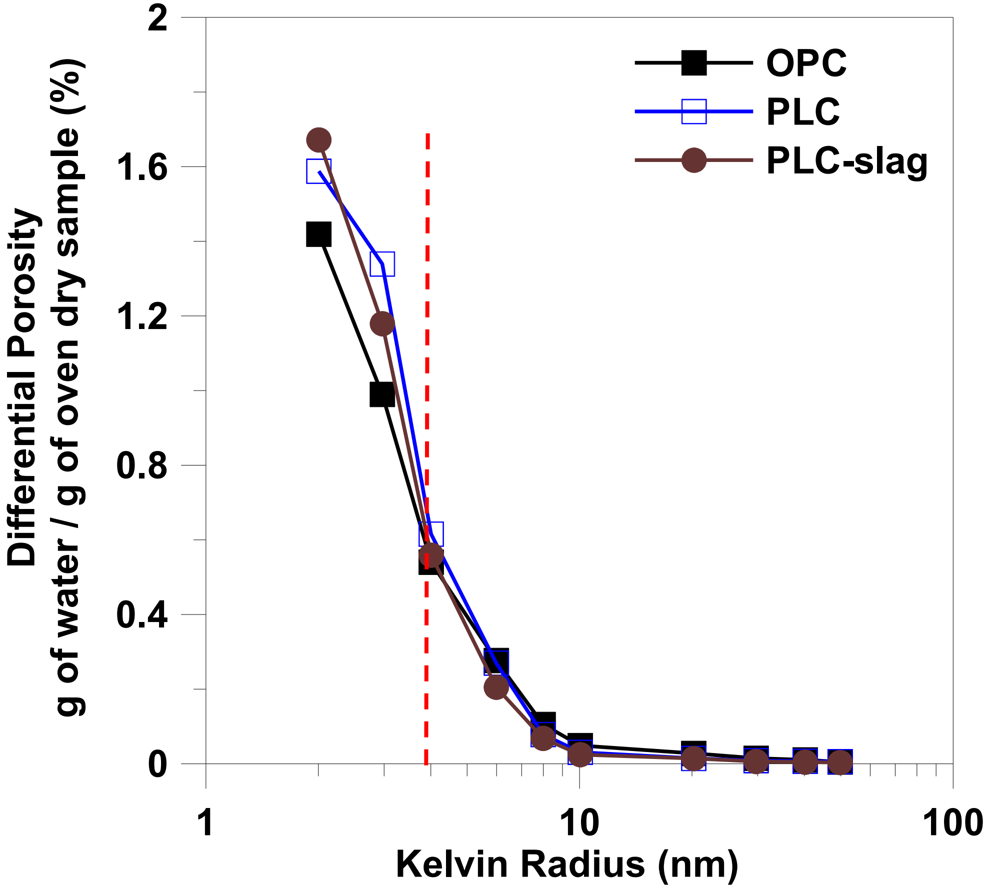


Particle Size Distribution - Cumulative



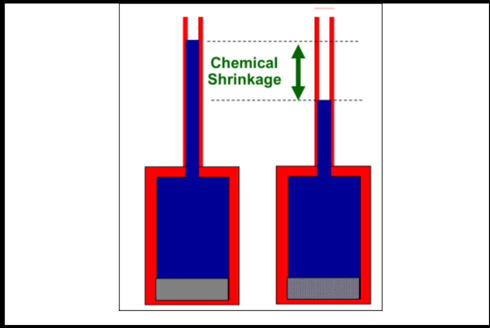
Specimens	Density (g/cm³)	Mean particle size (μm)	Median particle size (μm)
GU OPC	3.13	13.98	9.71
GUL PLC	3.06	11.84	8.51
GULB-S PLC	3.06	10.92	8.13

Pore Size Distribution



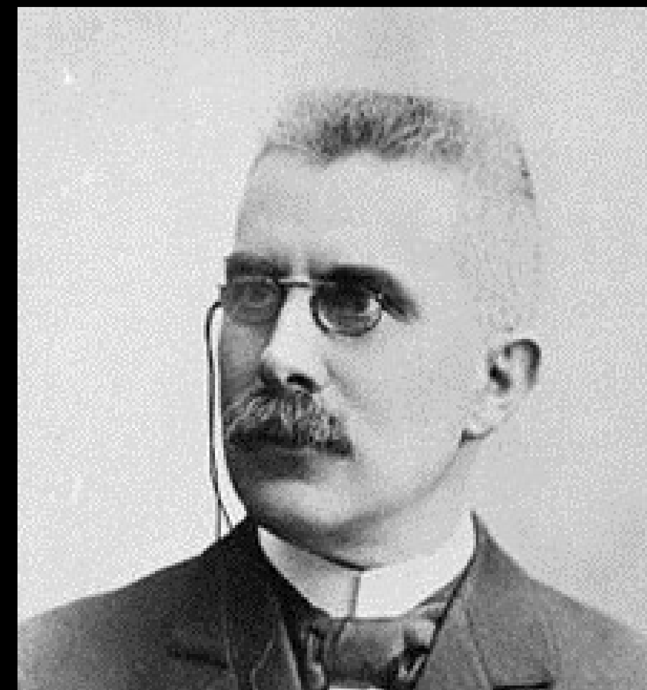
Study Outline

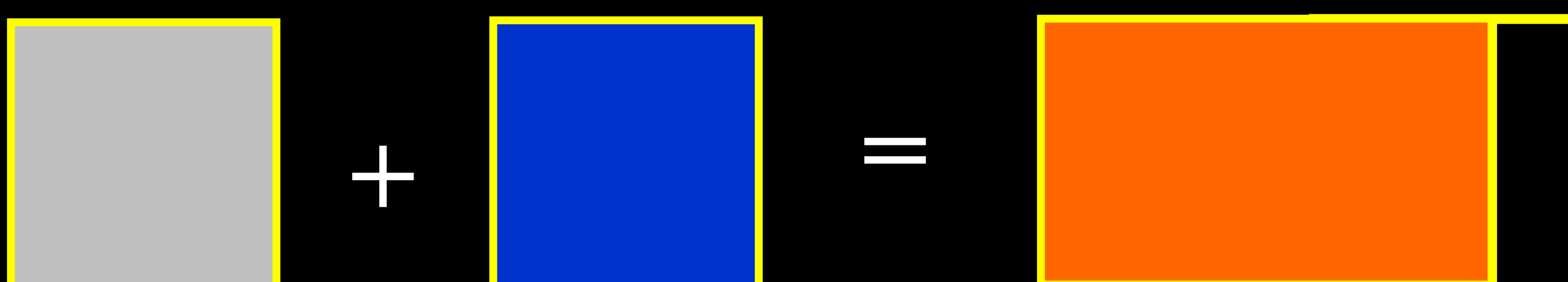
- Task 2: Chemical Shrinkage



Fundamental Volume Change

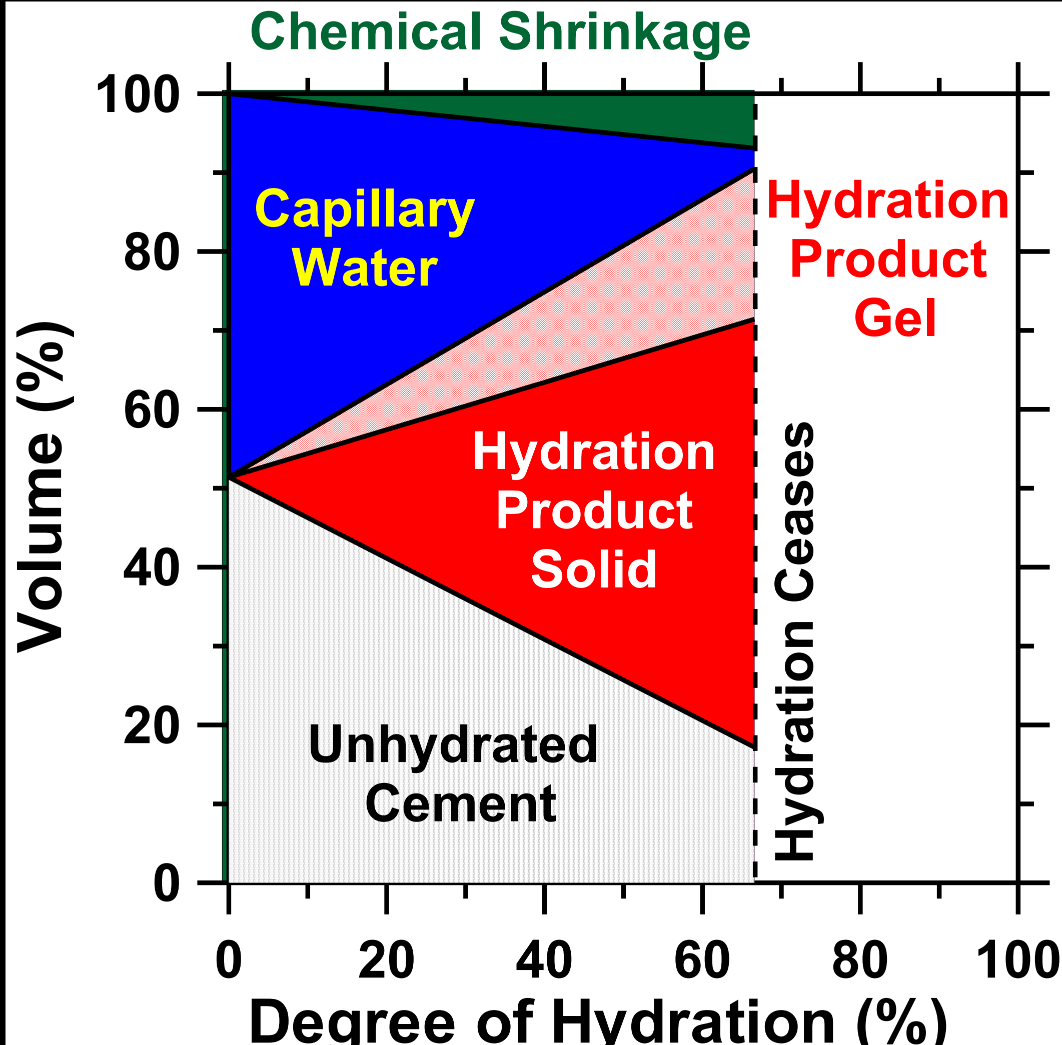
- Le Chatelier
- 1850-1936
- Volume of the reactants larger than the volume of the products
- Chemical Shrinkage





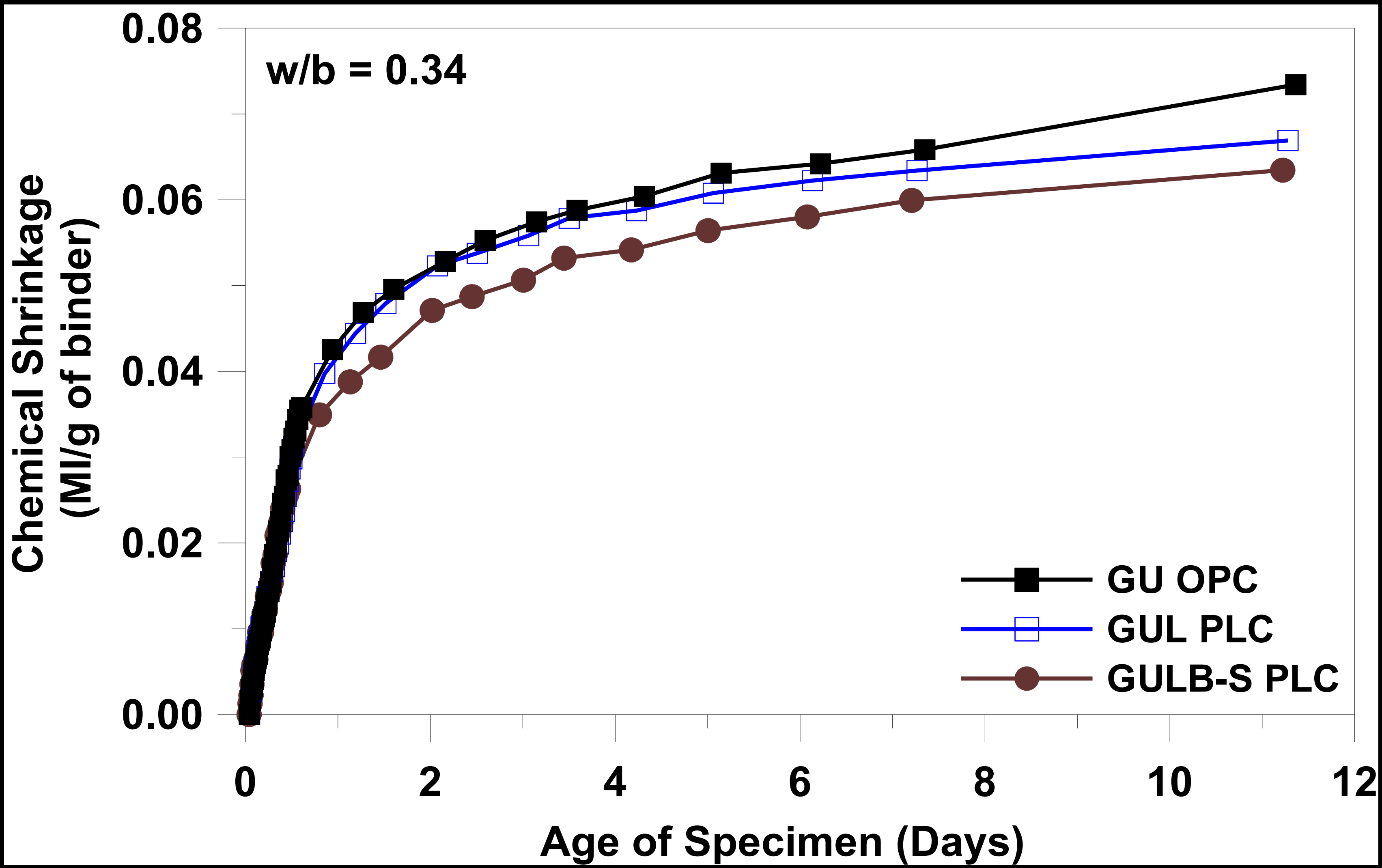
Chemical Shrinkage

- Observed by Le Chatelier over a century ago
- "the volume reduction associated with the hydration reactions in a cementitious material"
- Powers conceptual model shown ~ 6.4% reduction



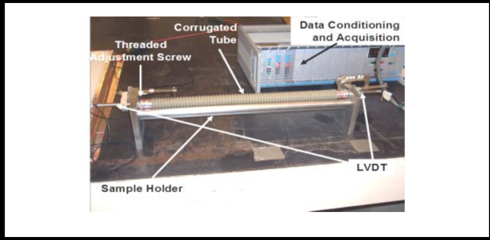
(after Powers)

Chemical Shrinkage per gram of binder

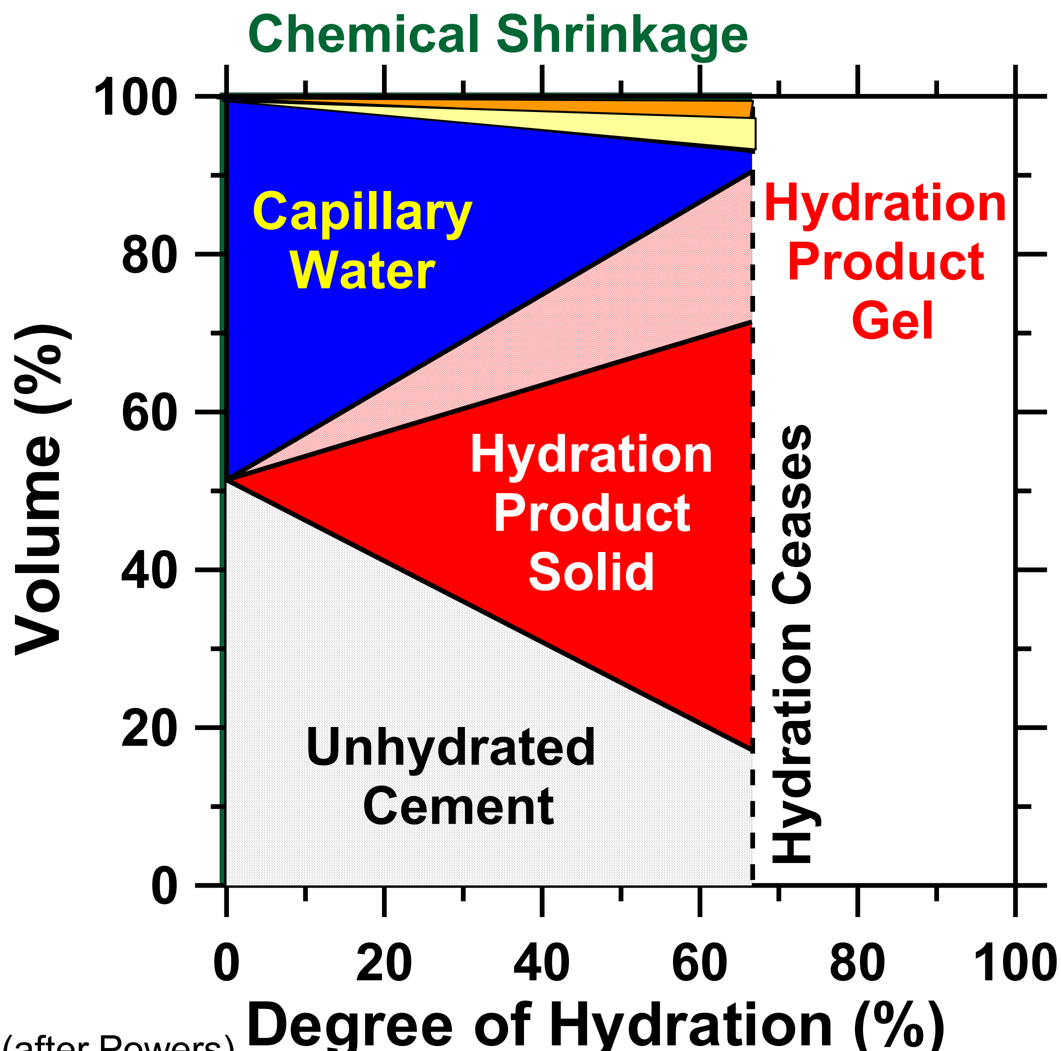


Study Outline

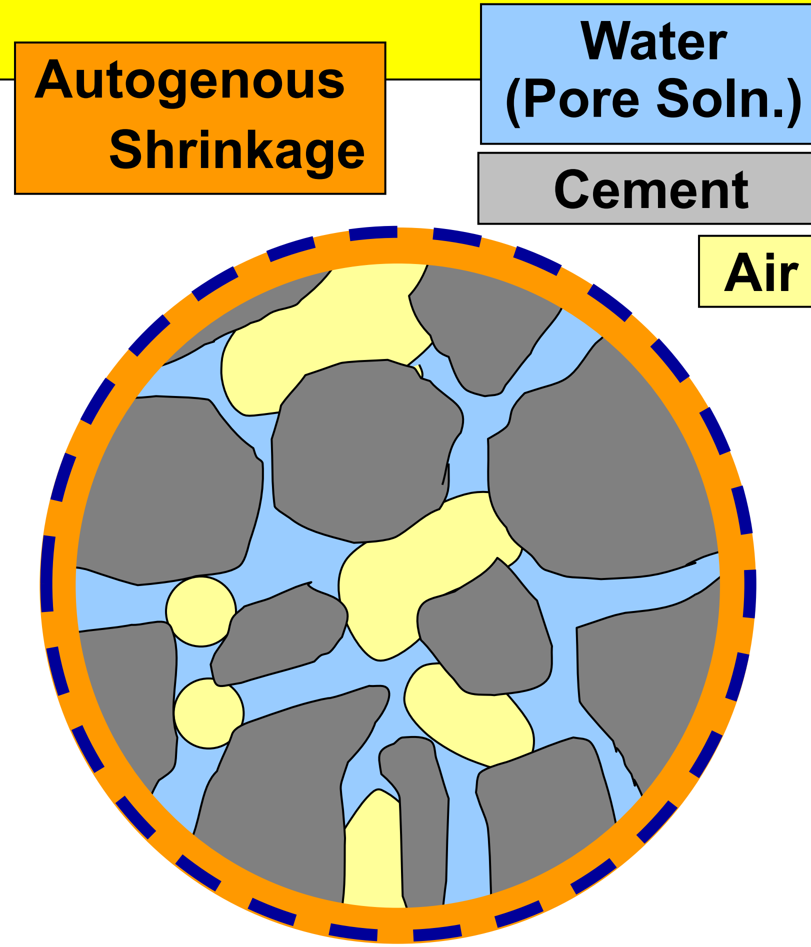
- Task 3: Autogenous Shrinkage



Autogenous strain is “the bulk strain of a closed, isothermal, cementitious material system not subjected to external forces



(after Powers)

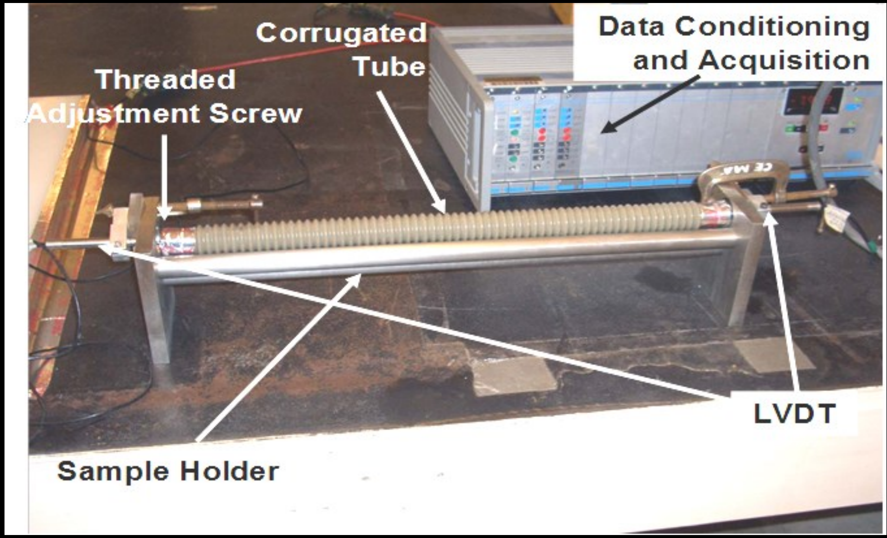


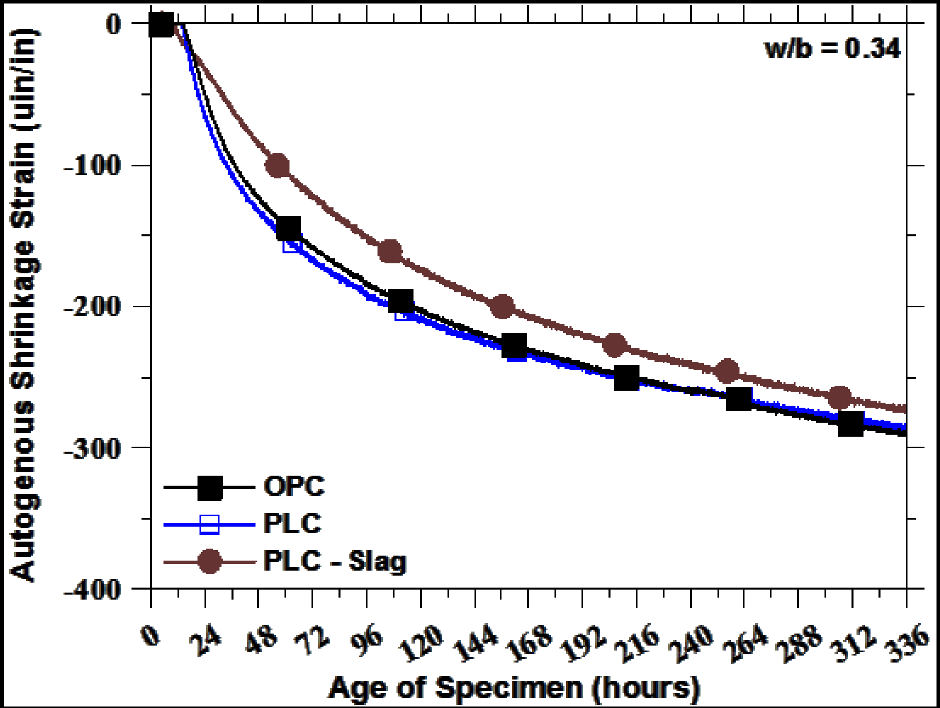
Measured by External Deformation of a Sealed Body

(after Jensen & Hansen 2001)

ASTM C 1698 Autogenous Shrinkage

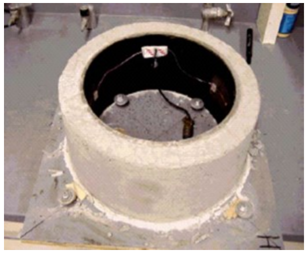
- Autogenous shrinkage (Corrugated Tube)
- OPC and PLC have similar shrinkage
- PLC-S has a slightly lower early shrinkage





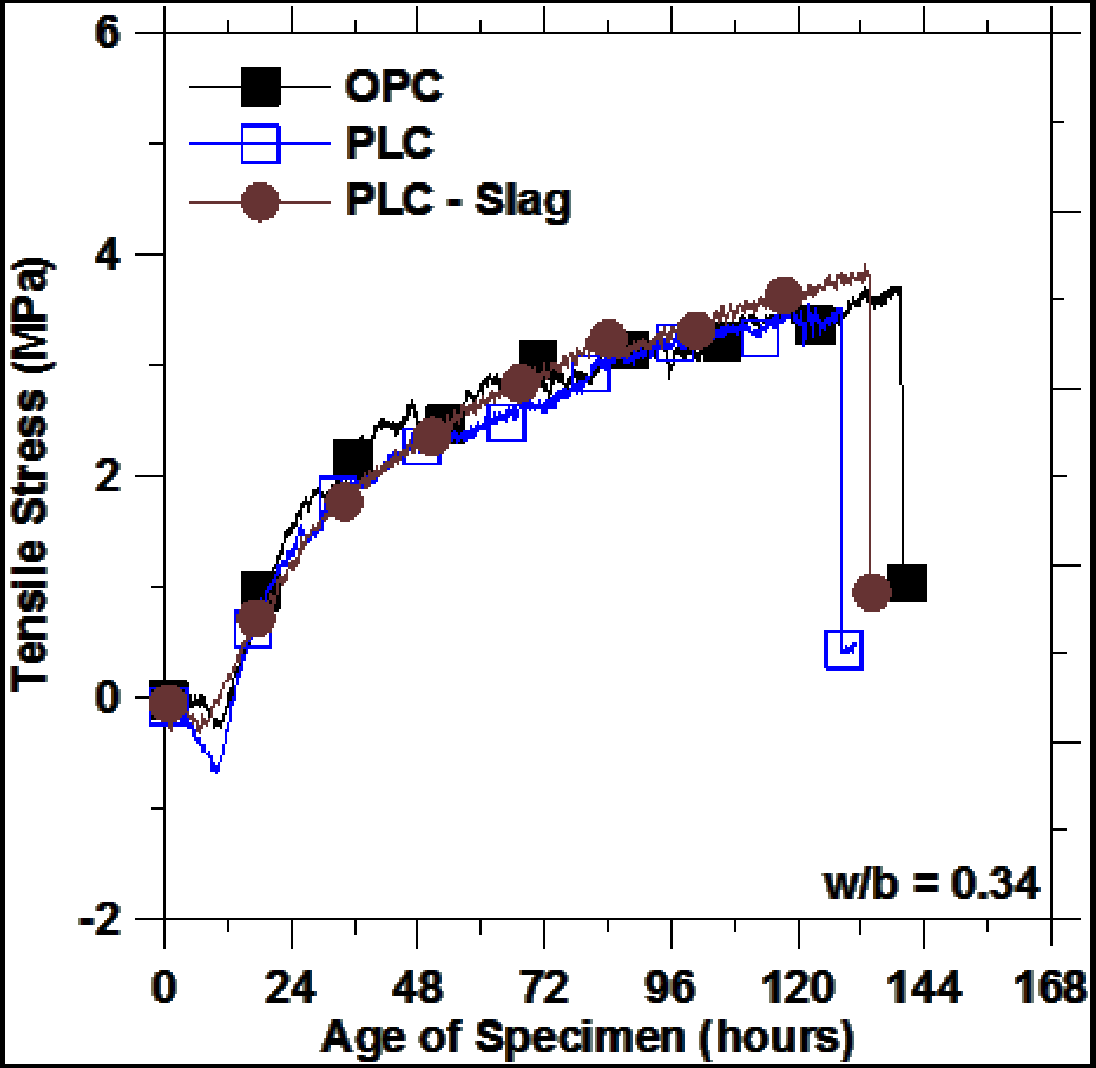
Study Outline

- Task 4: Restrained Shrinkage



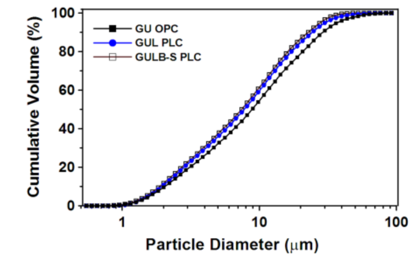
Restrained Shrinkage

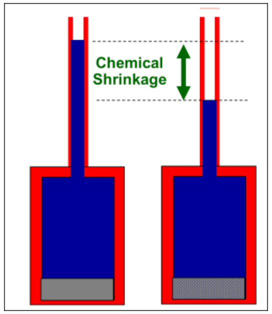
- Dual restrained ring test
- Shows similar stress development and age of cracking

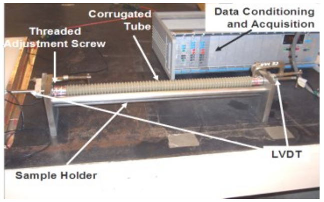


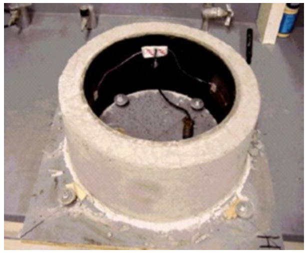
Study Outline - Summary

- Task 1: Particle Size and Pore Size Distribution
  - – Less big particles PLC, PLCS
  - – pores similar as related to shrinkage
- Task 2: Chemical Shrinkage
  - – Less early age chemical shrinkage
- Task 3: Autogenous Shrinkage
  - – Lower shrinkage for PLC, PLCS
- Task 4: Restrained Shrinkage
  - – OPC, PLC, PLCS Similar









Summary

- PLC is not just a dilution of OPC
- PLC, PLC-Slag are engineered differently to obtain ‘Similar Performance’ (f’c at 28 days)
- Have shown similar or less autogenous shrinkage and similar or less restrained shrinkage cracking
- Explained using Young-Laplace equation showing that the increase in Blaine fineness does not alter pores in range of interest