A Source of Interfacial Porosity in Cemented Femoral Stems

Stephen H. Spiegelberg
Gareth H. McKinley
Cambridge Polymer Group, Inc.

11 Ward St.
Somerville, MA 02143
http://www.campoly.com

Background

- Asceptic loosening necessitates revision surgery in 1-12% of THR
- Retrieved components indicated that debonding at the cement-stem interface initiates failure of fixation(Jasty et al, 1991)
- Fracture analysis shows crack initiation from pores in the cement (James et al, 1992)
- No dependence on surface finish, centrifugation, or alloy (James et al, 1993)

Theory of Interfacial Porosity

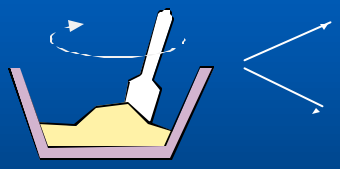
- Related to the rheological (flow) properties of the bone cement
- Relationship between the response time of the cement and the insertion rate of the femoral stem

Experimental Program

- Two step program
  - Characterize the rheological properties of the bone cement
  - Perform stem insertion studies at different times during cure and insertion rates
  - Quantify conditions that lead to extensive interfacial porosity

Experimental Program

Howmedica Simplex P™



Mixing at 4 C for 1 minute, 23 C for 1 minute. Tests begin 4 minutes into cure.

1. Shear Rheometry

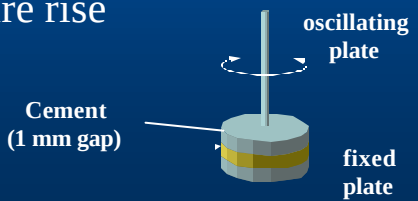
Viscosity
% shrinkage
relaxation time, λ

2. Stem Insertion

Interfacial porosity vs. cure time and insertion speed

Rheological Characterization

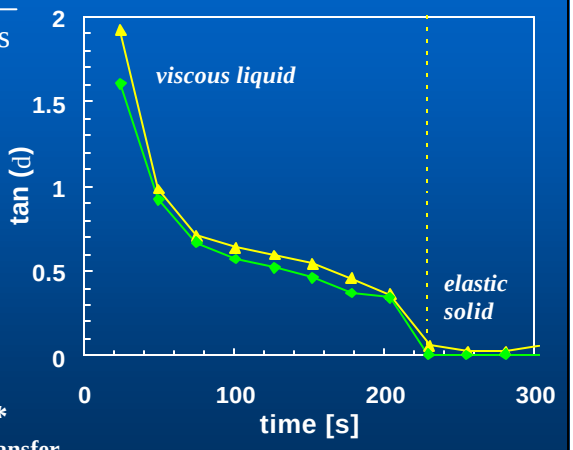
- Parallel plate controlled stress rheometer
  - measure torque as a function of displacement
- Performed small amplitude oscillatory test as a function of time
- Measure complex viscosity, volumetric shrinkage, temperature rise



Cure Time

$$\tan d = \frac{G''}{G'} = \frac{\text{loss modulus}}{\text{elastic modulus}}$$

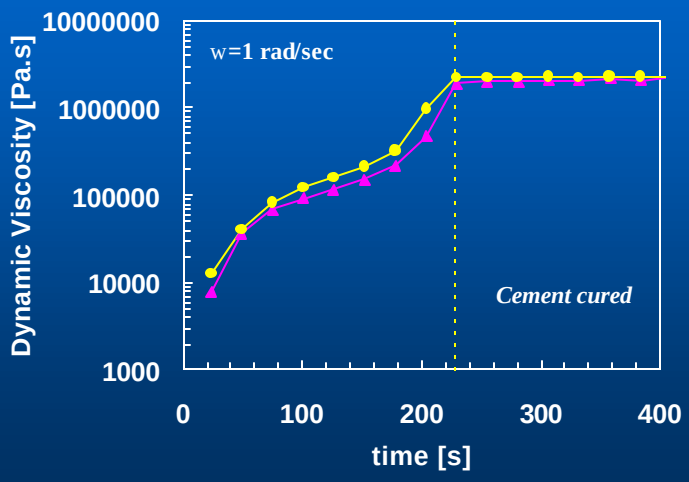
liquid	**tan** d → ¥
solid	**tan** d → 0



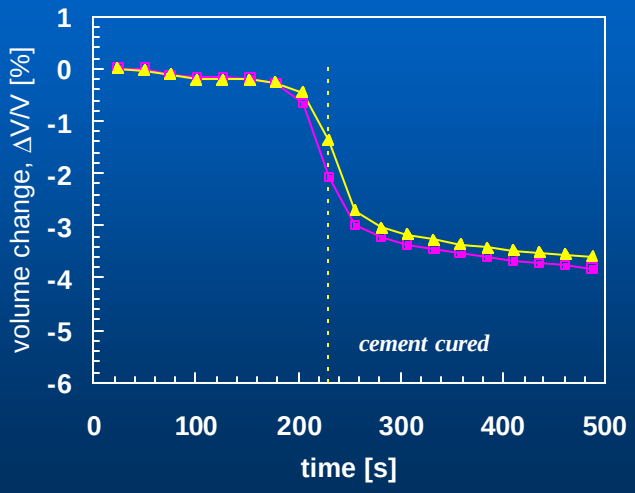
- **Cure time: 264 seconds***

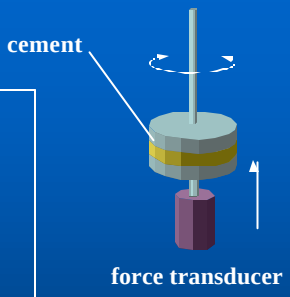
***following 4 minutes of mixing/transfer**

Transient Viscosity



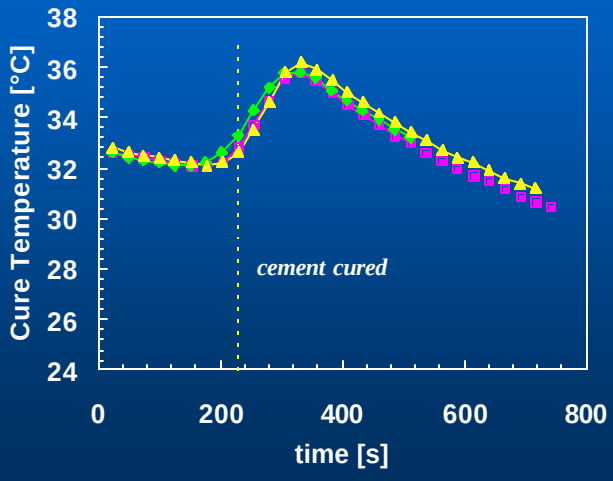
Volumetric Shrinkage

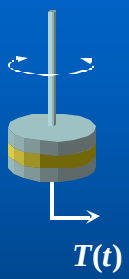




- Haas (1975): 5%

Temperature Rise





Relaxation Time

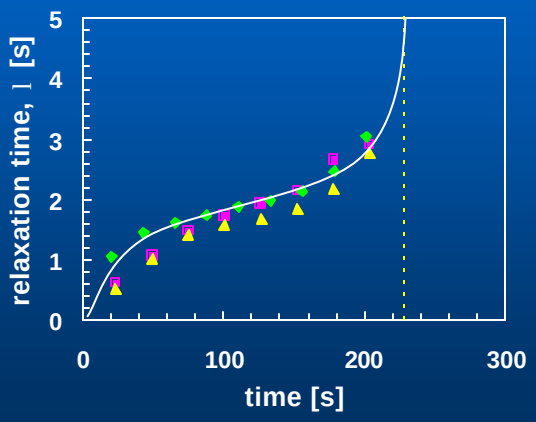
- Characterizes '*response time*' of cement

$$l = \frac{1}{w \tan d(w)}$$

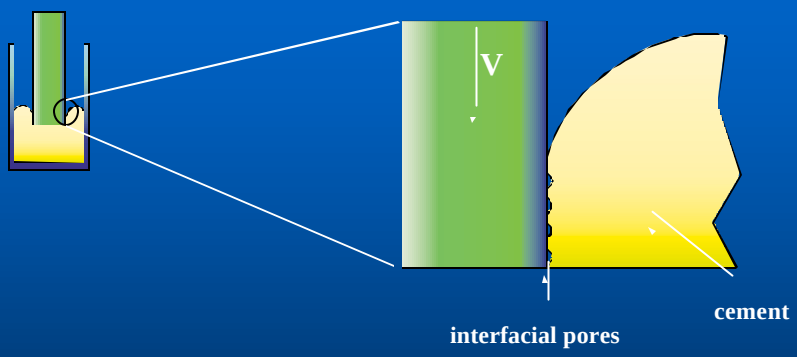
λ for water: 10^{-11} sec

λ for polymer: 1 sec

λ for solid: $\rightarrow \infty$ sec

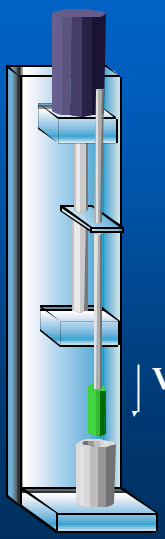


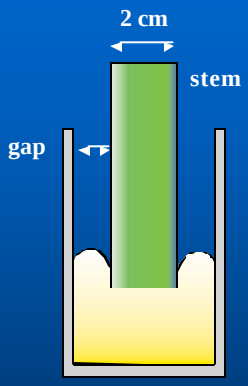
Hypothesis for Porosity Formation



- Cement spreads on surface : relaxation time λ
- If stem insertion time scale *f*(V) << λ
  - greater pore formation at interface

Stem Insertion Studies



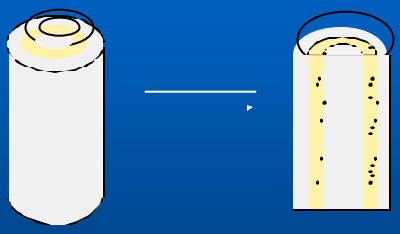


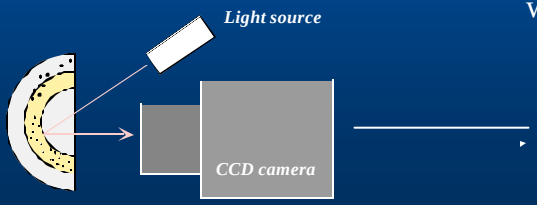
Stem: PMMA
Stem insertion, V: 1-5 cm/s
Insertion time: 22-204 seconds*
Gap: 2.5 mm

*** following 4 min. of mixing and loading**

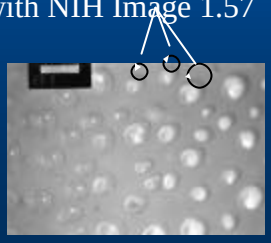
Stem Insertion Studies

- Section and polish



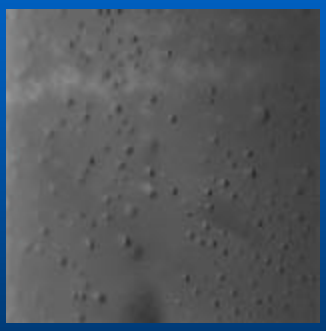


Analyze pore distribution with NIH Image 1.57

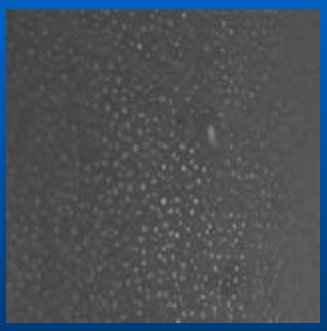


Stem Insertion Studies

Insertion Velocity: 5 cm/sec



Time into cure: 24 sec*

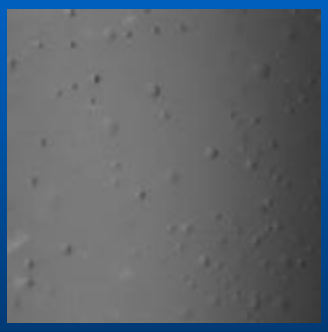


Time into cure: 204 sec*

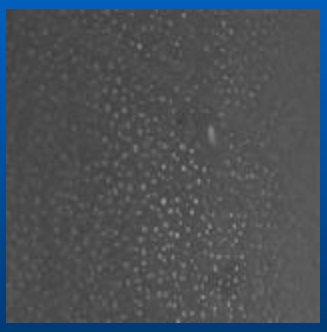
***Following 4 minutes of mixing and sample loading**

Stem Insertion Studies

Time into cure: 204 sec*



Insertion rate: 1 cm/sec

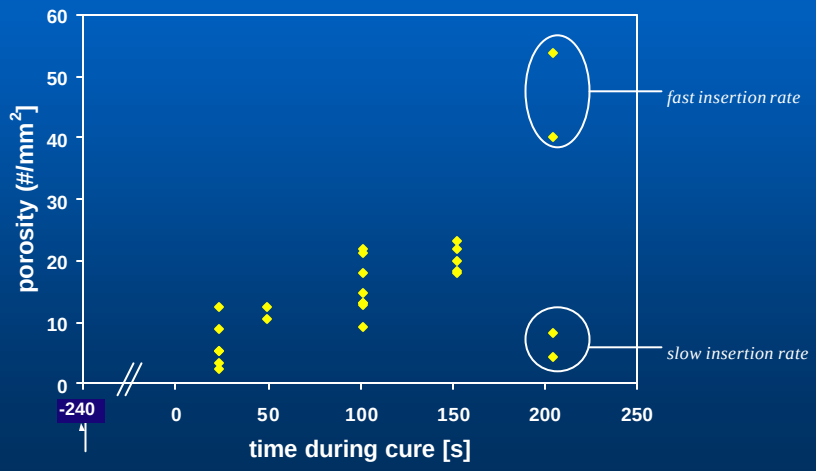


Insertion rate: 5 cm/sec

***Following 4 minutes of mixing and sample loading**

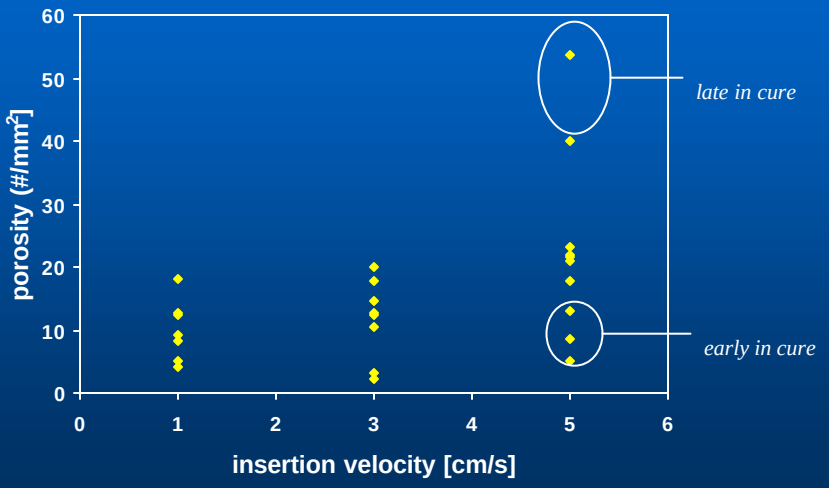
Cement-Stem Interfacial Porosity

- Pore diameter 100-300 μm



Start mixing cement

Cement-Stem Interfacial Porosity



Cement-Stem Interfacial Porosity

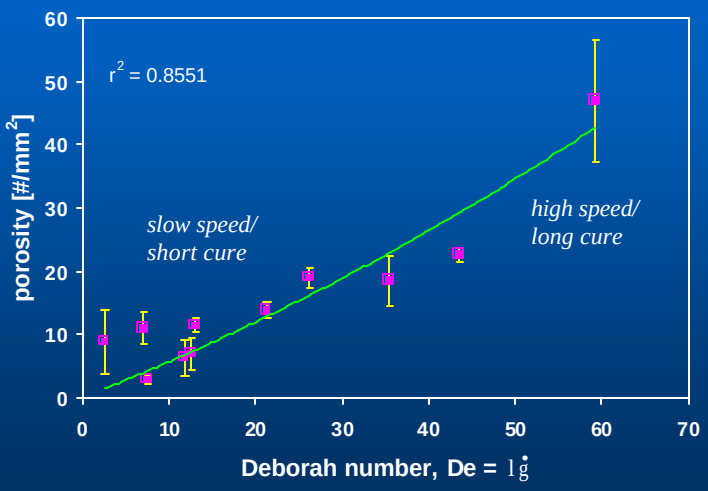
- Combine 2 parameters into one universal parameter
  - time during cure
  - stem insertion velocity
- Deborah number, *De*

$$De = \frac{\text{response time of cement}}{\text{characteristic time of experiment}} = \frac{l}{(1/\dot{g})} = l\dot{g}$$

λ = relaxation time of cement (rheometry) = *f*(time during cure)

$\dot{\gamma}$ = shear rate in gap between stem and bone = *f*(stem insertion rate)

Cement-Stem Interfacial Porosity



Conclusions

- Shear rheometry a good technique to characterize the cure behavior of acrylic bone cement
  - viscosity
  - temperature rise
  - cure time
  - volumetric shrinkage
  - relaxation time (response time of material)

Conclusions

- Interfacial porosity increases both with stem insertion speed and with time during cure
- Porosity scales well with Deborah number (relative rate of insertion *vs.* response time of cement).
- Results serve as an operating window for minimizing interfacial porosity

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