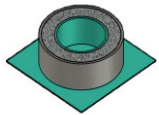


# ICRI 2017 Spring Convention March 15-17, 2017

## Evaluating Shrinkage Cracking Potential of Concrete Using Ring Test

- Bruce G. Menu, PhD candidate, Laval University, Canada
- Marc Jolin, professor, Laval University, Canada
- Benoît Bissonnette, professor, Laval University, Canada
- Laurent Molez, associate professor, INSA, Rennes, France



# Overview

- ❑ Early-age shrinkage cracking
  - ❖ Shotcrete
  - ❖ AASHTO PP34-99 “Ring Test”
- ❑ Restrained shrinkage analysis
  - ❖ Stress development and stress rate
  - ❖ Creep evaluation
- ❑ Results and discussions
  - ❖ Free “Ring Test”
  - ❖ AASHTO PP34-99 “Ring Test”
- ❑ Summary



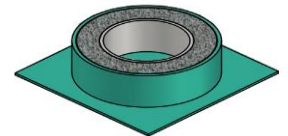
- General Objectives

- Predict the likelihood of restrained shrinkage cracking occurrence in repair materials

- Specific Objectives

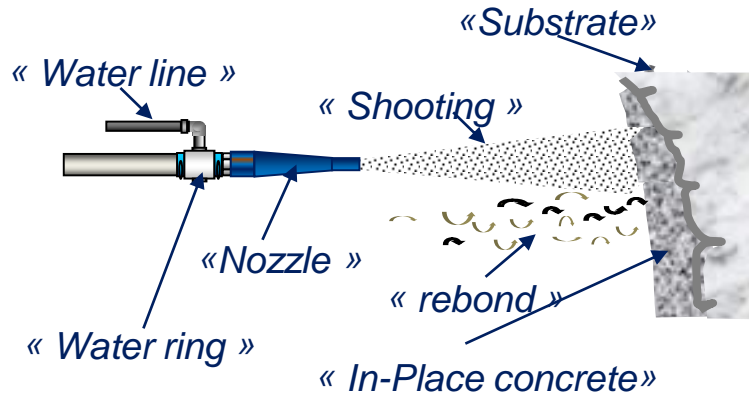
1. Study the influence of curing on shrinkage cracking
2. Understand the relationship between volumetric compatibility and cracking potential (using 'ring test')
3. Find a correlation between stress rate and the time-to-cracking
4. Quantify tensile creep behavior of concrete using the ring tests

Ultimate goal => crack free repair material



# Shotcrete

- What is shotcrete
  - ❖ A technology for placing concrete
    - Mortar or concrete sprayed on a surface under pneumatic pressure
    - There are two ways to do this: a **wet mix** and a **dry mix** process



McCormick Dam and Power Station, QC, CA  
– **KING Shotcrete Solution**

# In search of crack free concrete

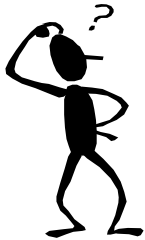
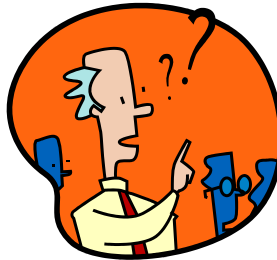
## □ Basic principles

- Limit paste content
  - Aggregates usually are volume stable, does NOT shrink
- Use of supplementary cementitious materials
  - Silica fume
  - Fly Ash (*reduced water demand*)
- Proper use of admixtures
  - High range Water reducers (HRWR)
  - Shrinkage reducing admixtures (SRA) → *direct shrinkage reduction - up to 40 %*
  - Expansive admixtures (EA) → *shrinkage compensation*
- Fibers
  - Reduction of early age cracks → No direct influence on the shrinkage itself
- Use wet curing and protect the surface of the concrete
  - Delays drying

**Extremely important**

# The problem with all concretes: *Cracking*

- Why does concrete crack?

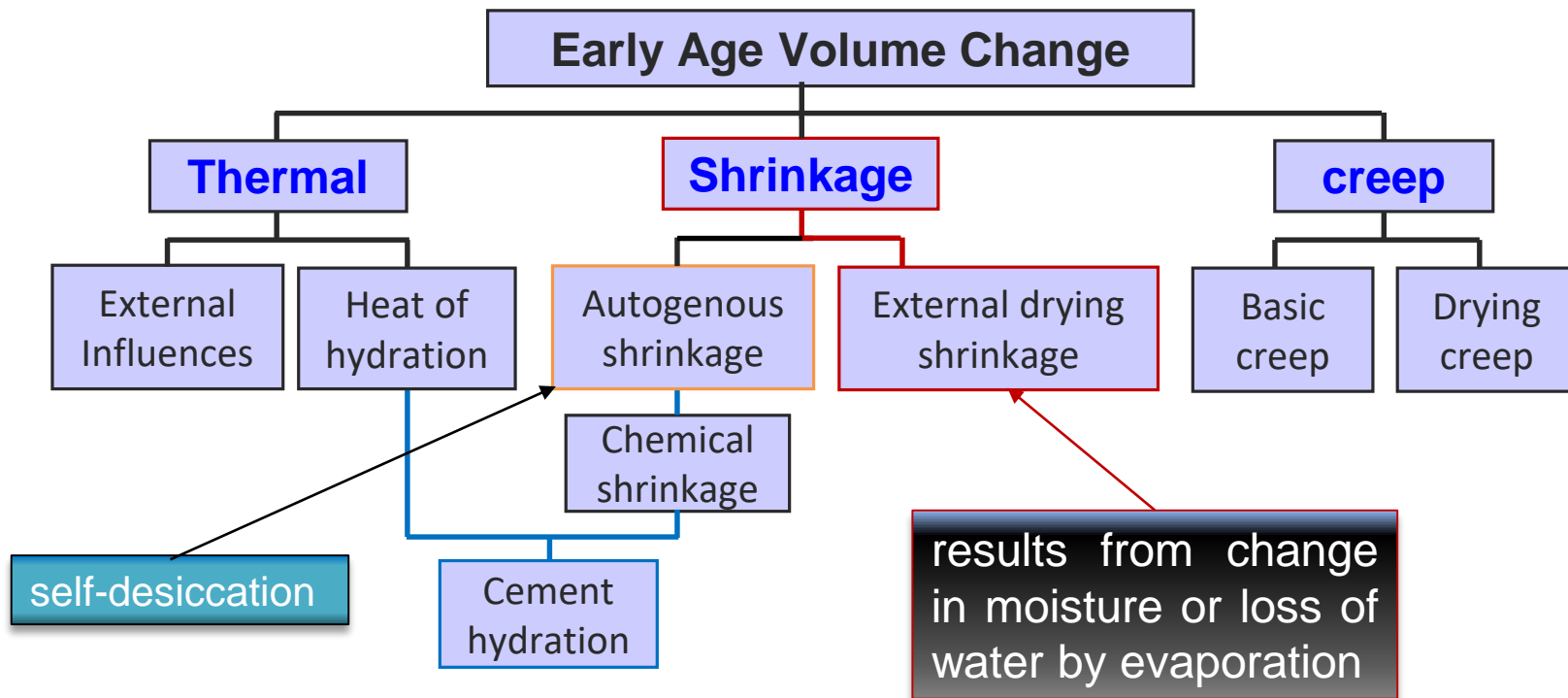


**YES!**



# Time-dependent volume changes

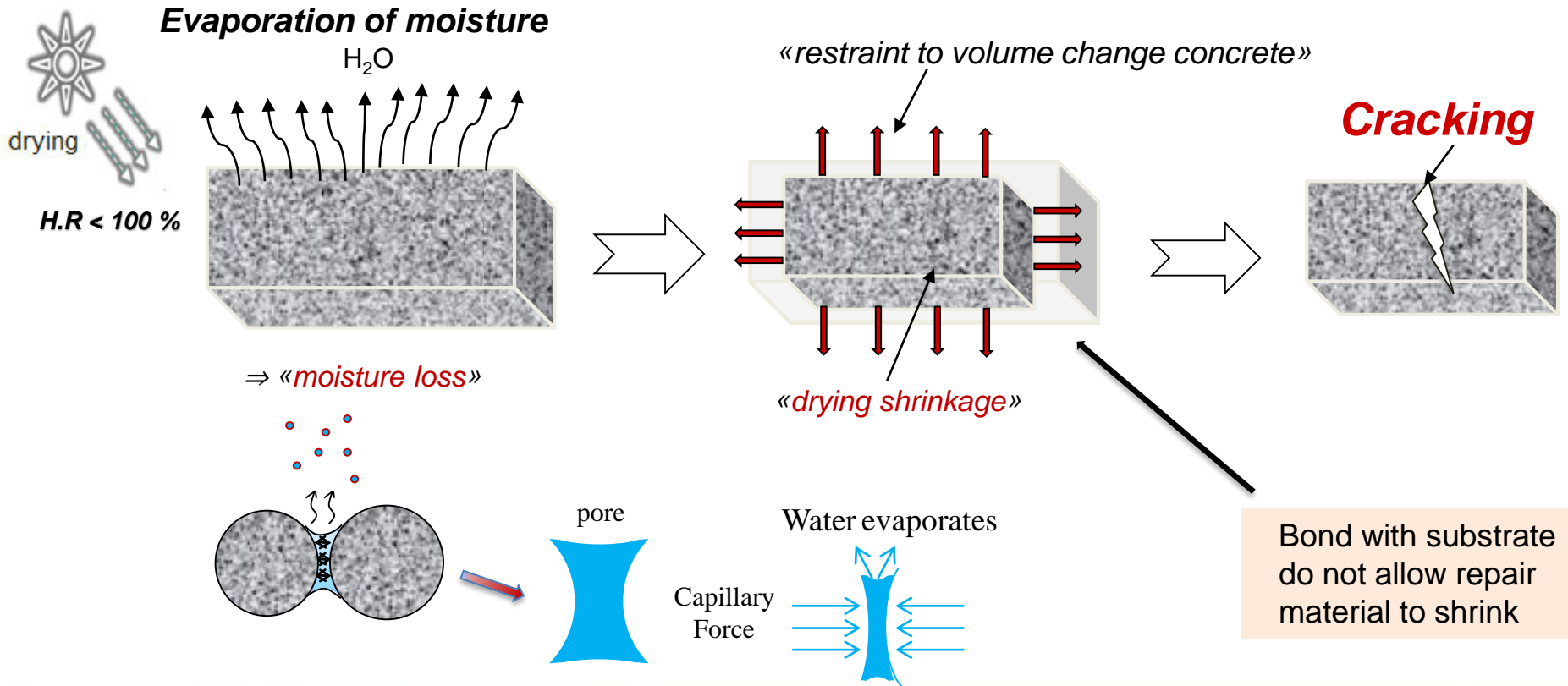
- Volume change starts soon after cement and water come in contact
  - ❑ All possible types of volume change are *interrelated* (very complex problem)





# Drying shrinkage cracking

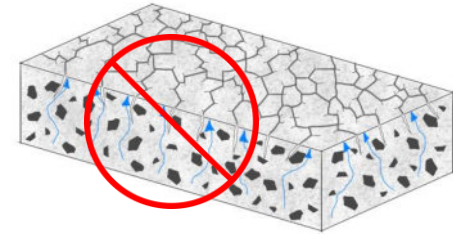
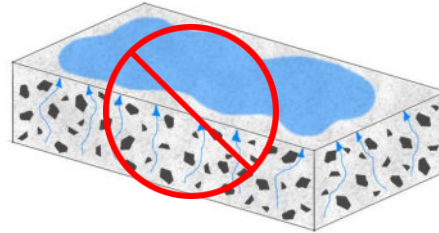
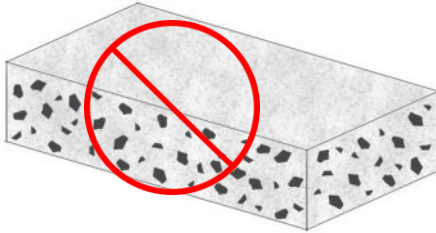
- Volumetric behavior of concrete exposed to drying
  - Drying shrinkage





# Drying shrinkage cracking

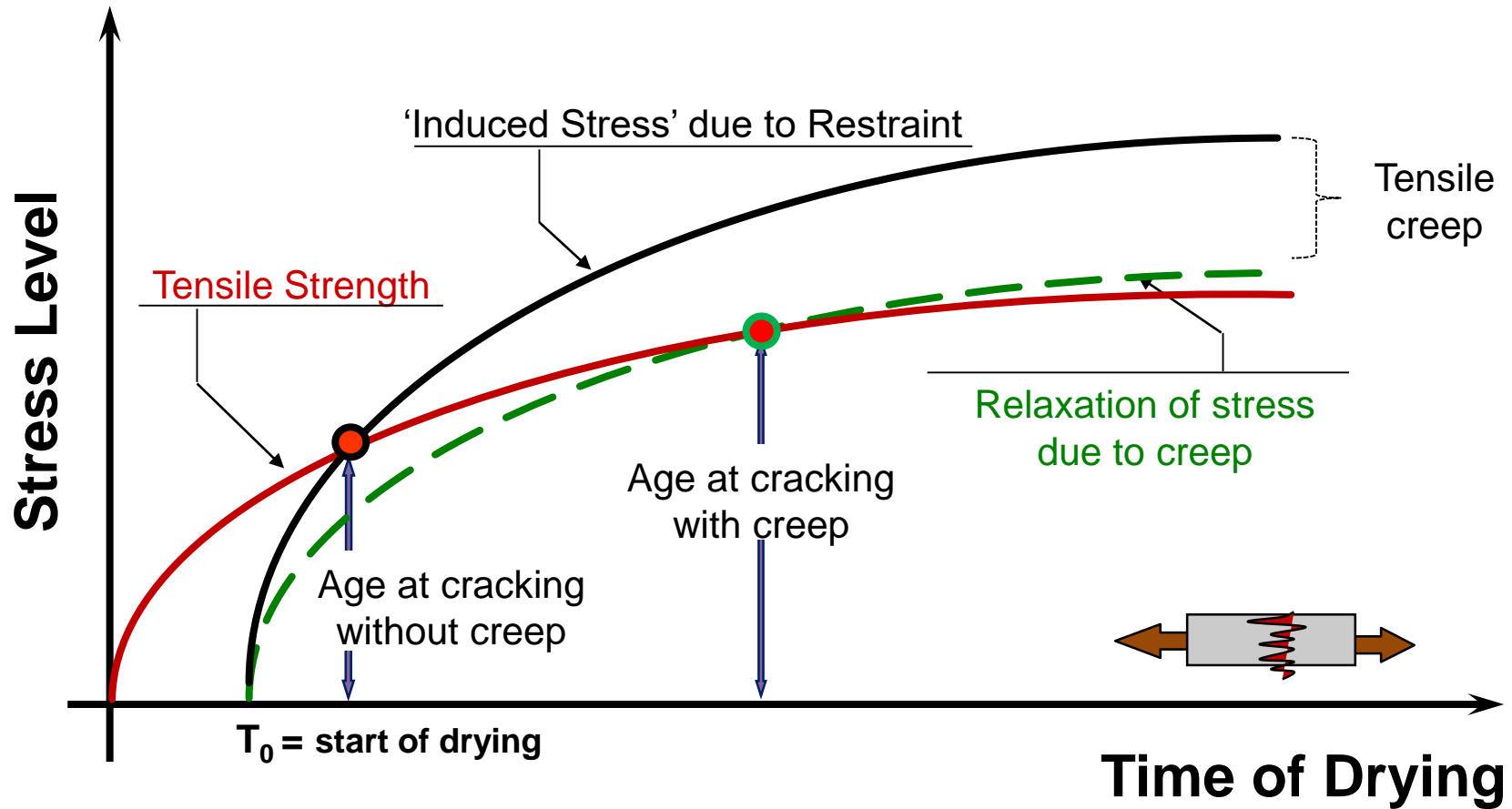
- Why curing is important
  - Prevent early surface desiccation
  - Provide the right conditions for cement hydration
  - Minimize shrinkage and shrinkage cracking



No Drying = No Drying Shrinkage = No Drying Shrinkage Cracking



# When will shrinkage cracking occur?

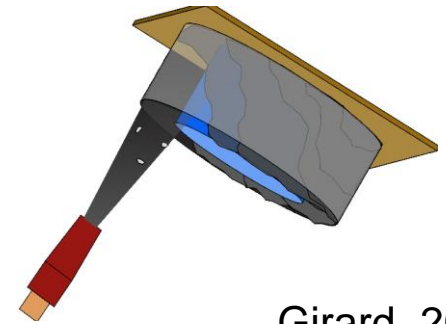
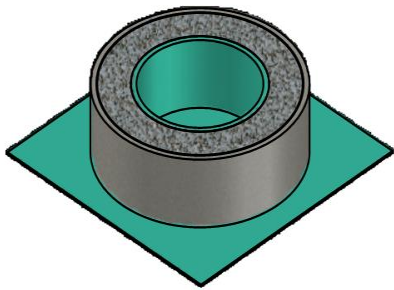


# Quantifying Shrinkage Cracking

- How do we capture the combined effect of shrinkage and tensile creep simultaneously in a *scientifically sound test* ?



- Answer : The **RING TEST**



Girard, 2013

# Shrinkage cracking characterization

- Ring test
  - Measures the resistance of concrete to cracking under restrained shrinkage

## Restrained ring

Strain Gauge    Steel Restraining Ring



Standardized Test

AASHTO PP-34-99

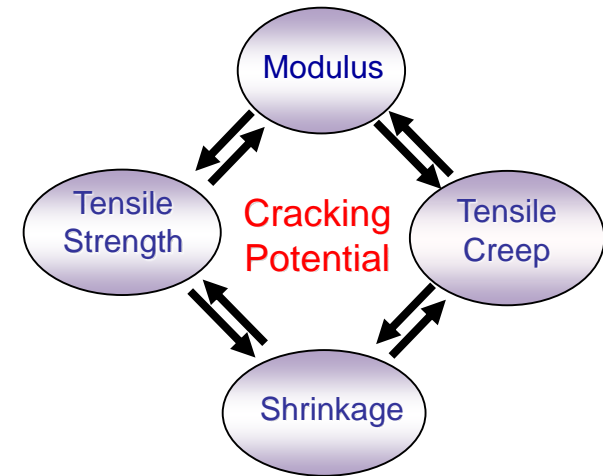
## Free ring

Polystyrene Insert Ring



Non-Standardized Test

Alternative for ASTM C 157



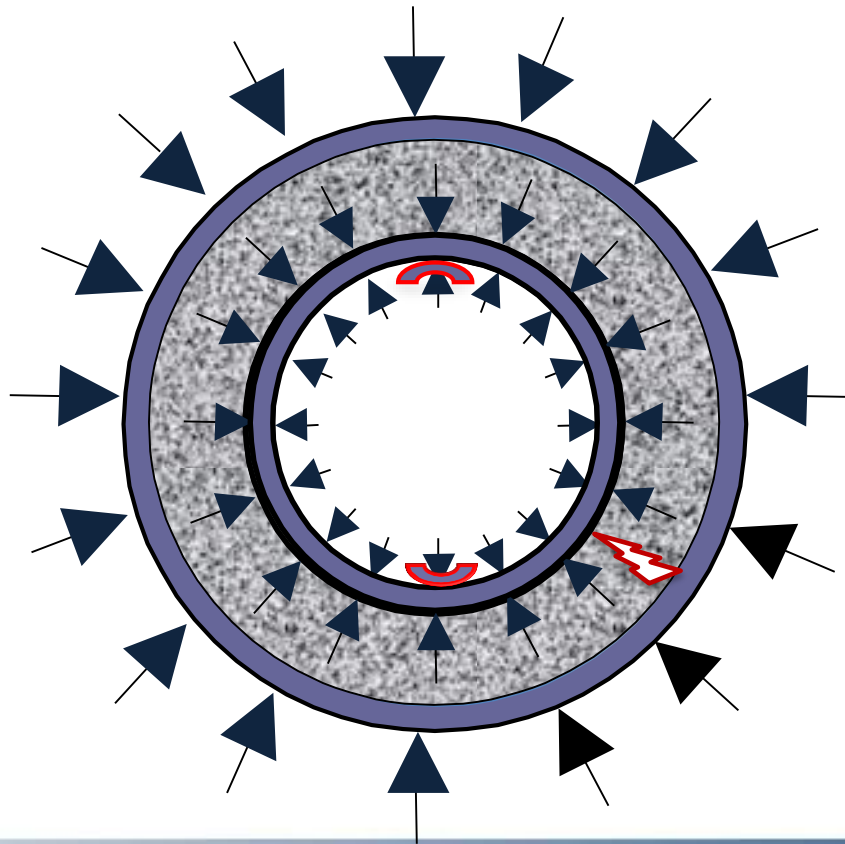
Cracking Index:  $CI = \sigma(t) / f_t'$

residual stress

tensile strength

# Shrinkage cracking characterization

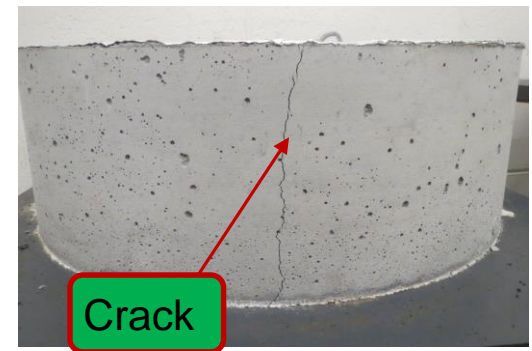
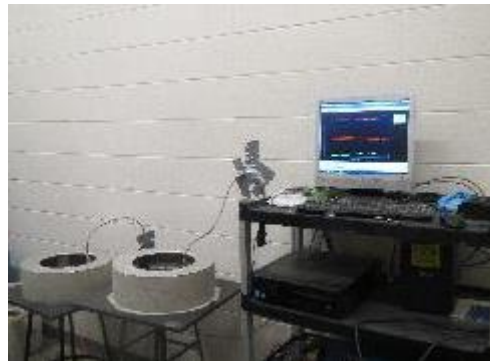
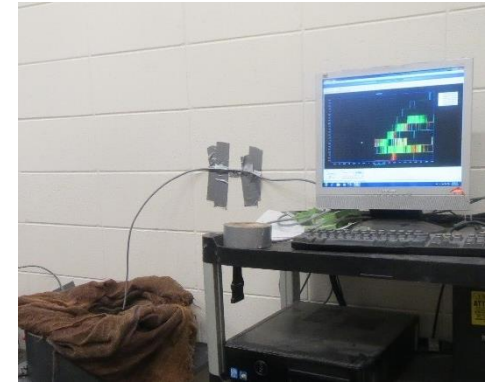
- The concept of restrained ring test
  - $T=23 \pm 4 \text{ } ^\circ\text{C}$  @  $50 \pm 4\%$  RH





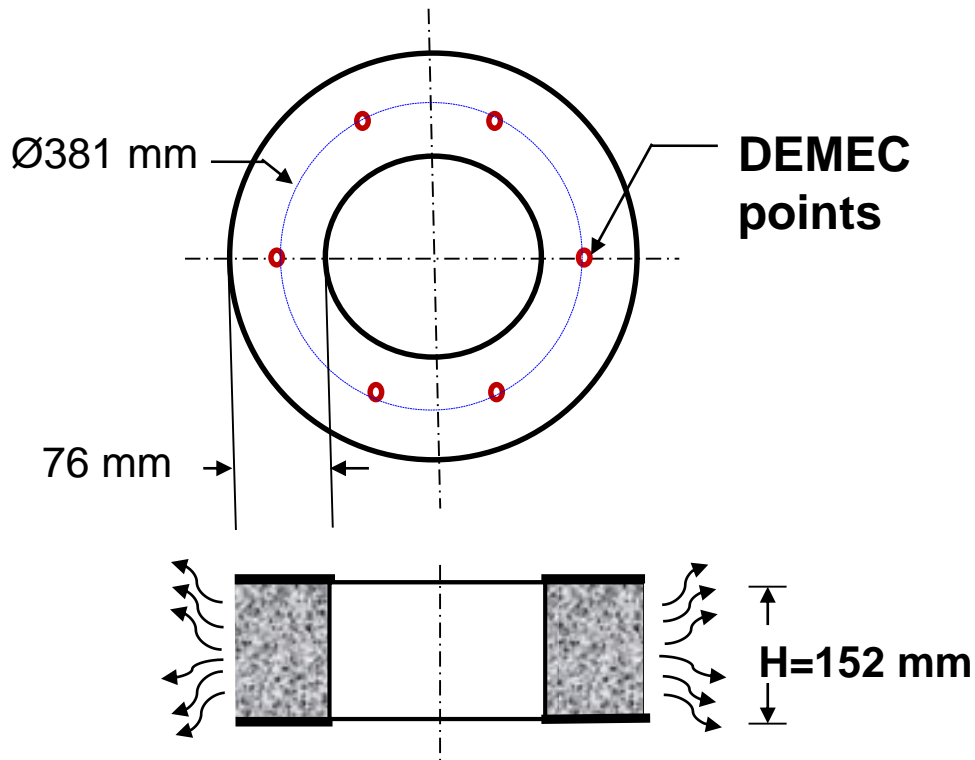
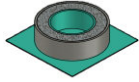
# Shrinkage cracking characterization

- The restrained ring test experimental procedure



# Shrinkage cracking characterization

- Unrestrained ring test (New experimental set-up)



Template for positioning of the DEMEC



DEmountable MEChanical strain gauge



# Shrinkage cracking characterization

- The restrained and free ring specimen exposed to drying

Restrained ring specimen

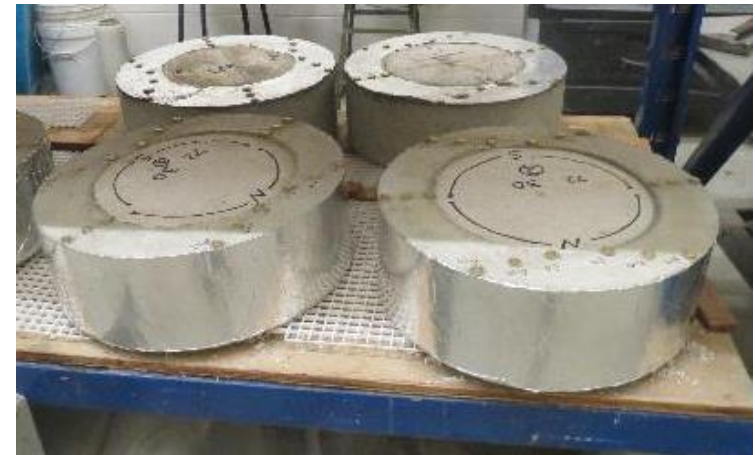


(Circumferential drying)

Free ring specimen

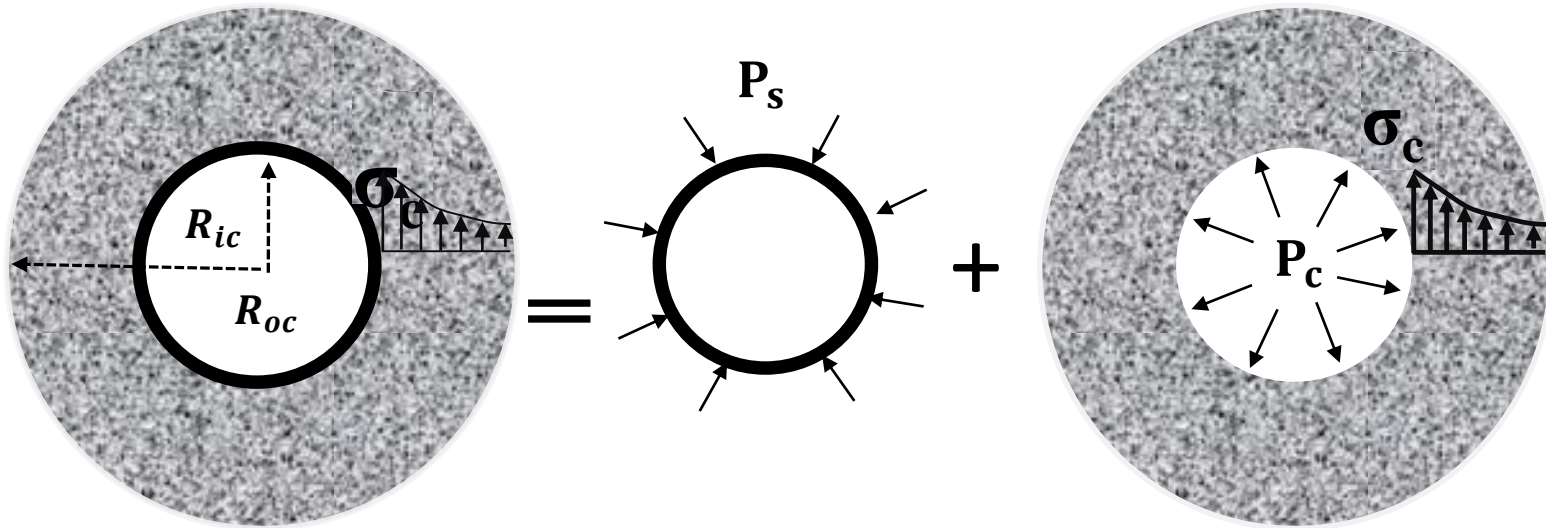


(Top & Bottom drying)



# Stress development in the concrete ring

- stress distribution in the ring



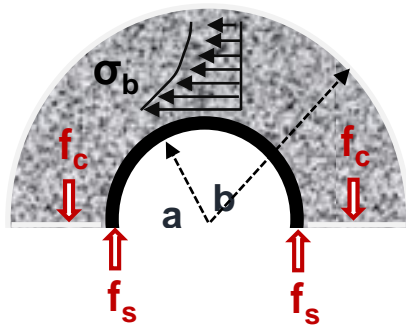
$$\sigma_{\theta\theta}(r) = \frac{1}{r^2} \frac{R_{os}^2 (r^2 + R_{oc}^2)}{R_{oc}^2 - R_{os}^2} P_s$$



# Stress development in the concrete ring

## ➤ Average tensile stress analysis:

Equilibrium of forces :



$$F_s(t) = -F_c(t)$$

force in steel ↑      ↓ force in concrete

$$\sigma_{s\_avg}(t) A_s = \sigma_{c\_avg}(t) A_c$$

area of steel ↑      ↓ area of concrete

$$F_c = 2 \cdot f_c \quad | \quad F_s = 2 \cdot f_s$$

steel average residual stress ↑

$$\sigma_{s\_avg}(t) = \frac{1}{2} E_s(t) \varepsilon_s(t) \frac{b+a}{b}$$

↑ Steel elastic modulus

residual stress ↑

$$\sigma_{c\_avg}(t) = -\frac{1}{2} \frac{A_s}{A_c} E_s(t) \varepsilon_s(t) \frac{b+a}{b}$$

→

$$\sigma_{c\_avg}(t) = K \varepsilon_s(t)$$

K = 31.55 GPa

## ➤ Stress rate

Adapted from  
See et al. [1]

$$S(t) = \frac{d\sigma_{c\_avg}(t)}{dt} = K \left| \frac{d\varepsilon_s}{dt} \right|$$

where  $d\varepsilon_s/dt$  is the net strain rate at time t

$\varepsilon_s$  as function of time is a regression fit given as:

$$\varepsilon_s(t) = \alpha \sqrt{t} + c$$

$\alpha$  is the slope of the line

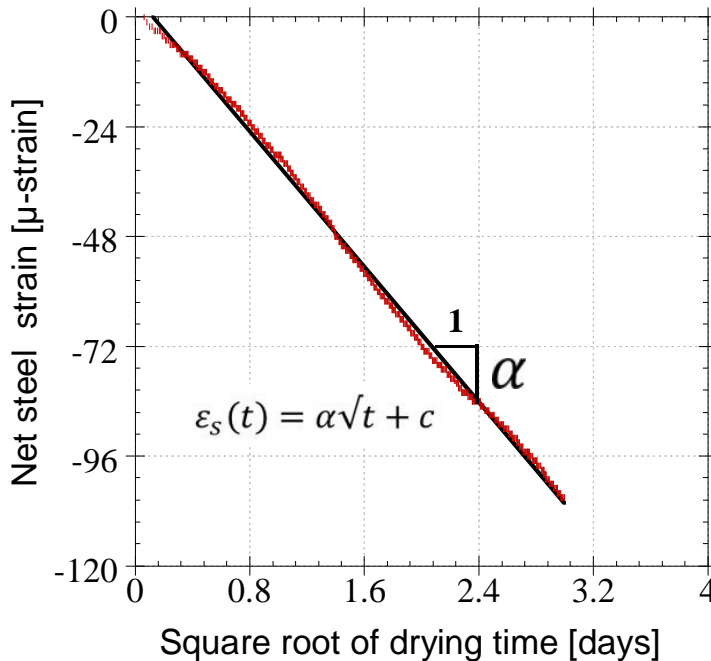
The stress rate after drying is given by :

$$S(t) = \frac{K |\alpha|}{2\sqrt{t}}$$

t is time to cracking

# Shrinkage cracking characterization

- Example of time-to-cracking versus square root of time

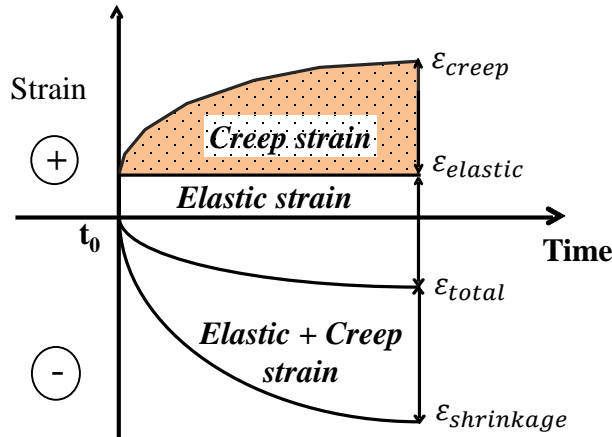


$\alpha$  is the slope of the line and is known as the **strain rate**

# Quantifying tensile creep behavior

- Principle of superposition of strains:

## Concrete strain components:



$$\epsilon_{total}(t) = \epsilon_{elastic}(t) + \epsilon_{shrinkage}(t) + \epsilon_{creep}(t)$$

↑ steel deformation  $\epsilon_{total} = \epsilon_{steel}$

$$\epsilon_{creep}(t) = \epsilon_{steel}(t) - \epsilon_{elastic}(t) - \epsilon_{shrinkage}(t)$$

where:

$$\epsilon_{elastic}(t) = \frac{\sigma_{avg-c}(t)}{E_c(t)} = -\frac{K}{E_c(t)} \epsilon_s(t)$$

↑ elastic modulus

$$\text{Tensile strain capacity} = \epsilon_{elastic}(t) + \epsilon_{creep}(t)$$

↑ creep coefficient

$$= \epsilon_{elastic}(t) [1 + \phi(t)]$$

↑

$$\phi(t) = \frac{\epsilon_{creep}(t)}{\epsilon_{elastic}(t)} = \frac{[\epsilon_{steel}(t) - \epsilon_{shrinkage}(t)]}{\epsilon_{elastic}(t)} - 1$$

$$\phi(t) = \frac{1}{K} E_c(t) \left[ \frac{\epsilon_{shrinkage}(t)}{\epsilon_{steel}(t)} - 1 \right] - 1$$

# Shrinkage cracking characterization

- Characteristics of the concrete mixture studied (at 28-days)

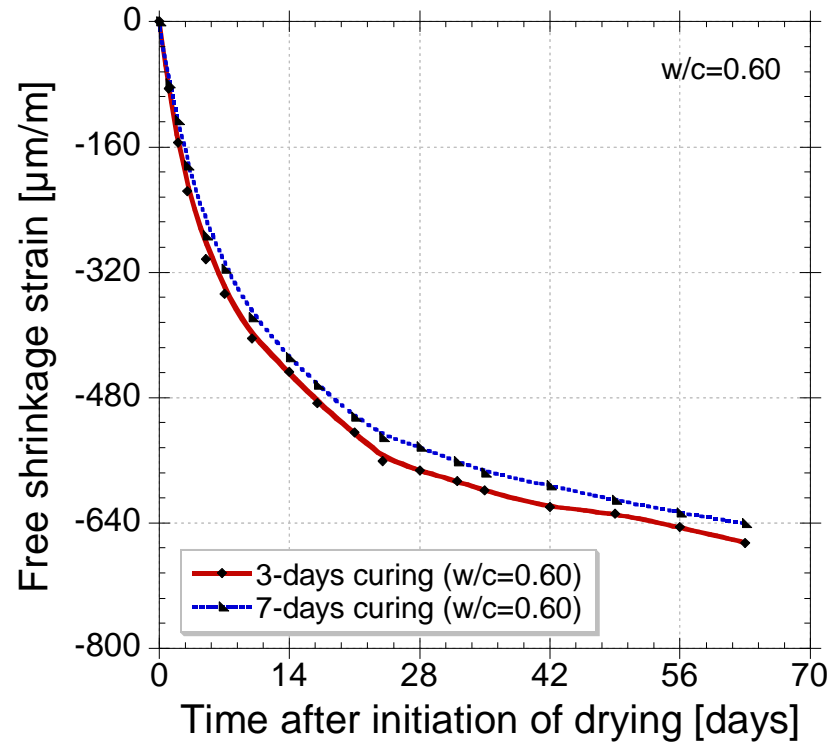
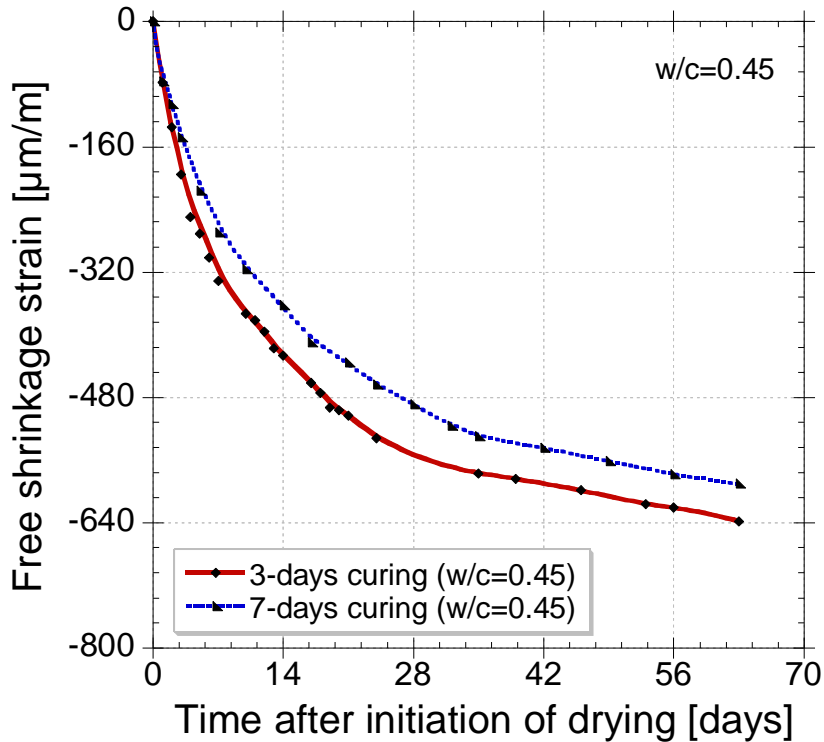
	w/c=0.45	w/c=0.60
Compressive strength (MPa)	34.5	33.1
Tensile strength (MPa)	3.22	2.74
Elastic modulus (GPa)	30.0	28.8
Poisson's ratio	0.18	0.13

Mix ID	Cement (kg/m <sup>3</sup> )	Coarse aggregate (kg/m <sup>3</sup> )	Fine aggregate (kg/m <sup>3</sup> )	Water (kg/m <sup>3</sup> )	w/c
S1	445	736	1054	197	0.45
S2	417	689	988	247	0.60



# Results and discussion

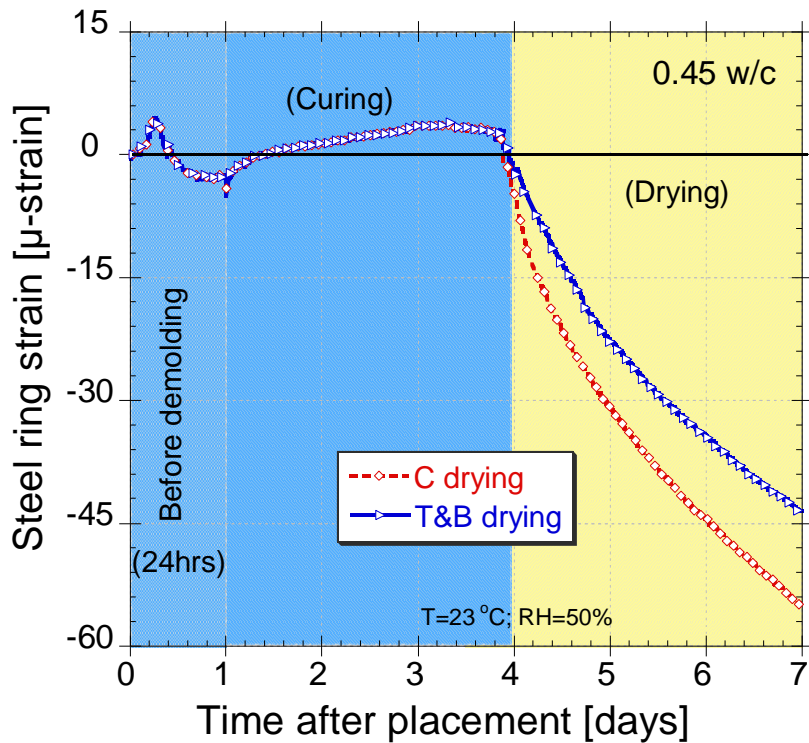
- Free ring shrinkage (circumferential drying)



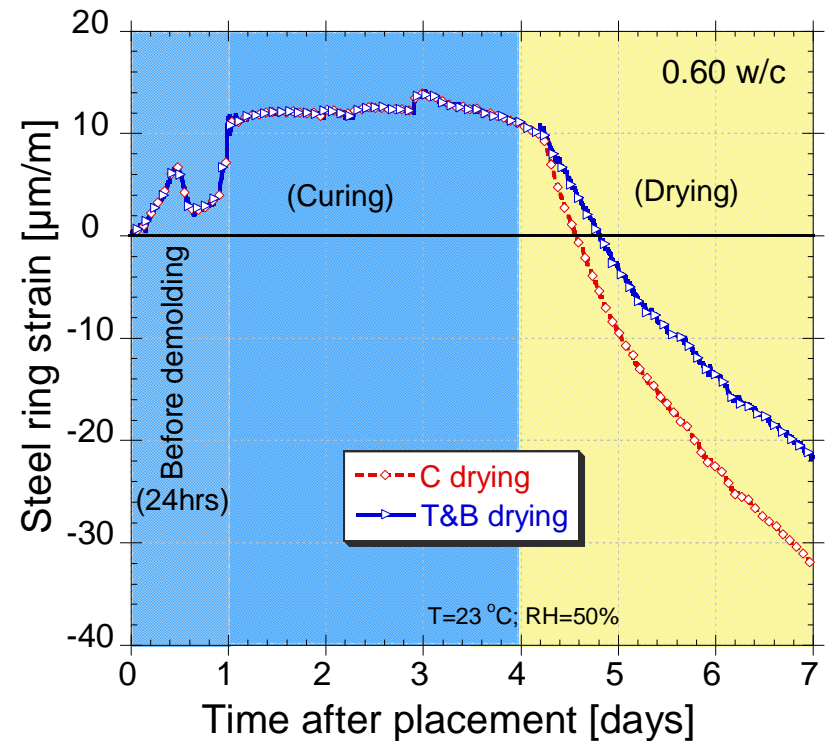


# Results and discussion

- Strain recorded during curing of the ring specimen



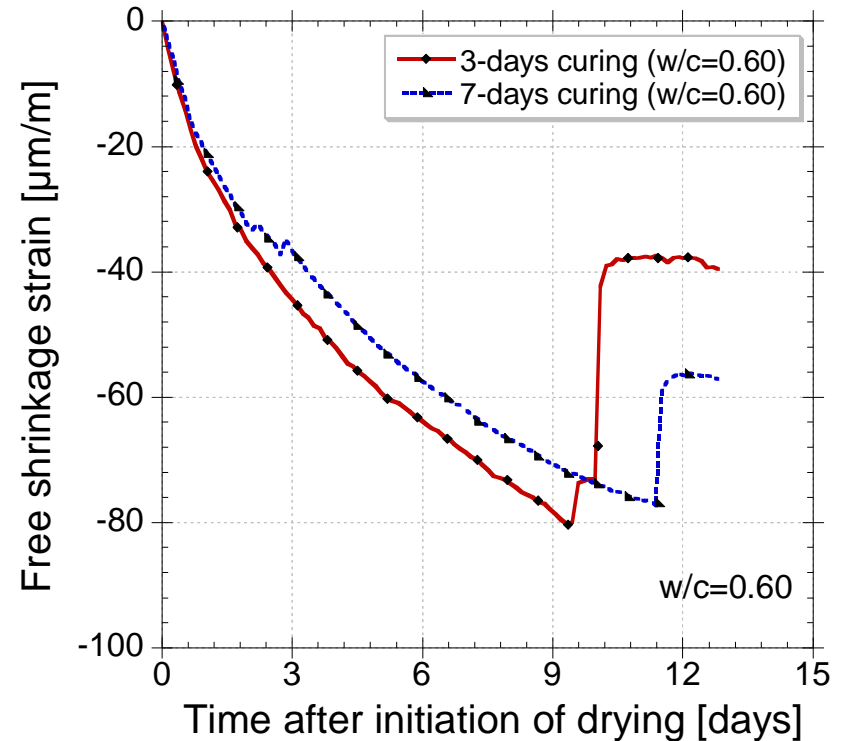
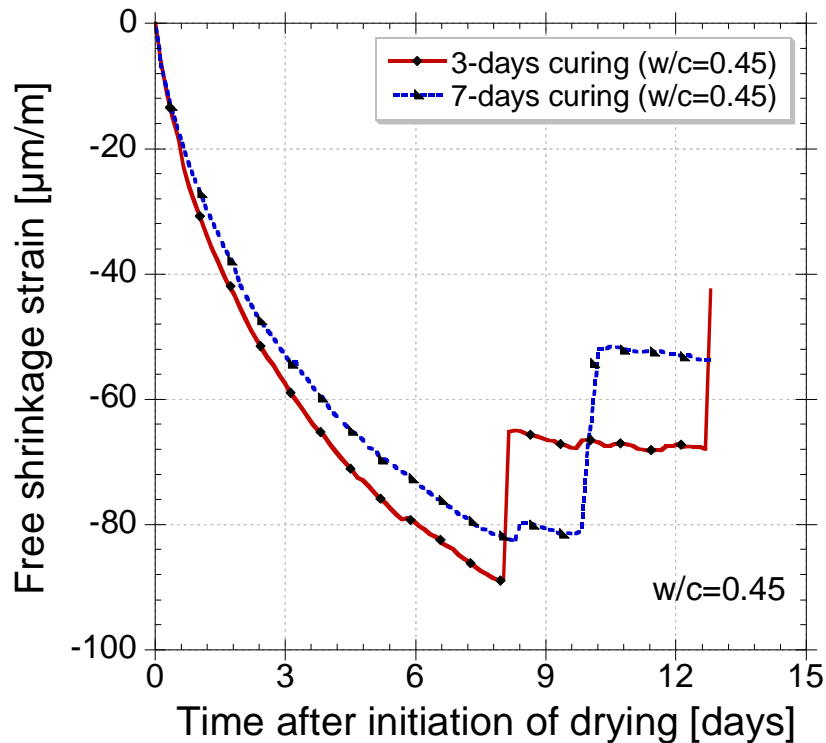
**w/c = 0.45**



**w/c = 0.60**

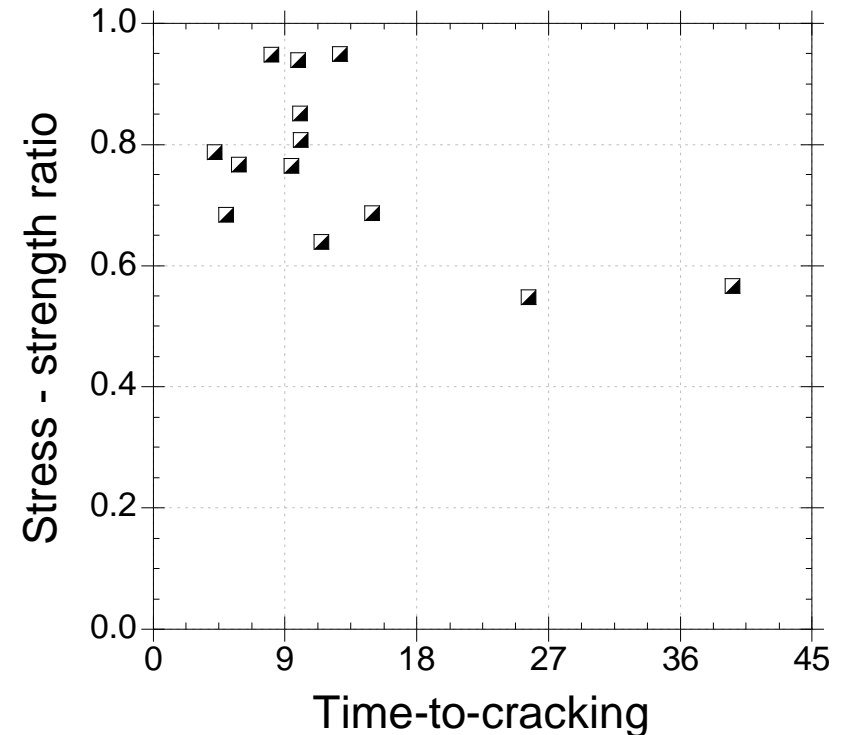
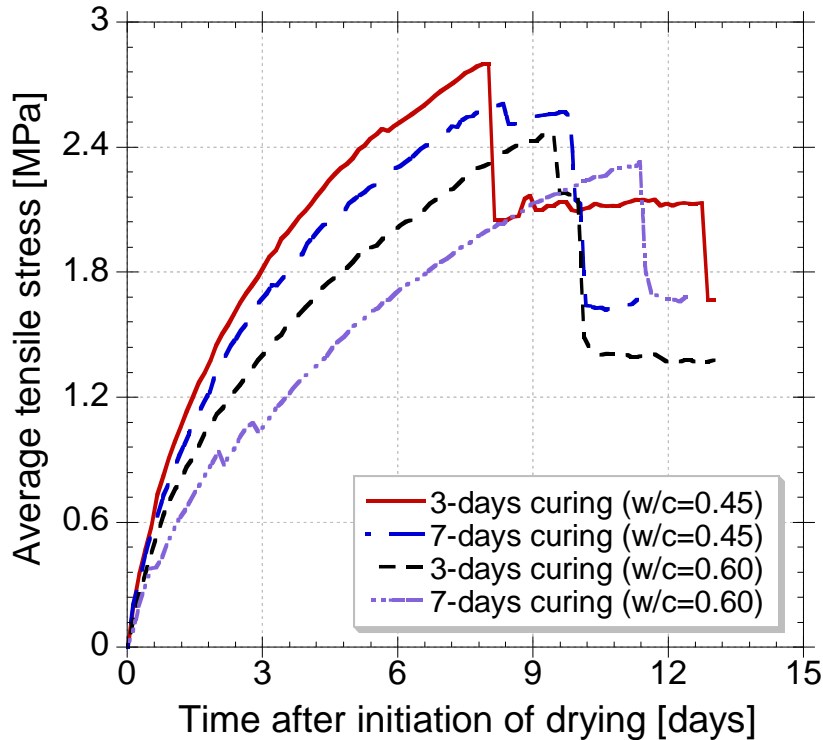
# Results and discussion

- Restrained ring shrinkage (circumferential drying)



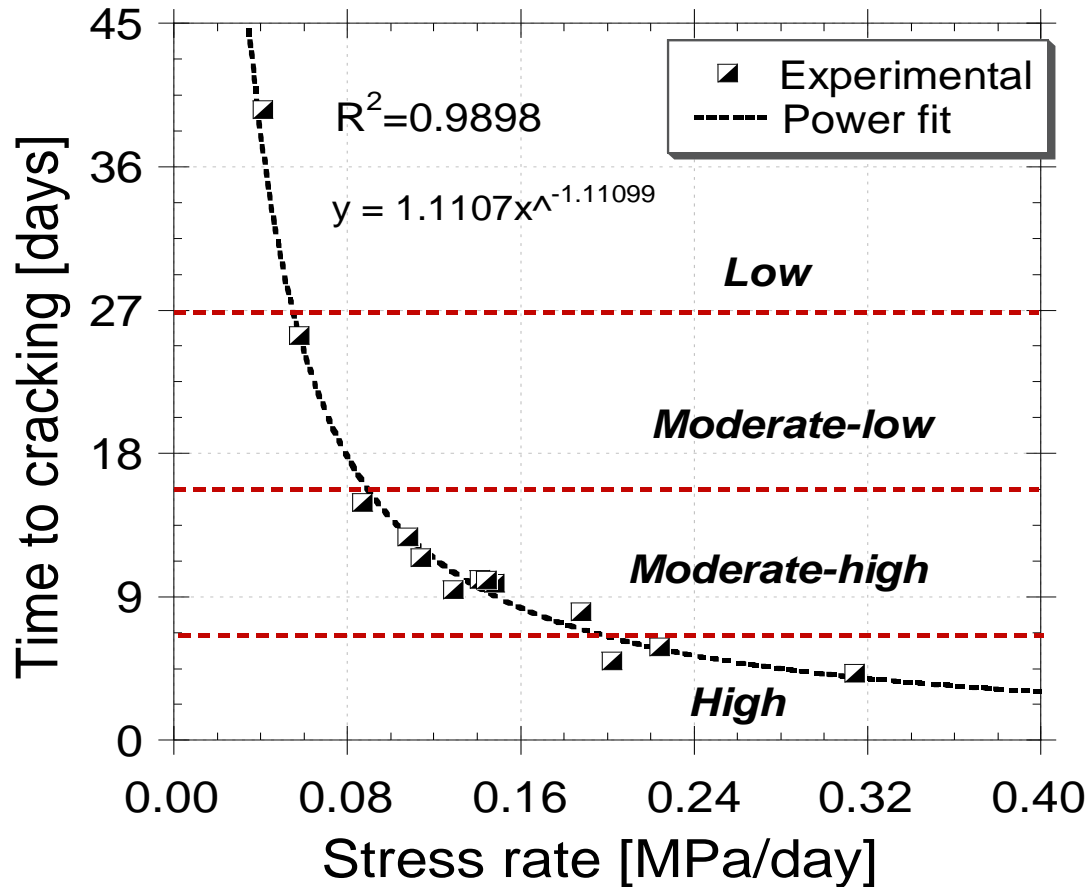
# Results and discussion

- Stress development and stress-to-strength ration (cracking index)



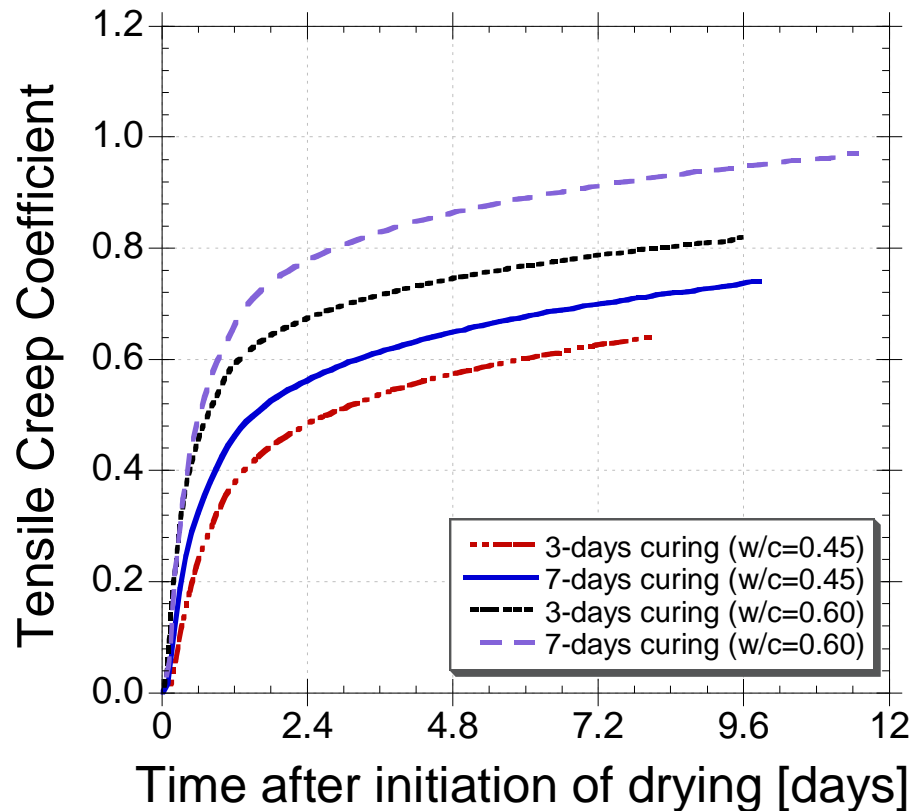
# Results and discussion

- Stress rate in the ring specimen



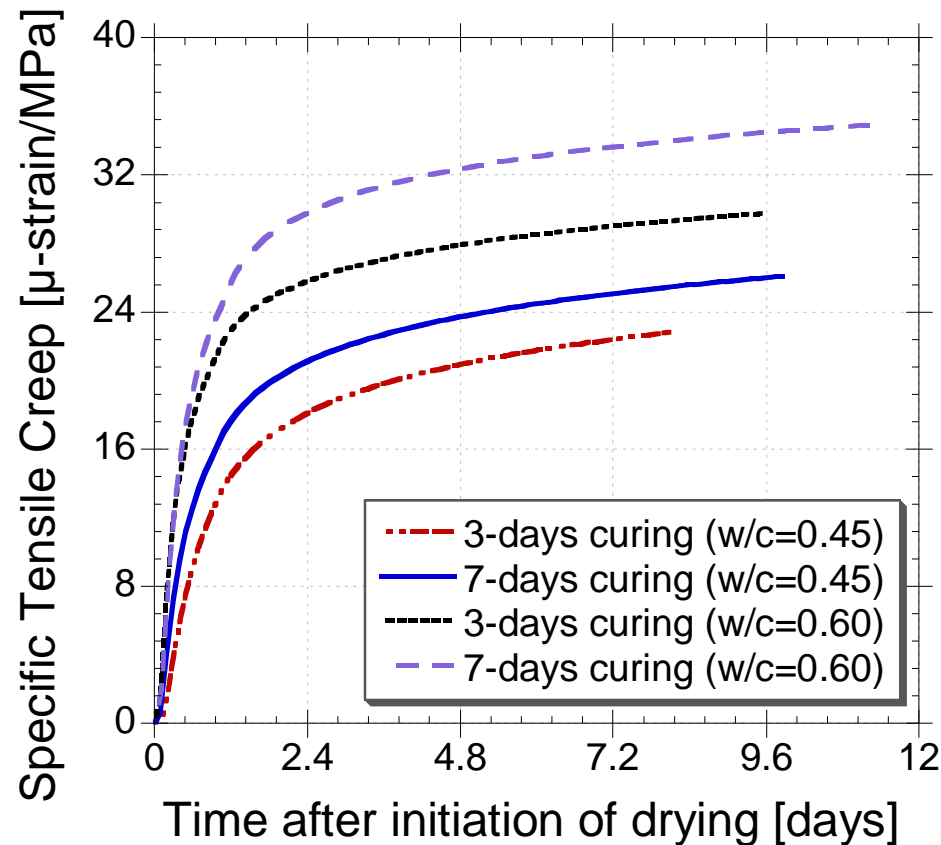
# Results and discussion

- Evaluation of tensile creep parameters from “ring tests” (up to time of cracking)



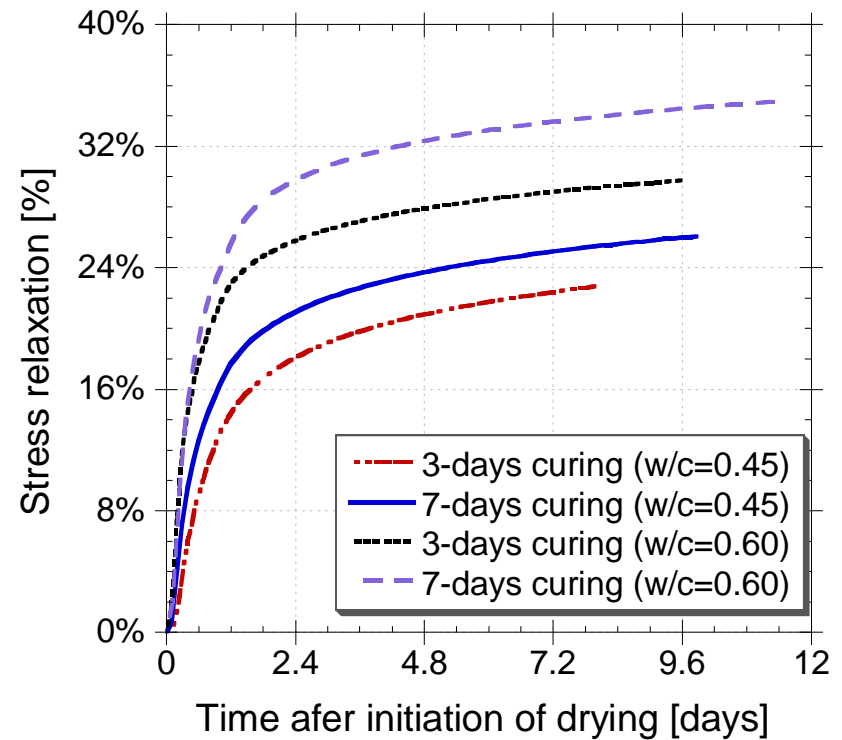
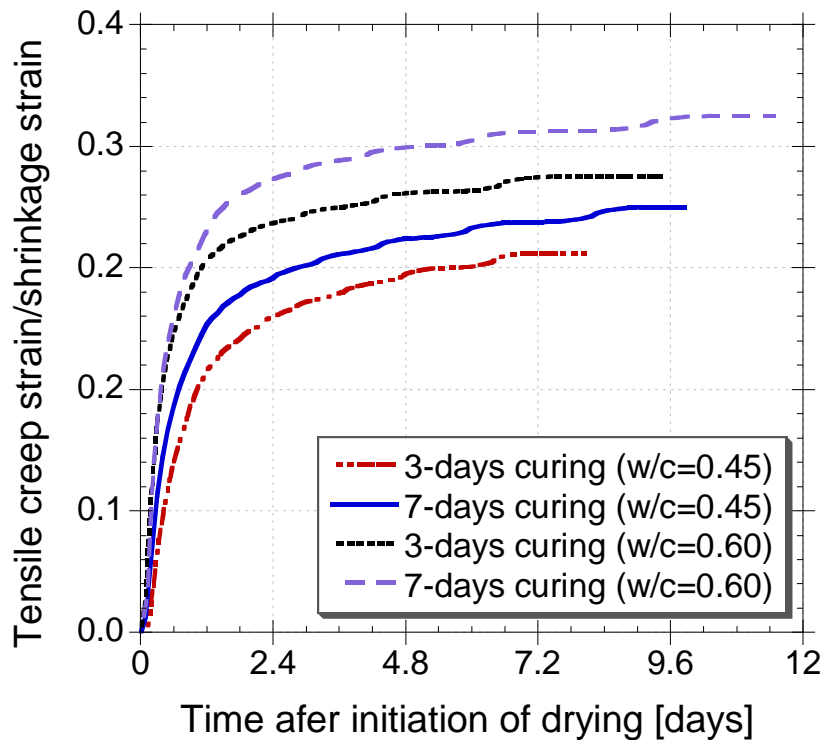
# Results and discussion

- Evaluation of tensile creep parameters from “ring tests” (up to time of cracking)



# Results and discussion

- Evaluation of tensile creep parameters from “ring tests” (up to time of cracking)





# In Summary...

- ❖ The restrained ring test facilitates the prediction of cracking resistance and is suitable for **evaluating the tensile creep behavior** of concrete exposed to drying
- ❖ Cracking resistance of concrete under restrained shrinkage depends on the combined properties of shrinkage (**stress rate**), tensile creep, and tensile strength
- ❖ The cracking potential of concrete can be evaluated based on either the time-to-cracking or the rate of stress development
- ❖ The lower the stress rate, the longer the cracking time under restrained shrinkage
- ❖ A simple procedure is developed for a quantifying creep behavior using free shrinkage, restrained shrinkage and modulus

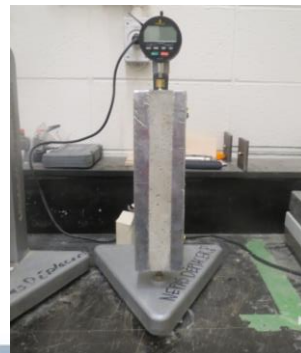
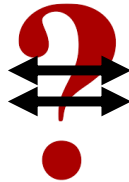
$$\phi(t) = \frac{1}{k} E_{c.(t)} \left[ \frac{\varepsilon_{shrinkage}^{(t)}}{\varepsilon_{steel}^{(t)}} - 1 \right] - 1$$

# In Summary...

- ❖ Restrained stress to strength ratio can be used to define limits for stress development (or cracking index) to minimize shrinkage cracking
  - This limit may be in the range of 50-60%, **but** further research is needed for a definitive conclusion
- ❖ **Prolonged moist curing** has the potential of delaying cracking of a concrete under restrained shrinkage
- ❖ Additional **evaluations are ongoing** to evaluate the influence of other parameters such as drying condition, surface-to-volume ratio and curing on cracking



Free ring test



ASTM C157



# References

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2. See, H. T., Attiogbe, E. K., & Miltenberger, M. A. (2003). Shrinkage cracking characteristics of concrete using ring specimens. *ACI Materials Journal*, 100(3)
3. Attiogbe, Emmanuel K, WJ Weiss, and Heather T See. 2004. "A look at the stress rate versus time of cracking relationship observed in the restrained ring test. a Rilem International Conference
4. See, Heather T, Emmanuel K Attiogbe, and Matthew A Miltenberger. 2004. "Potential for restrained shrinkage cracking of concrete and mortar." *Cement, concrete and aggregates* 26 (2):1-8
5. Benoit, B., Le fluage en traction: un aspect important de la problématique des réparations minces en béton, in Thèse de doctorat. 1996, Département de génie civil, Université Laval, Canada. p. 279 pages.

# Acknowledgements

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**NSERC**  
**CRSNG**



# THANKS FOR YOUR ATTENTION!



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# Commentaires? Questions?



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- Strain recorded for the first 24 hours after casting the ring specimen

