ICRI 2017 Spring Convention March 15-17, 2017

Evaluating Shrinkage Cracking Potential of Concrete Using Ring Test

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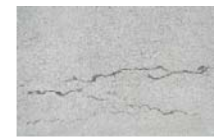
Overview

- ❑ 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



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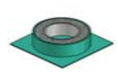
Objectives

- 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



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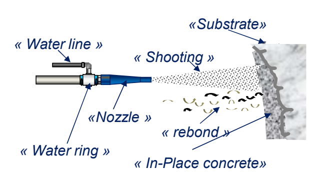
Shotcrete

- 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*

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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

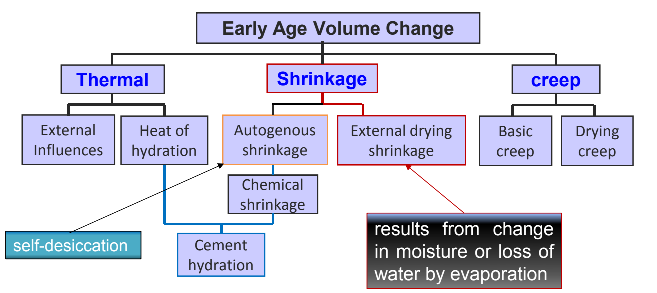
The problem with all concretes: *Cracking*

- Why does concrete crack?

Time-dependent volume changes

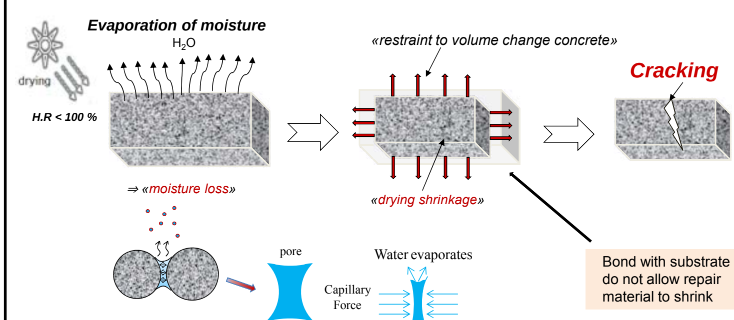
- Volume change starts soon after cement and water come in contact

❑ All possible types of volume change are *interrelated* (very complex problem)



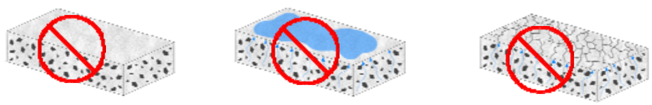
Drying shrinkage cracking

- Volumetric behavior of concrete exposed to drying
  - ➢ Drying shrinkage



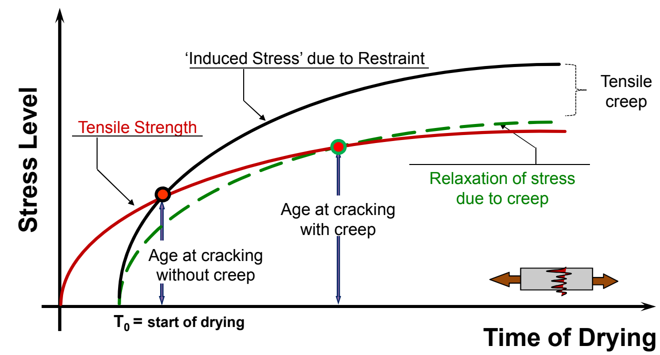
Drying shrinkage cracking

- 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* ?

- Shrinkage → Stress rate, Tensile creep (relaxation) } = actual cracking time

- **Answer : The RING TEST**

Girard, 2013

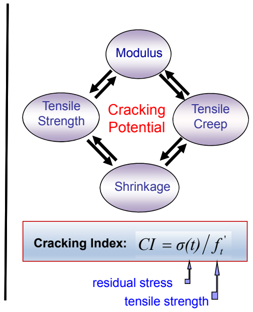
Shrinkage cracking characterization

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

Restrained ring | **Free ring**

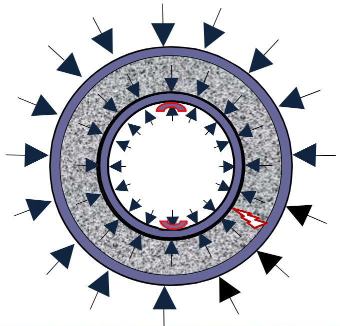
Standardized Test
AASHTO PP-34-99

Non-Standardized Test
Alternative for ASTM C 157



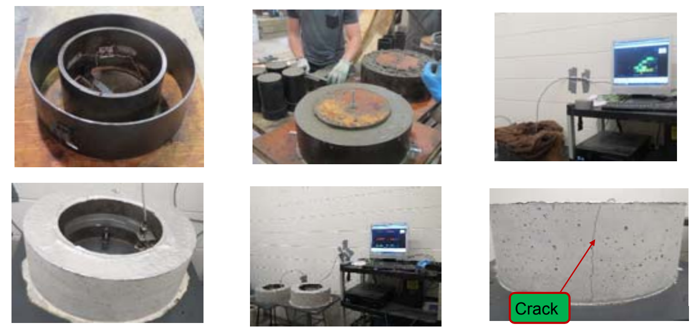
Shrinkage cracking characterization

- The concept of restrained ring test
  - T=23 ± 4 °C @ 50 ± 4% RH



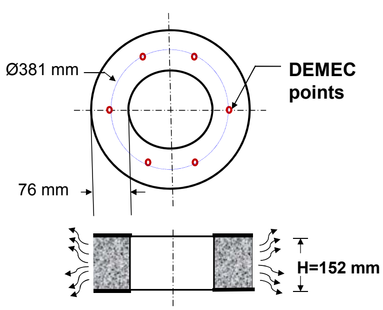
Shrinkage cracking characterization

- The restrained ring test experimental procedure



Shrinkage cracking characterization

- Unrestrained ring test (New experimental set-up)



Template for positioning of the DEMEC

DEmountable **MEC**hanical strain gauge

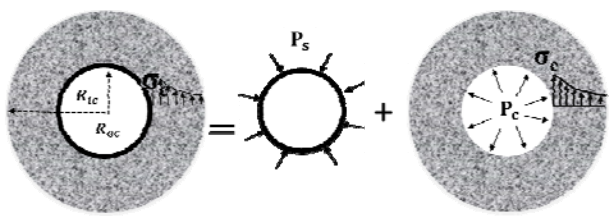
Shrinkage cracking characterization

- The restrained and free ring specimen exposed to drying

Restrained ring specimen | **Free ring specimen**

Stress development in the concrete ring

- stress distribution in the ring

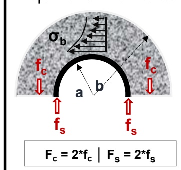


$$\sigma_{\theta\theta}(r) = \frac{1}{r^2}\frac{R_{os}^2(r^2+R_{oc}^2)}{R_{oc}^2-R_{os}^2}P_s$$

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)

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

(steel average residual stress; Steel elastic modulus)

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

(residual stress)

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

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

ε_s as function of time is a regression fit given as:

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

α is the slope of the line

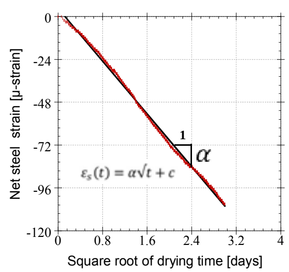
The stress rate after drying is given by :

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

t is time to cracking

Shrinkage cracking characterization

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

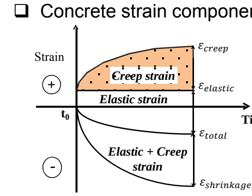


α is the slope of the line and is known as the **strain rate**

Quantifying tensile creep behavior

- Principle of superposition of strains:

❑ Concrete strain components:



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

(steel deformation $\varepsilon_{total} = \varepsilon_{steel}$; free shrinkage)

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

where: $\varepsilon_{elastic}(t) = \frac{\sigma_{avg\_c}(t)}{E_c(t)} = -\frac{K}{E_c(t)}\varepsilon_s(t)$ (elastic modulus)

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

$= \varepsilon_{elastic}(t)[1+\phi(t)]$ (creep coefficient)

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

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

Shrinkage cracking characterization

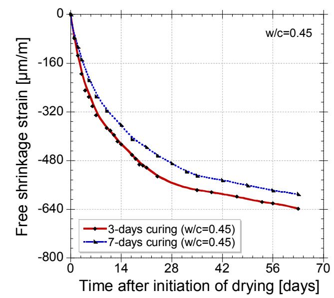
- Characteristics of the concrete mixture studied (at 28-days)

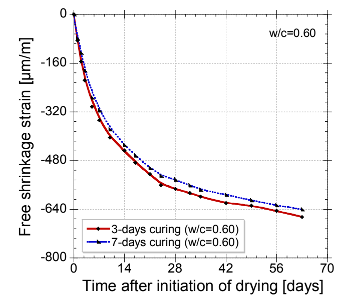
	w/c=0.45	w/c=0.62
Compressive strength (MPa)	34.5	33.1
Tensile strength (MPa)	3.22	2.74
Elastic modulus (GPa)	30.0	28.8
Poisson's ratio	0.18	0.13

Mix ID	Cement (kg/m³)	Coarse aggregate (kg/m³)	Fine aggregate (kg/m³)	Water (kg/m³)	w/c
S1	445	736	1054	197	0.45
S2	417	689	988	247	0.60

Results and discussion

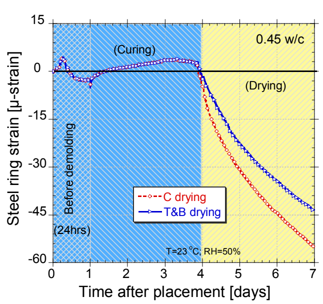
- Free ring shrinkage (circumferential drying)



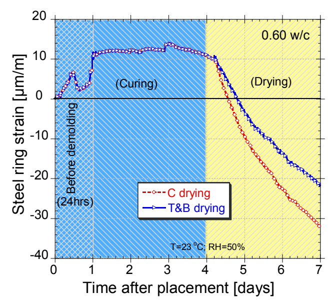


Results and discussion

- Strain recorded during curing of the ring specimen



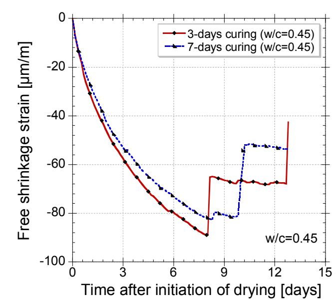
w/c = 0.45

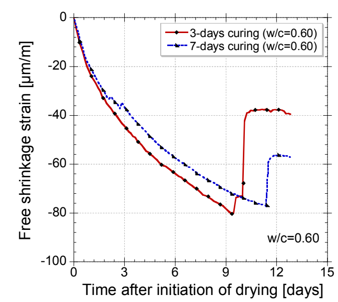


w/c = 0.60

Results and discussion

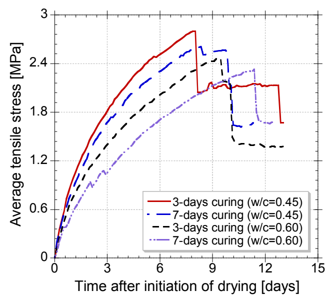
- Restrained ring shrinkage (circumferential drying)

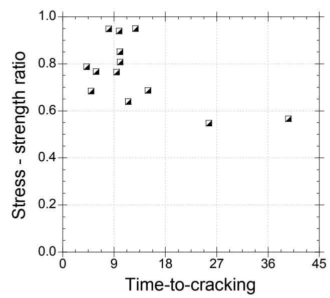




Results and discussion

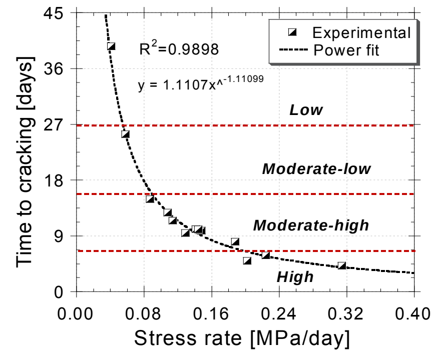
- Stress development and stress-to-strength ration (cracking index)





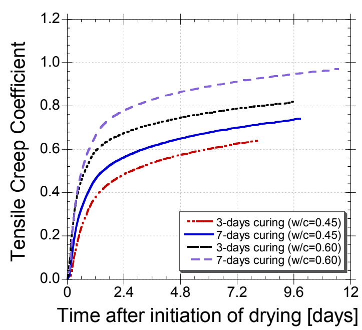
Results and discussion

- Stress rate in the ring specimen



Results and discussion

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



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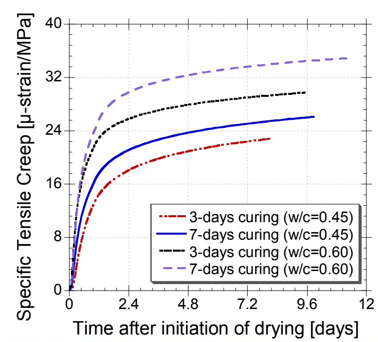

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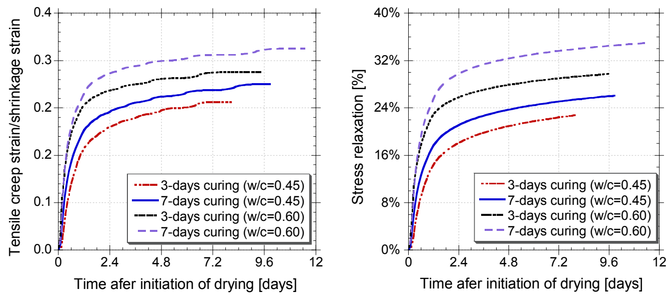

In Summary…

- 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

References

1. AASHTO, PP-34-99. 1999. " Standard Practice for Estimating the Cracking Tendency of Concrete," American Association of State Highway and Transportation Officials, Washington, DC
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
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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.

Acknowlegements

KING SHOTCRETE SOLUTIONS

NSERC CRSNG

CRIB Centre de recherche sur les infrastructures en béton

THANKS FOR YOUR ATTENTION!

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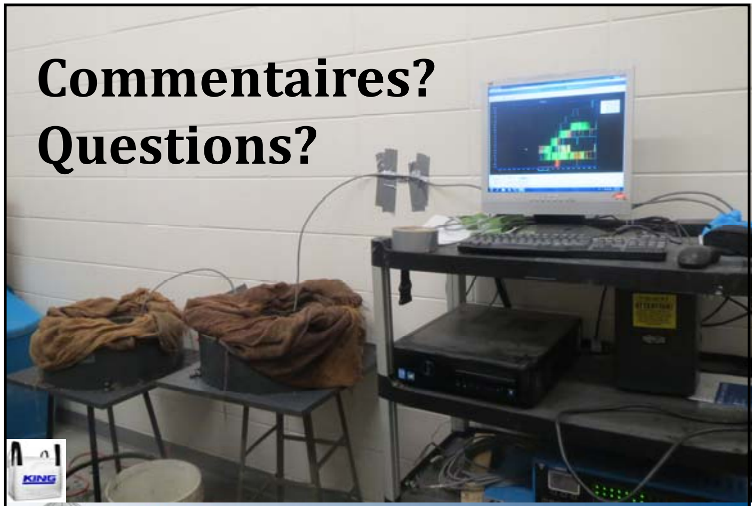
Commentaires?
Questions?



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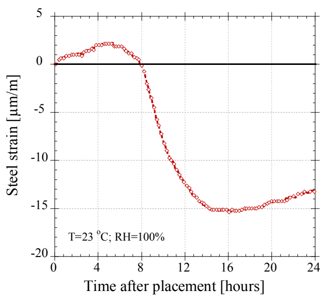
Curing

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



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