11-18-2019

Evaluating the cracking potential of shotcrete

Marc Jolin
Laval University, Canada, marc.jolin@gci.ulaval.ca

Marc JOLIN
Benoît BISSONNETTE
Bruce MENU
Émile BLOUIN-DALLAIRE
Alexandre PÉPIN-BEAUDET

Evaluating the Cracking Potential of Shotcrete

Shotcrete for Underground Support XIV
Nong Nouch Garden, Pattaya, Thailand
18 November 2019

Photo credit : Coastal Gunite

Presentation

- Background
  - Understanding cracking in concrete
  - Preventing cracking
- Evaluating the cracking potential of shotcrete

Cracking in *-sprayed-* Concrete

Hypothesis: ***you care about whether your concrete cracks or not !***

Cracking in *-sprayed-* Concrete

➡ Cracking is the ***result*** of a number of ***phenomena*** in concrete, originating from:

- thermal variations
- hygrometric variations
- internal stresses
- chemical reactions

→ *volume changes in concrete*

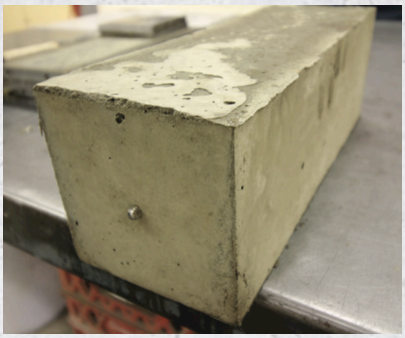
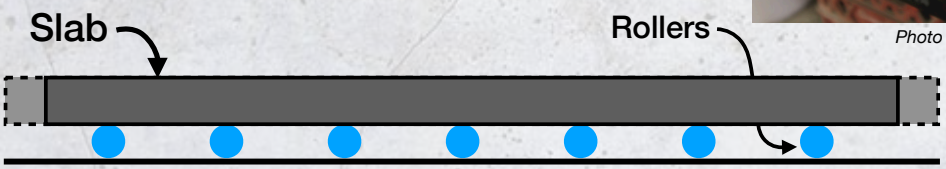


Photo credit : Euclid Chemicals



Shrinkage + freedom to move = NO CRACKS

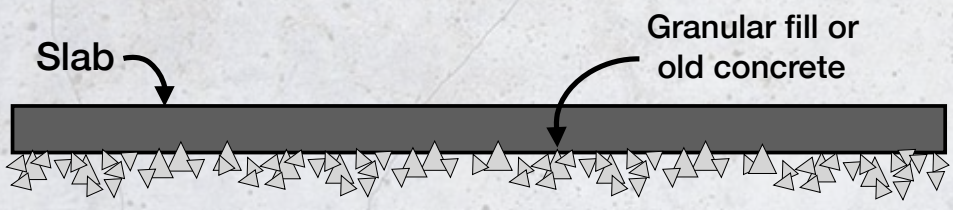
Cracking in -*sprayed*- Concrete

➡ Cracking is the ***result*** of a number of ***phenomena*** in concrete, originating from:

volume changes in concrete
-shrinkage-

Restriction of movement

Will it crack ?



Shrinkage + substrate restraint = *Internal Tensile Stresses*

Cracking in -*sprayed*- Concrete

Restriction of movement

Will it crack ?

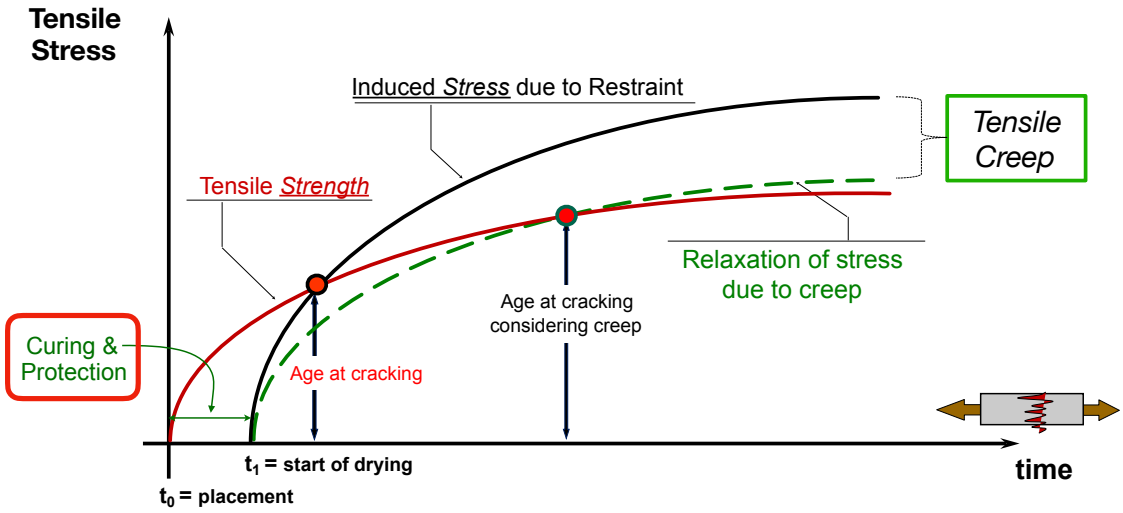
Thermal Shrinkage

Driving force:
ΔT (°C)
α_{th} = 12 με/°C

External Drying Shrinkage

Driving force:
water evaporation
ε_{sh}: 200-800 με

Drying Shrinkage & Cracking



Discussion on Cracking

- Drying shrinkage:
  - *WE* control when it starts: importance of early curing and protection
  - Caution with mix design: it is the *paste* that shrinks

Shotcrete Inspector

The relative humidity in the tunnel is always above 80%, and we all know that this is enough to maintain hydration of the concrete. So why should we protect it and worry about shrinkage?

Material Scientist

Well, it is the water vapor pressure that needs to be above 0.8 in the concrete to continue hydration.*

Shotcrete Inspector

isn't that the same ?

Material Scientist

Only if there is NO wind, and NO ΔT° between air and concrete

Shotcrete Inspector

So how do I deal with it?

* T. C. POWERS, A discussion of cement hydration in relation to the curing of concrete, Proc. Highw. Res. Bd., 27, pp. 178–88 (Washington, 1947).

Shotcrete Inspector

So how do I deal with it?

Material Scientist

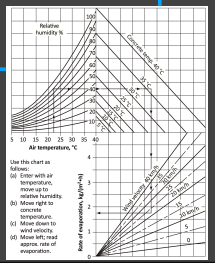
It is usually simpler to talk in terms of maximum concrete surface water loss, for example 1 kg/m²/hour

Shotcrete Inspector

How do I find this number?

Material Scientist

This 1 kg/m²/hour is often used for regular concrete slabs. See the chart attached…



Shotcrete Inspector

I don't like it, too complicated!

Material Scientist

There is also an approximate equation:

$$E = 5[(T_c + 18)^{2.5} - RH(T_a + 18)^{2.5}]\cdot(V+4)$$

(^oC, km/h → kg/m²/hour)

Shotcrete Inspector

So I punch it and 1.0 is the upper limit ? No curing necessary?

Almost… the thing is, the 1 kg/m²/hour is used for ordinary concrete that has some bleed water to offer.

Since shotcrete has no bleed water (like many good quality concrete), it is recommended to limit that value to 0.5 kg/m²/hour, anything above, you need curing!

Shotcrete Inspector

You are killing me, give me real life numbers I can use!

Material Scientist

Here you go: for a maximum of evaporation rate of 0.5 kg/m²/h*

* ACI 305R-10, *Hot Weather Concreting*, Farmington Hills, MI, USA, 28 p.

Concrete Temperature T_c (^oC)	Air Temperature T_a (^oC)	Relative Humidity %
35	29	100
32	27	100
29	24	95
27	21	85

* for 16 km/h wind

I work in Asia! That means I'll have to provide protection and curing for all my projects!

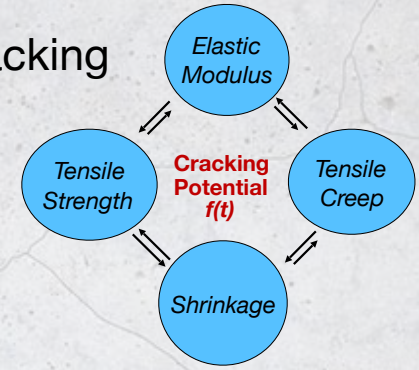
EXACTLY !

Discussion on Cracking

- Drying shrinkage:
  - *WE* control when it starts: importance of early curing and protection
  - Caution with mix design: it is the *paste* that shrinks
- Tensile Creep:
  - the unsung hero, often saving the day
- Thermal shrinkage is a different discussion:
  - beware of high early heat development caused by accelerators (setting *vs* strength development control; initial support *vs* final layer)

Discussion on Cracking

- *The Question:* How to characterize the cracking potential of a concrete mix?



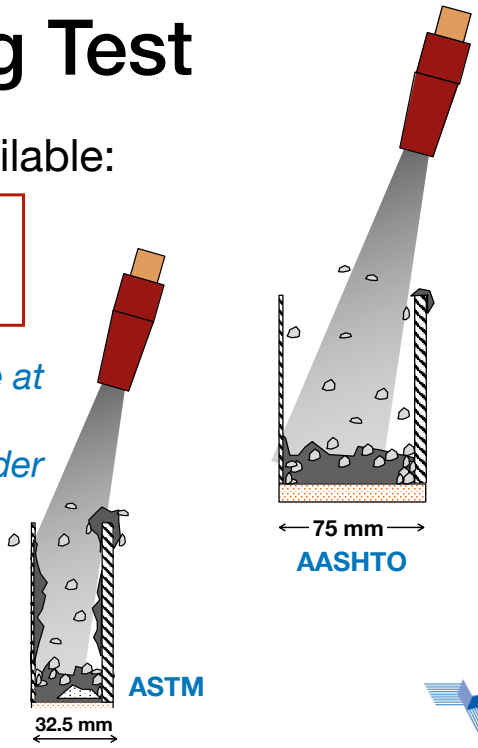
1. by *measuring* stiffness, drying shrinkage and tensile creep characteristics *over time*
2. by selecting a test that will capture the *effect* of these characteristics:
   - Use of a *Restrained Ring Test* specimen

Restrained Ring Test

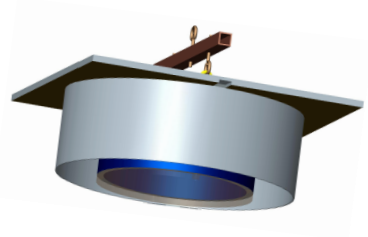
- There are two such test methods available:

1. *Standard Practice for Estimating the Crack Tendency of Concrete*, AASHTO T 334-08

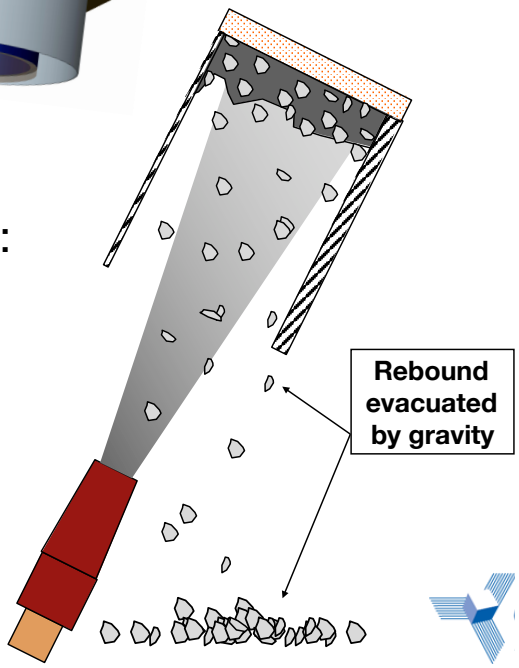
2. *Standard Test Method for Determining Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete under Restrained Shrinkage*, ASTM C1581



Restrained Ring Test - AASHTO



AASHTO T334 - modified



- A full M.Sc. project was dedicated at adapting the test method for *shotcrete*:

1. *Many spraying orientations and nozzle movement patterns were investigated*

2. Inter-batch and inter-operator validity was evaluated (3 batches; 3 operators)

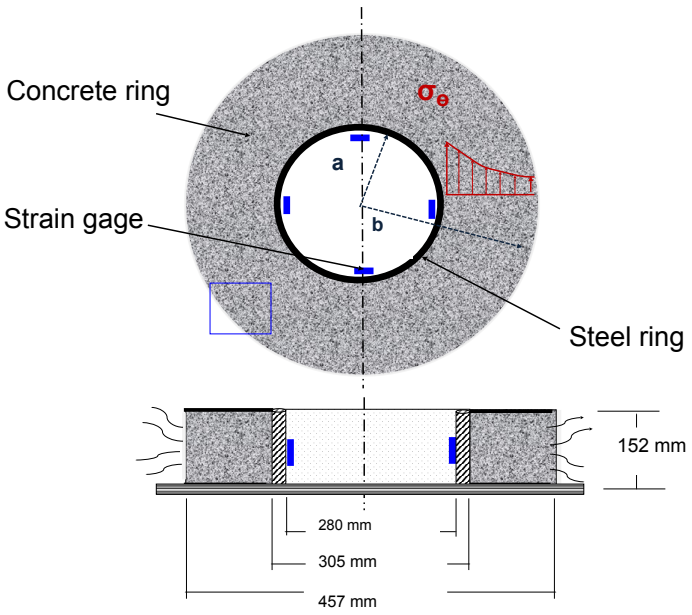
S.Girard, M.Jolin, B.Bissonnette and JD.Lemay (2017) 'Measuring the Cracking Potential of Shotcrete'. Concrete International, 39(8)

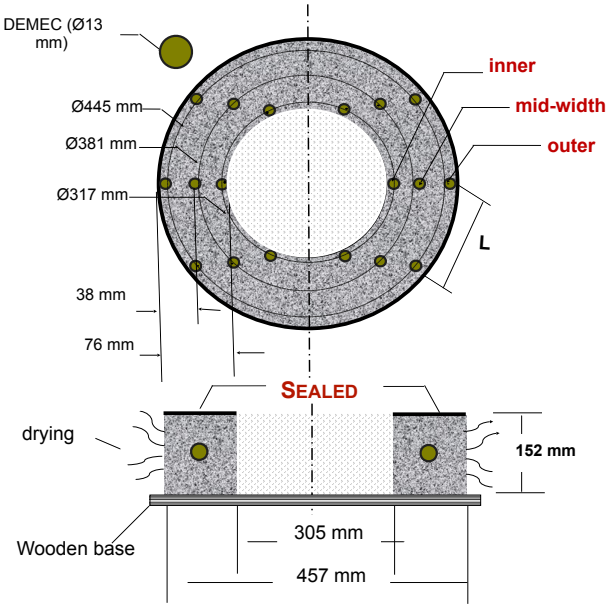
Placement Method

Exemple of Results AASHTO T334

Process	Mix Design/Curing	Time to Cracking
Dry	*Reference:* OPC+SF, 12mm agg, 3 days curing	3 days
Dry	Ref without SF	10 days
Dry	Ref, 1 day curing	3 days
Dry	Ref, 7 day curing	9 days
Dry	internal curing (absorbing particles)	6 days
Dry	ref+ mineral micro fibres	3 days
Dry	ref + expansive admixture (type G)	6 days
Dry	ref + polymer	16 days
Wet	same as ref.-dry	6 days
Wet	ref + SRA	18 days

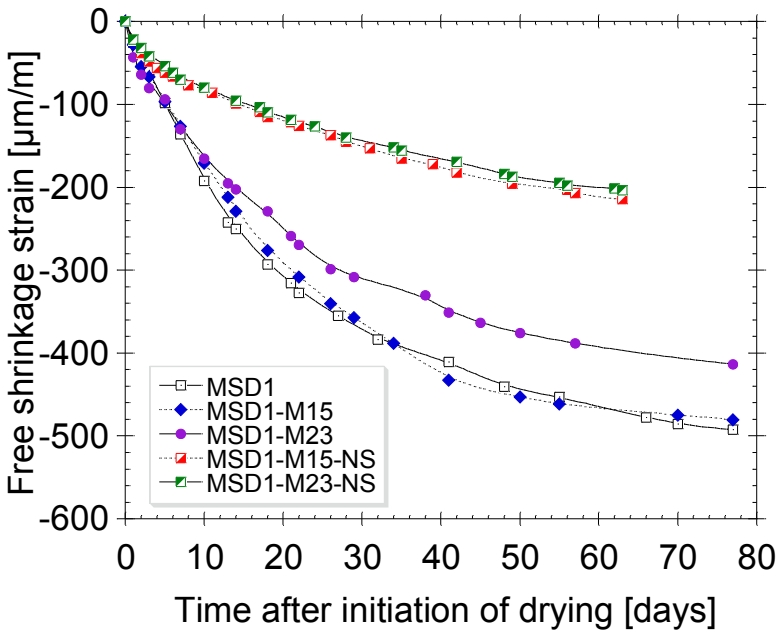
Two Rings: Restrained & Free





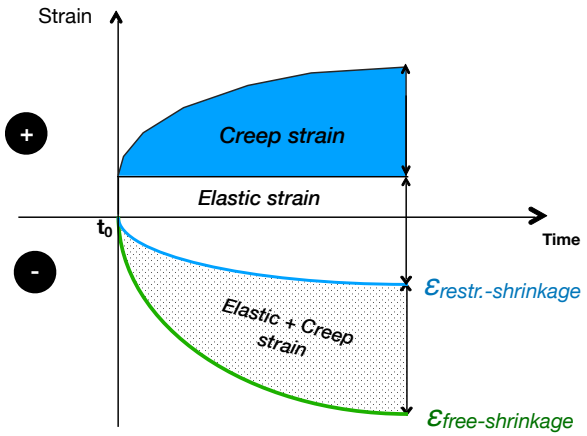
DEmountable **MEC**hanical strain gauge

Ring Test: Free shrinkage of shotcrete



- *Shrinkage is reduced by about 40% to 60% when SRA is used*
- *Increasing coarse aggregate content reduces shrinkage (!)*

Concrete strain components:



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

free shrinkage

steel deformation

$$\varepsilon_{total} = \varepsilon_{steel}$$

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

CREEP COEFFICIENT

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

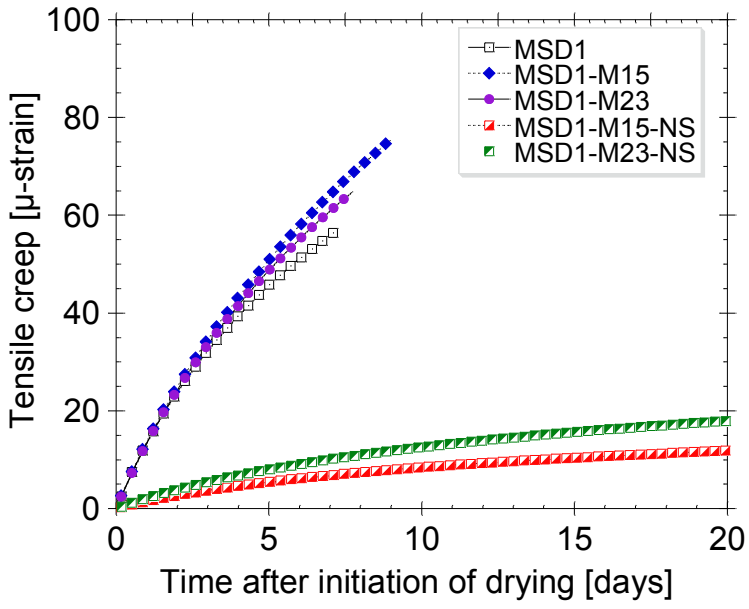
Tensile strain capacity $= \varepsilon_{elastic}(t) + \varepsilon_{creep}(t)$

creep coefficient

$$= \varepsilon_{elastic}(t)\left[1 + \phi(t)\right]$$

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

Post processing: Tensile Creep



- *SRA significantly reduces tensile creep this is due to the lower shrinkage when the SRA is added*
- *SF only mixtures have higher creep, but higher shrinkage potential hence sensitive to cracking*

Stress development in the concrete ring

➢ Residual stress:

Equilibrium of forces : $F_s(t) = -F_c(t)$

force in steel / force in concrete

Average Concrete Stress

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

area of concrete

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]

Curve fit of restrained shrinkage strains

$$\varepsilon_s(t) = \alpha(t)^{1/2} + c$$

where

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

« STRESS RATE »

$$S(t) = \frac{K \cdot |\alpha|}{2(t)^{1/2}}$$

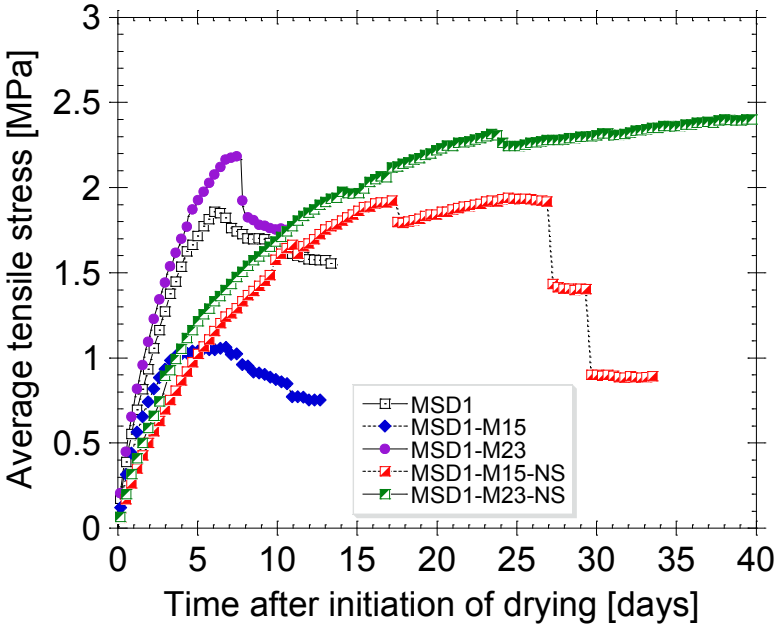
The st … y :

$$S(t) = \frac{1}{2\sqrt{t}}$$

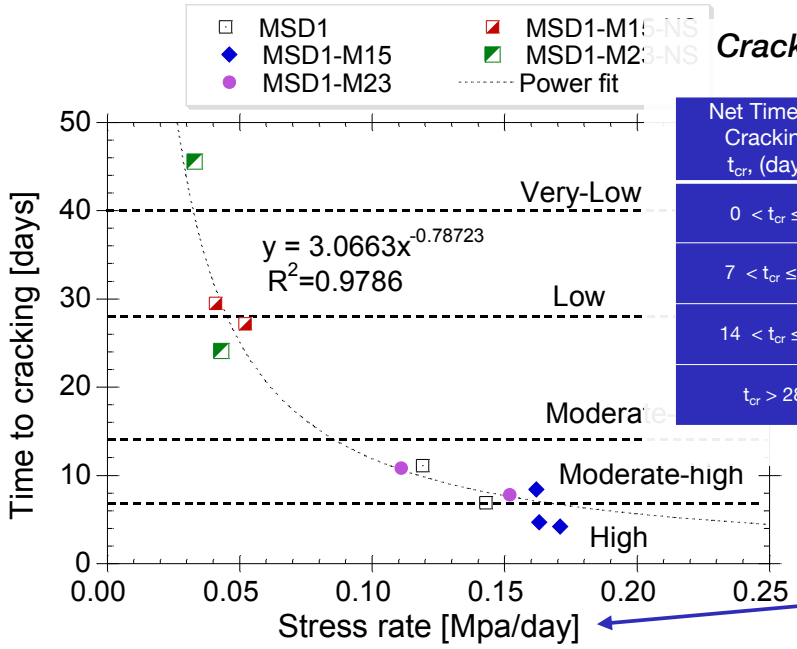
t is time to cracking

Post processing: Residual Stresses

- *SRA effectively reduces the potential for cracking*
- *However, the stress/ strength approach does not accurately predict cracking*
  - *cracking occurs at <1.0*



Cracking of shotcrete : Stress Rate Approach



Cracking potential classification

Net Time-to-Cracking, t_{cr}, (days)	Stress Rate at Cracking, (MPa/day)	Potential for Cracking
$0 < t_{cr} \leq 7$	$S \geq 0.17$	High
$7 < t_{cr} \leq 14$	$0.11 \leq S \leq 0.17$	Moderate-high
$14 < t_{cr} \leq 28$	$0.05 \leq S \leq 0.11$	Moderate-Low
$t_{cr} > 28$	$0.05 < S$	Low

Common scale for different ring drying conditions

In Summary: Restrained Shrinkage Ring Test

- The ring test can be successfully used to evaluate cracking of shotcrete
  - It is possible to spray high-quality reliable shotcrete rings that comply with the AASHTO T334-08 restrained ring test standard
- Proposed Usage :
  - 1st approach: Quantify the risk of cracking – residual stress and stress/strength approach
  - 2nd approach: Classify according to potential for cracking – Stress rate
  - 3rd approach: Tensile creep and relaxation
- Mix design and early curing & protection
  - If cracking is a concern: very early protection & curing necessary, @100%HR!

Next Challenges

- Can we find a direct relationship between the *Restrained Ring Test* results and the *on-site cracking potential* as a *f*(exposure condition) ?
- How can the effect of curing and protection be included in this analysis?
  - In other words, if I know the exposure conditions and the mix design, can I specify a curing method (and duration)?

Measurement of volume changes @ t = 0

Contributors

KING
A SIKA COMPANY

NSERC
CRSNG

CRIB
Centre de recherche sur les infrastructures en béton

UNIVERSITÉ LAVAL