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UHPC Innovations for Durability and Resiliency

ACI Fall 2013 Convention
October 20 - 24, Phoenix, AZ

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ACI Fall Convention
Phoenix, October 19-24, 2013

Self healing capacity of High Performance Fiber Reinforced Cementitious Composites

Liberato Ferrara
Politecnico di Milano, Italy

Concrete cracking

Eurocode 2: § 7.3 - Model Code 2010: § 7.6.4

(2) Cracking is normal in reinforced concrete structures subjected to bending, shear, torsion or tension resulting from either direct loading or restraint or imposed deformation.

(1) PRINCIPLE
Cracking shall be limited to an extent that will not impair the proper functioning or durability of the structure or cause its appearance to be unacceptable

(3) Cracks may also arise from other causes such as plastic shrinkage or expansive chemical reactions within the hardened concrete. Such cracks may be unacceptably large but their avoidance and contol lies outside the scope of this section.

Durability

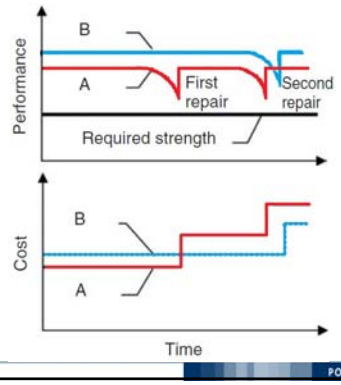
EN 1990 § 2.4

(1)P The structure shall be designed such that deterioration over its design working life does not impair the performance of the structure below that intended, having due regard to its environment and the anticipated level of maintenance.

Eurocode 2 § 4.1

(1)P A durable structure shall meet the requirements of serviceability, strength and stability throughout its design working life, without significant loss of utility or excessive unforeseen maintenance.

Durability

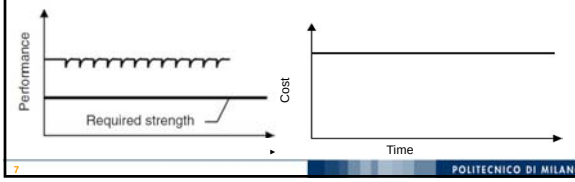


Sustainability

Model Code 2010 § 3.1 – basic principles of design!

ability of a material, structure or structural members to contribute positively to the fulfilment of the present needs of humankind with respect to nature, society and humans, without compromising the ability of future generations to meet their needs in a similar manner.

Provide the material an "inborn" capacity to recover its pristine level of performance thus "self-extending" its service life



Self sealing/healing

Definition of terms (RILEM TC221)

Self sealing/closing:
ability of closing cracks

Self healing:
ability of closing cracks and restoring physical/mechanical properties

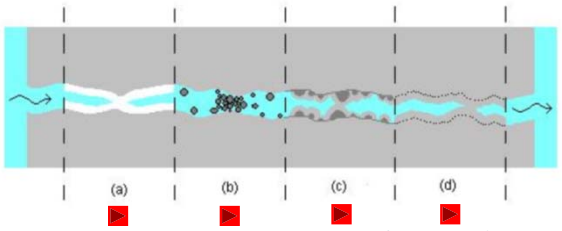
Autogeneous self sealing/healing
due to own concrete constituents

Autonomic (engineered) self sealing/healing
triggered by engineered additions.

Self healing

Cementitious composites may inherently possess the capacity of "self-healing" the cracks: "a concrete miracle"?

(Neville)



After Ter Heide 2005

Self healing

Cementitious composites may inherently possess the capacity of "self-healing" the cracks: "a concrete miracle"?

(Neville)

- a) reaction of C-S-H with CO_2 (atmosphere or dissolved in water, also as H_2CO_3): formation and precipitation of $CaCO_3$ crystals;
- b) crack obstruction due to sedimentation of particles which are formed because of cracking and/or may be transported by water flowing through cracks (in case)
- c) continued hydration of anhydrous cement particles which come in contact with water/mositure (atmospheric) and precipitation of C-S-H crystals
- d) swelling of the cement matrix when in contact with water/moisture

Self healing

GOVERNING PARAMETERS:

- CRACK OPENING
- STRESS STATE ALONG THE CRACK
- WATER TEMPERATURE
  (favorable?, Reinhardt & Joos, 2003)
- PRESENCE OF OTHER SUBSTANCES (CHLORIDES ETC.)

BENEFITS:

- Reduction of water permeability (Hearn and Morley, 1997; Hearn, 1998; Edvardsen, 1999; Aldea et al., 2000)
  (cause-effect?)
- strength and stiffness recovery? (Dhir et al., 1973 + recent studies on ECC/HPFRCCs)

Self healing

ENGINEERED SELF HEALING: different typologies

a) CHEMICAL ENCAPSULATION

b) BACTERIA ENCAPSULATION

c) CHEMICALS IN GLASS/BRITTLE TUBES

d) TAILORED ADMIXTURES

e) FIBERS: INTRINSIC SELF HEALING DUE TO TIGHT CRACK WIDTH AND PECULIAR COMPOSITION (HPFRCCs, ECCs)

Self healing of HPFRCC

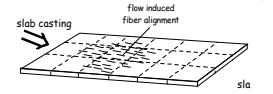
Constituent	Dosage (kg/m^3)
Cement type I 52.5	600
Slag	500
Water	200
Superplasticizer	27,5 (l/m^3)
Sand 0-2 mm	983
Straight steel fibres (l_f = 13 mm; df = 0.16 mm)	100

$f_{c,cube}$ = 150-180 N/mm^2

due to tight crack opening, high cement/cement substitute contents, low w/b ratio high potential for autogeneous self healing

Self healing of HPFRCC

Influence of flow-induced fiber orientation on multiple/single cracking



Self healing of HPFRCC

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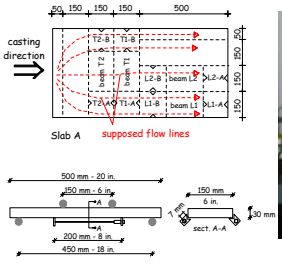

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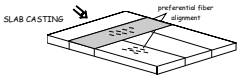
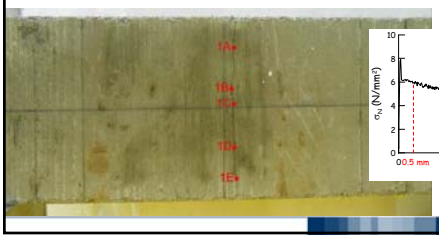


Fibers orthogonal to tensile stress



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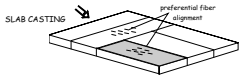
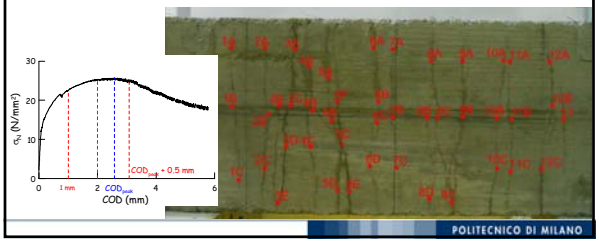


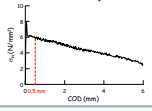
Fibers parallel to tensile stress



Self healing of HPFRCC

Experimental procedure: deflection softening HPFRCC

Pre-cracking (age: 6 months)



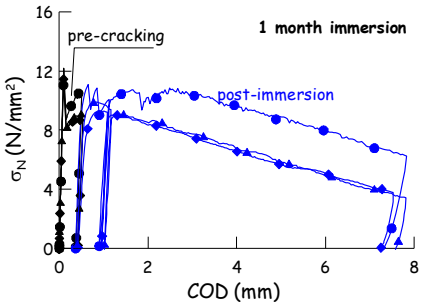
Immersion in water
1, 3,6, 12 months

Post-exposure testing to failure

Pre-crack opening (single crack)
0.5 mm

Self healing of HPFRCC

Deflection softening HPFRCC



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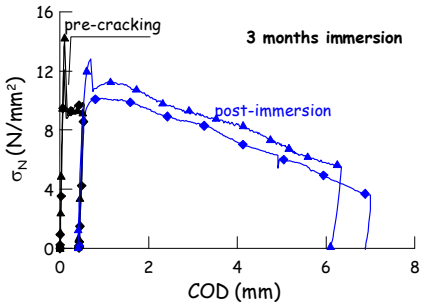
Self healing of HPFRCC

Deflection softening HPFRCC



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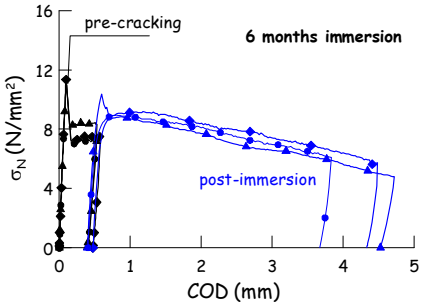
Self healing of HPFRCC

Deflection softening HPFRCC



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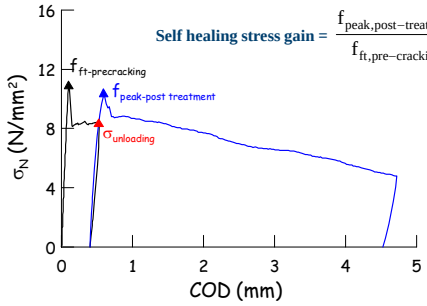
Self healing of HPFRCC

Deflection softening HPFRCC

$$\text{Self healing stress gain} = \frac{f_{peak,post-treatment} - \sigma_{unloading}}{f_{ft,pre-cracking} - \sigma_{unloading}}$$



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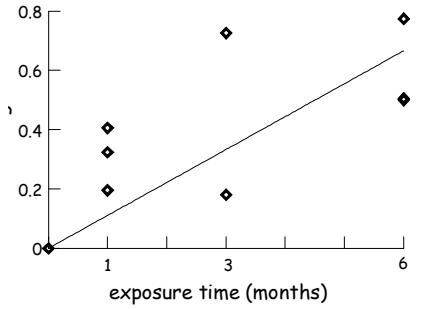
Self healing of HPFRCC

Deflection softening HPFRCC



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Self healing of HPFRCC

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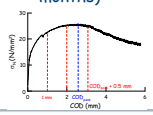

Immersion in water
1, 3,6, 12 months

Post-exposure testing to failure

Pre-crack opening (multiple cracks)
1 mm, 2 mm (pre-peak)
COD_{peak} + 0.5 mm

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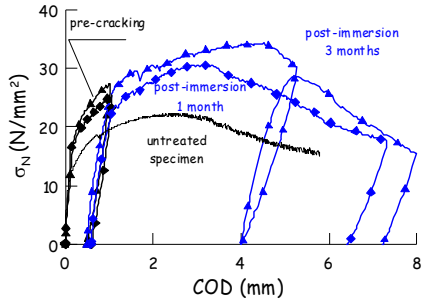
Self healing of HPFRCC

Deflection hardening HPFRCC: 1mm pre-cracking



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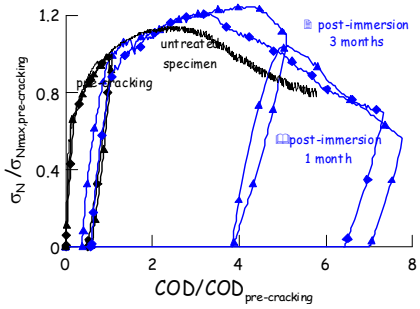
Self healing of HPFRCC

Deflection hardening HPFRCC: 1mm pre-cracking



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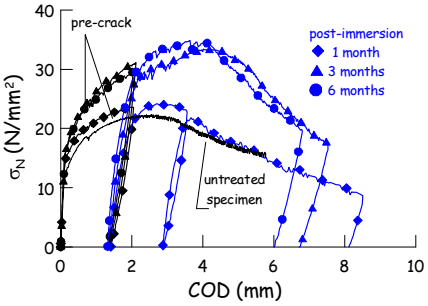
Self healing of HPFRCC

Deflection hardening HPFRCC: 2mm pre-cracking



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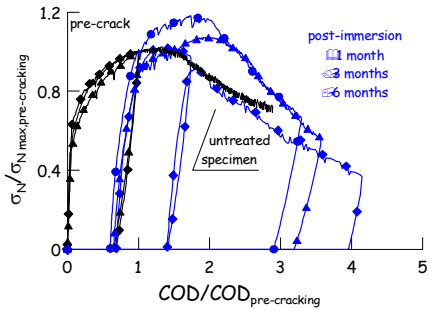
Self healing of HPFRCC

Deflection hardening HPFRCC: 2mm pre-cracking



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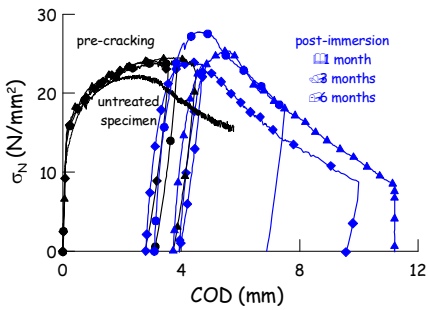
Self healing of HPFRCC

Deflection hardening HPFRCC: COD_{peak} +0.5 mm pre-cracking



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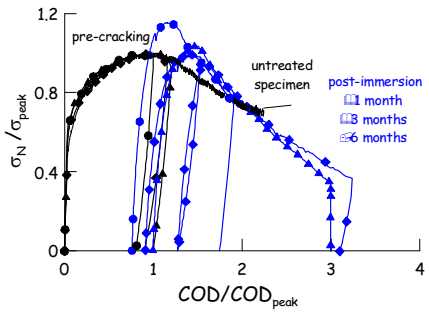
Self healing of HPFRCC

Deflection hardening HPFRCC: COD_{peak} +0.5 mm pre-cracking



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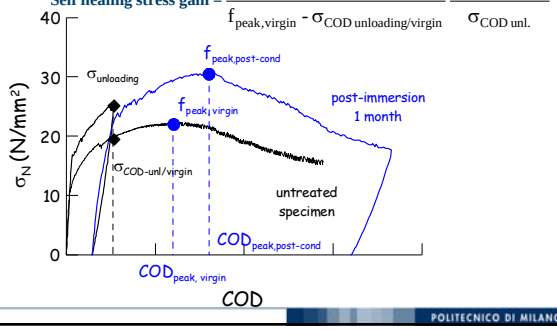
Self healing of HPFRCC

Deflection hardening HPFRCC

$$\text{Self healing stress gain} = \frac{f_{peak,post-cond.} - \sigma_{unloading}}{f_{peak,virgin} - \sigma_{COD\ unloading/virgin}} \quad \frac{\sigma_{COD\ unl/virgin}}{\sigma_{COD\ unl.}}$$



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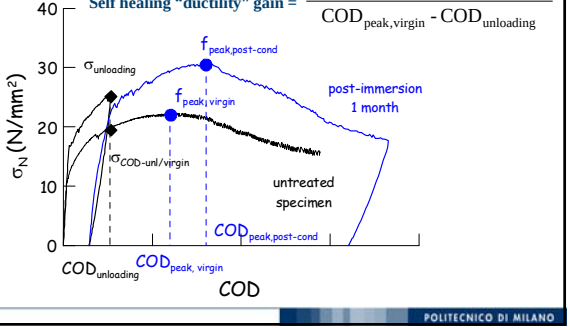
Self healing of HPFRCC

Deflection hardening HPFRCC

$$\text{Self healing "ductility" gain} = \frac{COD_{peak,post-cond.} - COD_{unloading}}{COD_{peak,virgin} - COD_{unloading}}$$



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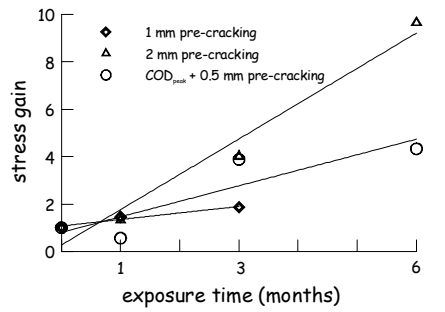
Self healing of HPFRCC

Deflection hardening HPFRCC



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Self healing of HPFRCC

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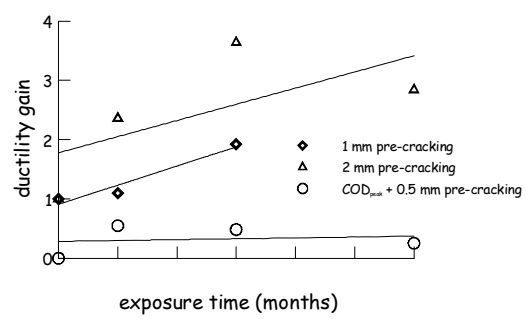

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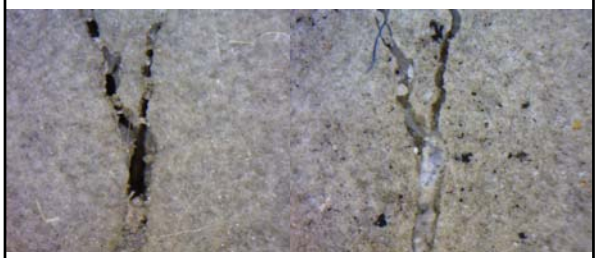
Self healing of HPFRCC



6 months old HPFRCC
Deflection hardening behaviour
precracking at COD_{peak} + 0.5 mm

after 1 month in water

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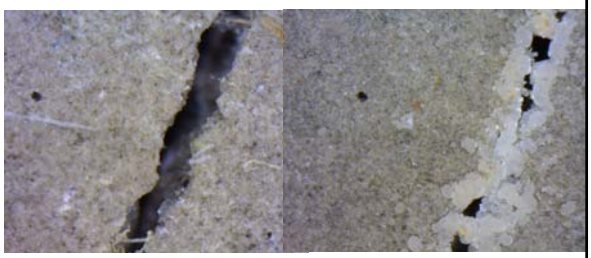
Self healing of HPFRCC



6 months old HPFRCC
Deflection hardening behaviour
precracking at COD_{peak} + 0.5 mm

after 3 month in water

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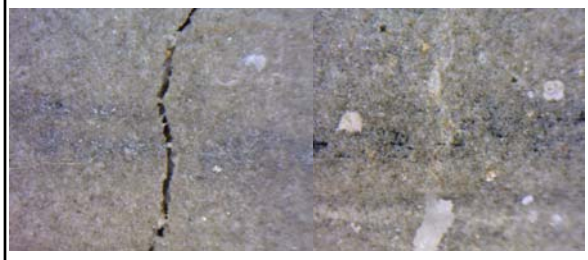
Self healing of HPFRCC



6 months old HPFRCC
Deflection hardening behaviour
precracking at COD_{peak} + 0.5 mm

after 6 month in water

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Self healing of HPFRCC

6 months old HPFRCC
Deflection softening behaviour
precracking at 0.5 mm

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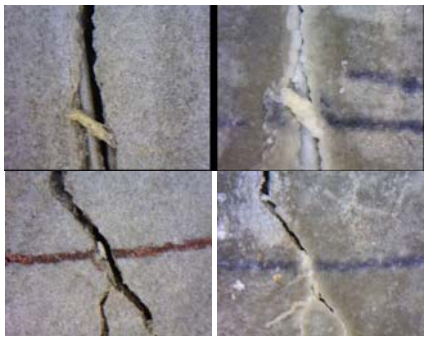

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Concluding remarks

HPFRCCs: autogenic self healing capacity due to high cement/binder content and lowe w/b ratio – delayed hydration of anhydrous cement clusters exposed to outdoor moisture upon cracking!

Dedicated experimental methodology to quantify effect of self healing on recovery of load bearing capacity and ductility, also as a function of flow induced orientation of fibers.

After about three to six months immersion in water:

- for deflection softening specimens cracks up to 0.5 mm almost completely closed
- deflection hardening specimens showed significant recovery of load bearing capacity and ductility; the further the specimen goes into multiple cracking stage (before localization) the better it heals!

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Work in progress

Investigate effect of:
- age of pre-cracking: 2 months vs. 6 months
- exposure conditions:
  - humid (RH 95%, T = 20°C) or
  - dry environment (Rh 55 %, T = 20°C)
  - open air
  - wet and dry cycles
  - …

Hybrid systems:
combine steel fibres with natural macrofibers (e.g. sisal), microfibres (eucalyptus) or nanofibers (cellulose pulps)
effects of fiber saturation and water release along time on self healing reactions
(in cooperation with UFRJ-Coppe, prof. R. Toledo Filho and dr. Flavio Silva)

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