POLITECNICO MILANO 1863 | DIPARTIMENTO DI INGEGNERIA CIVILE E AMBIENTALE

Mechanical damage and self-healing on high temperature exposed UHPC

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SMARTINCS

SELF-HEALING - MULTIFUNCTIONAL - ADVANCED REPAIR TECHNOLOGIES IN CEMENTITIOUS SYSTEMS

aci CONCRETE CONVENTION

Research significance: structural applications

TUNNEL

https://consolis.com/innovation-smart-tunnel-lining-segments/

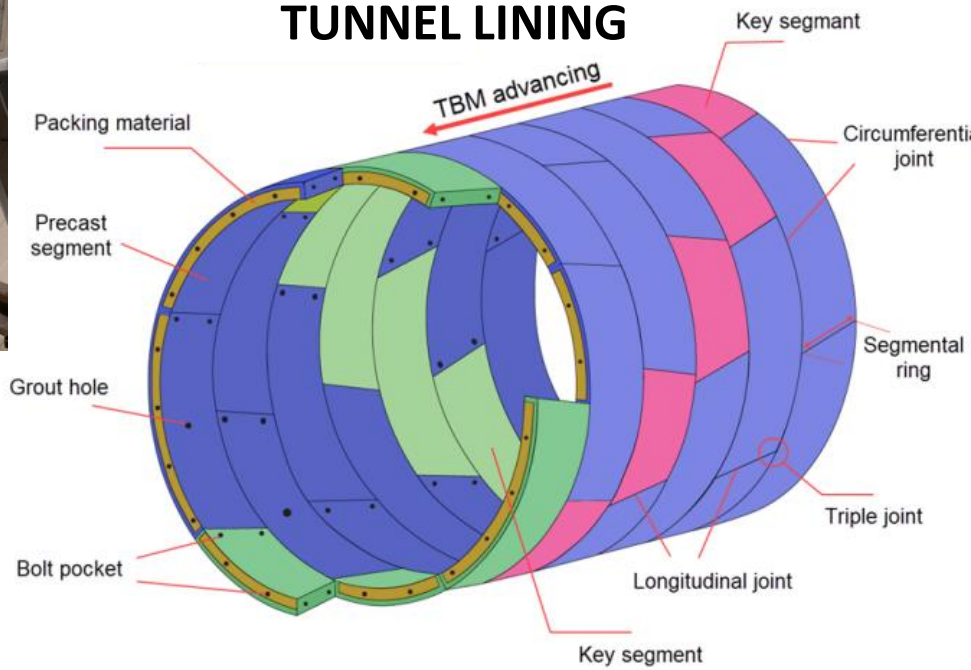
https://rdconcrete.com/research-development-concretes-rdc/

UHPC TRUSS BEAM

UHPC-JACKETING & STRENGTHENING

Fantilli A.P. et al., ACI 2021 Spring Concention.

SEGMENTAL TUNNEL LINING



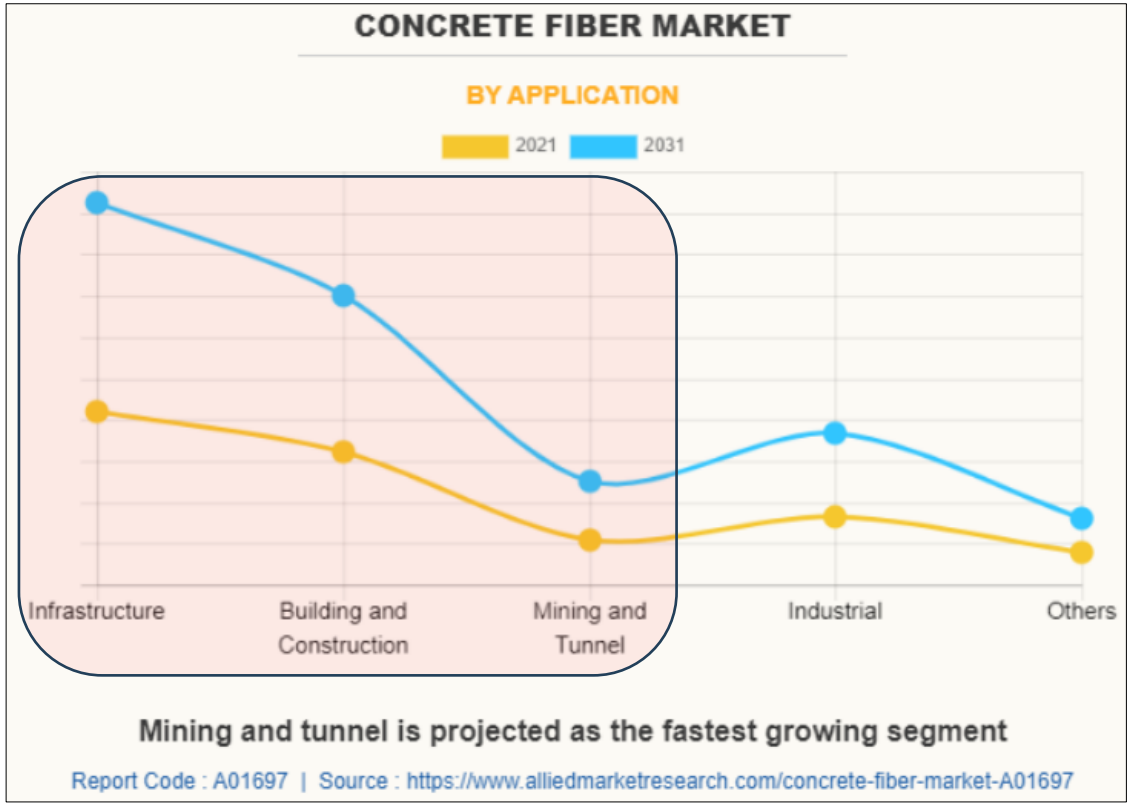
Ramesh, A.; Rashiddel, A.; Hajihassani, M.; Dias, D.; Kiani, M. Interaction of Segmental Tunnel Linings and Dip-Slip Faults—Tabriz Subway Tunnels. Appl. Sci. 2023, 13, 7866.

Research significance: structural applications

Tunnel Lining Construction Market Trends:

- ✓ Rapid Growth of Urban Metro and Railway Tunneling Projects: Major cities across India, China, and Europe are expanding metro and intercity train lines, driving significant demand for segmental lining systems capable of meeting tight construction schedules and design tolerances.
- ✓ Increasing Use of Fiber-Reinforced Shotcrete and High-Durability Linings: Advanced shotcrete mixes with macro- and microfibers are being used for immediate ground support and final linings, offering improved tensile strength, ductility, and fire resistance.

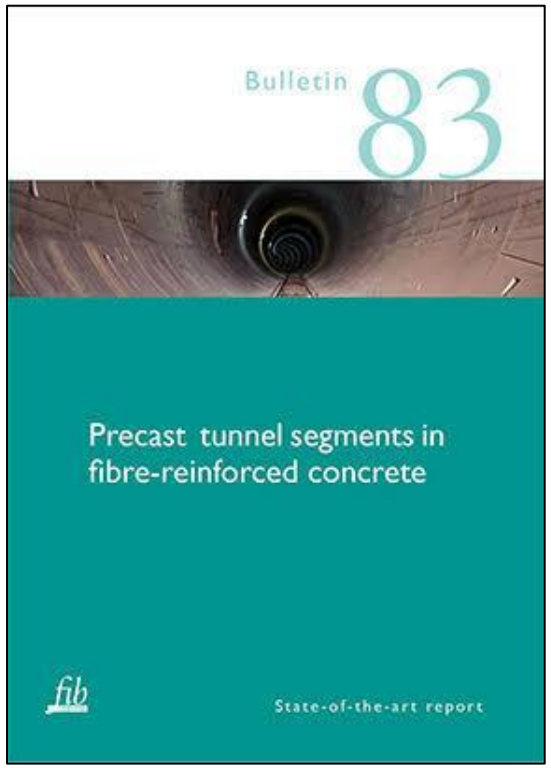
https://mobilityforesights.com/product/tunnel-lining-construction-market

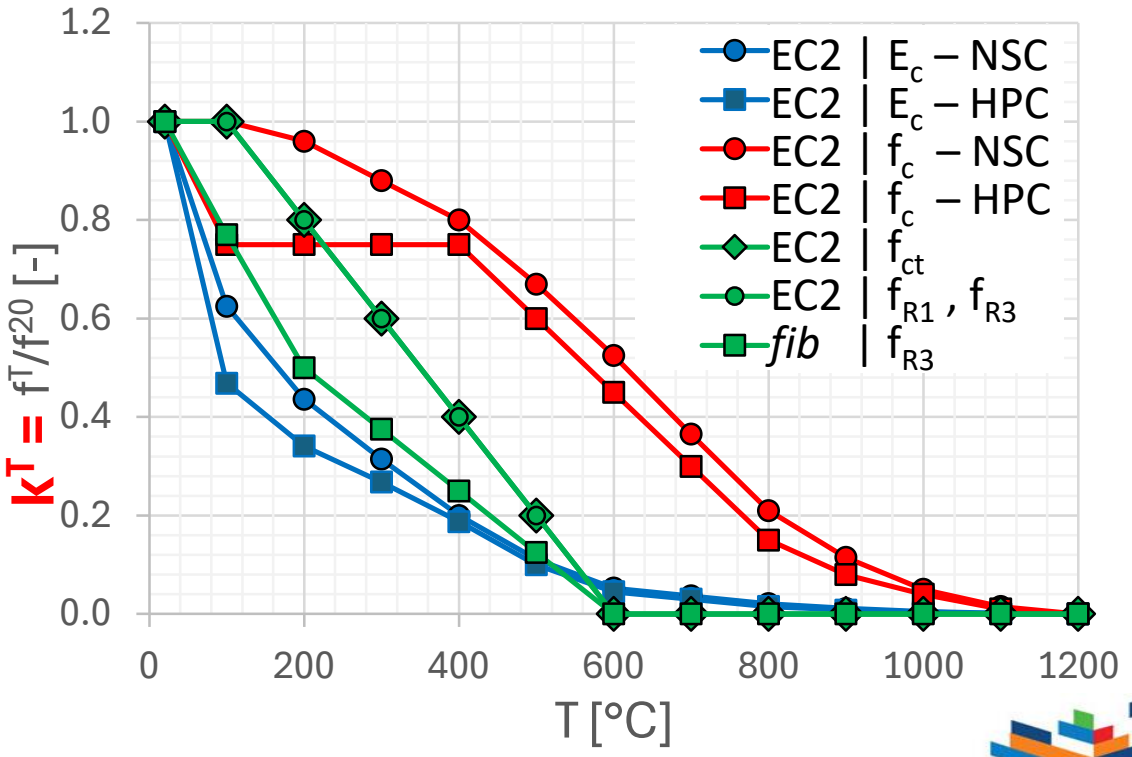


Fibre-Reinforced Concrete **market is expected to about double** in this decade (2020-2030)

Hot mechanical properties

- **EC2 - EN 1992-1-2:2004**. (2023). **Eurocode 2** - Design of concrete structures - Part 1-2: General rules - Structural fire design. European Committee for Standardization (CEN).
- ***fib* - Bulletin 83**. (2017). Precast tunnel segments in fibre-reinforced concrete. International Federation for Structural Concrete - fib.





Residual mechanical properties

❑ **EN 1992-1-2:2004**. (2023). **Eurocode 2** - Design of concrete structures - Part 1-2: General rules - Structural fire design. European Committee for Standardization (CEN).

(5) For thermal actions in accordance with EN 1991-1-2:—[1], 5.3 (Physically based models), when considering the cooling phase, the strength of concrete heated to a maximum temperature $\theta_{c,max}$ and having cooled down to 20 °C may be taken according to Formula (5.15):

$f_{c,\theta,20\,°C} = \varphi\, f_{ck}$ $\quad \varphi = \text{function of } \theta_{max}\ (= 0.9 \div 1.0 \cdot k^T)$ (5.15)

where for:

NSC

$f_{ck} < 70$ MPa

$\varphi = f_{c,\theta max}/f_{ck}$ $= 1.0 \cdot k^T$ for $20\,°C \le \theta_{max} < 100\,°C$ (5.16)

$\varphi = (-0{,}0005 \times \theta_{max} + 1{,}05)\ (f_{c,\theta max}/f_{ck})$ $= 0.9 \div 1.0 \cdot k^T$ for $100\,°C \le \theta_{max} < 300\,°C$ (5.17)

$\varphi = 0{,}9\ (f_{c,\theta max}/f_{ck})$ $= 0.9 \cdot k^T$ for $\theta_{max} \ge 300\,°C$ (5.18)

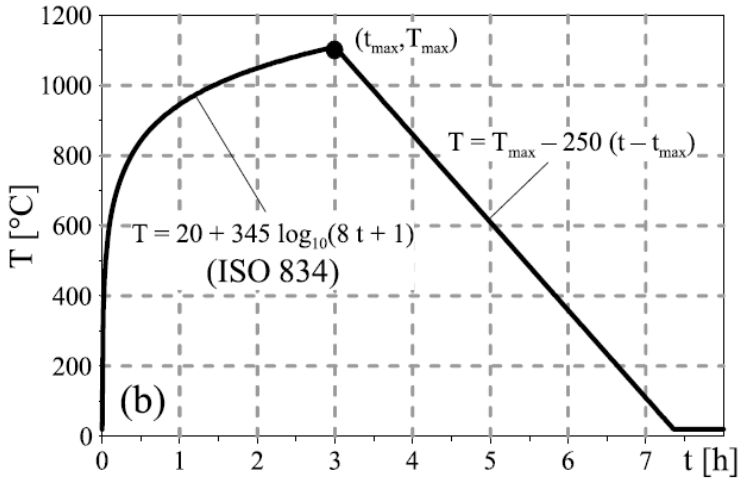
HPC

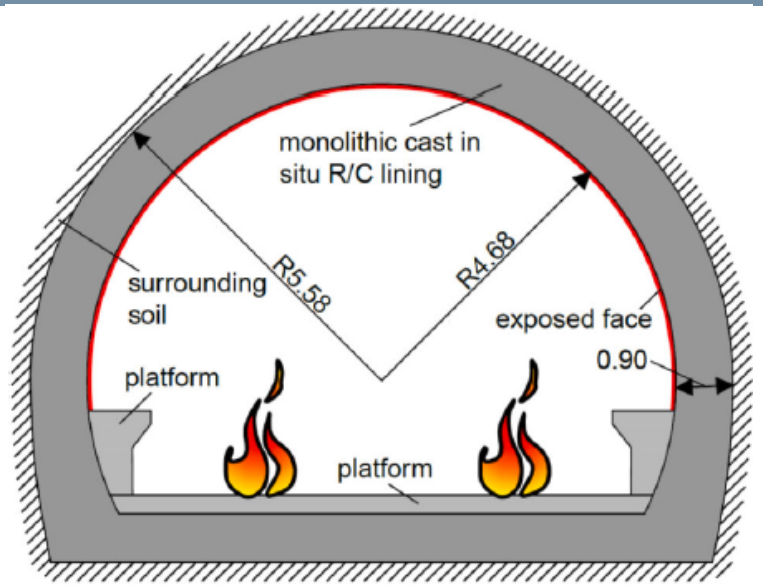
$f_{ck} \ge 70$ MPa

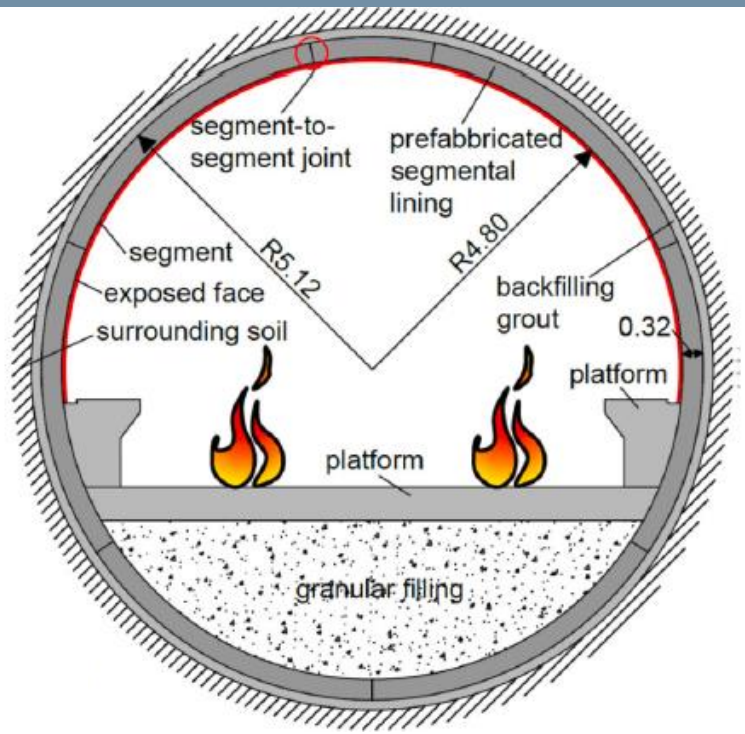
$\varphi = f_{c,\theta max}/f_{ck}$ $= 1.0 \cdot k^T$ for $20\,°C \le \theta_{max} < 1\,200\,°C$ (5.19)

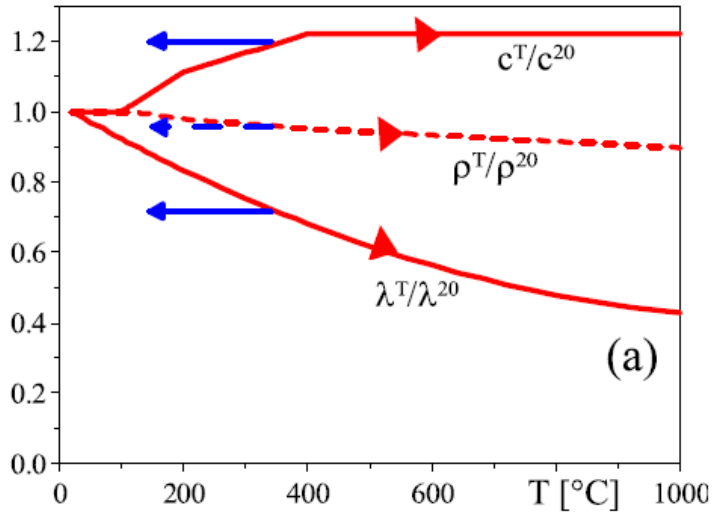
The reduction factor $(f_{c,\theta max}/f_{ck})$, which corresponds to the coefficient $(f_{c,\theta}/f_{ck})$ at the maximum temperature $\theta_{c,max}$, should be taken according to Table 5.1.

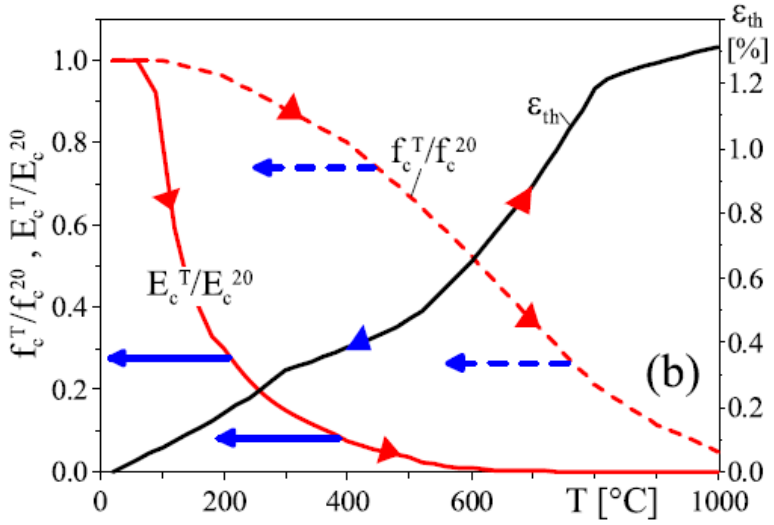
Do residual properties really matters?





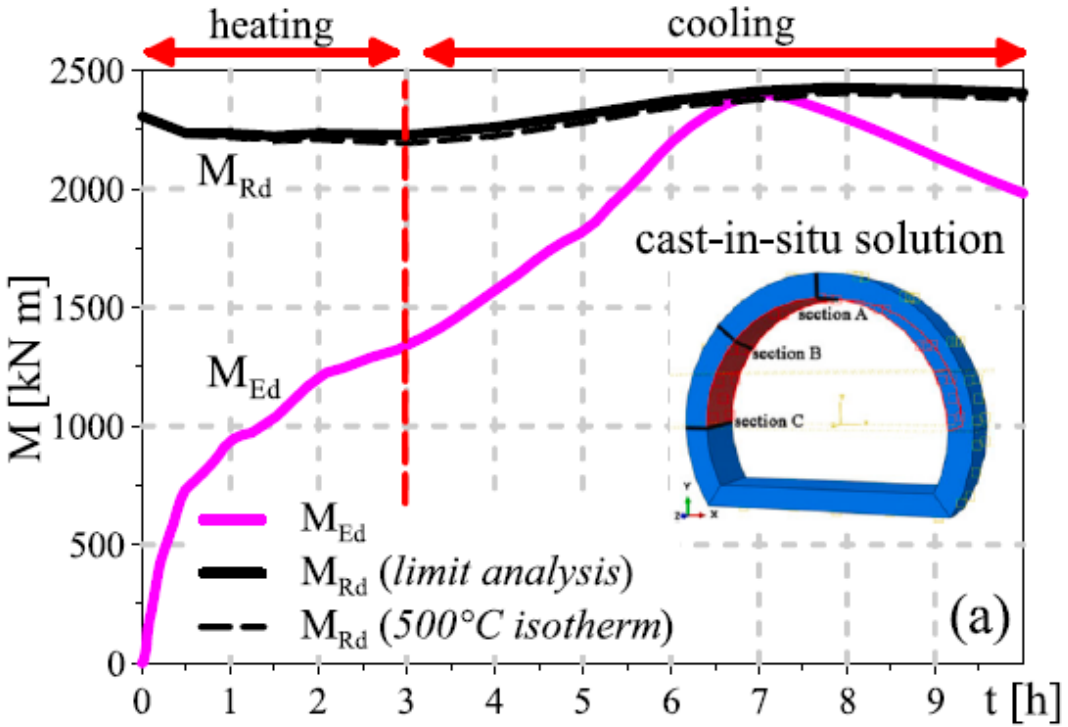


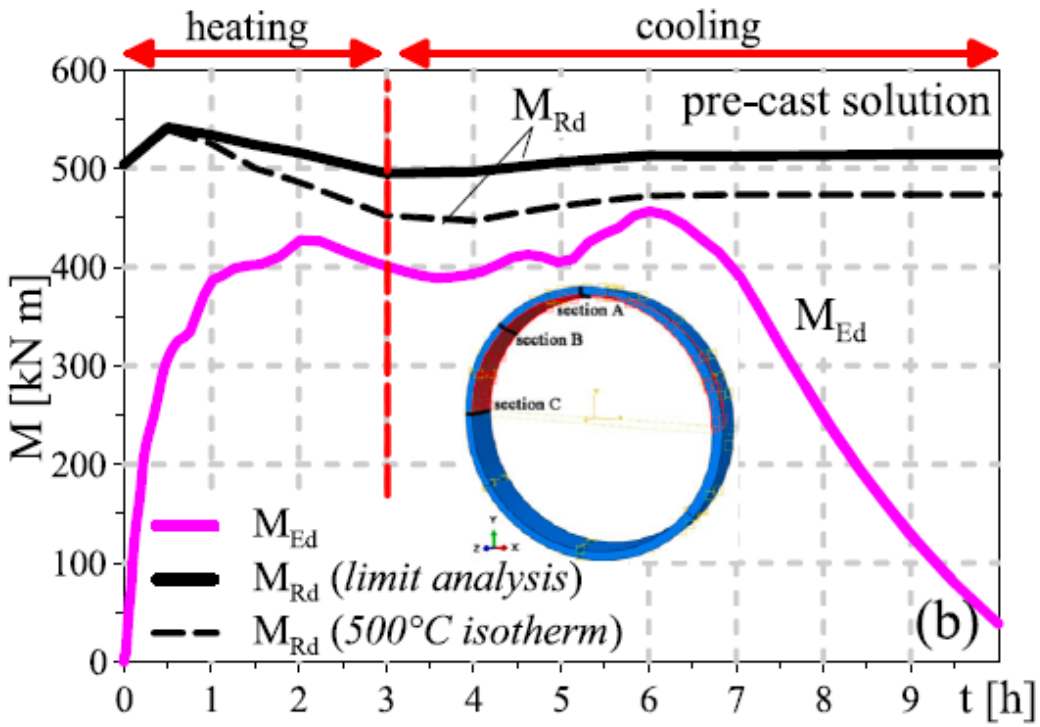




Lo Monte F., Bamonte P., Beltrami C, Study on the effects of cooling phase and construction technology on the fire performance of R/C tunnels(2023), 132, art. no. 104838

Do residual properties really matters?



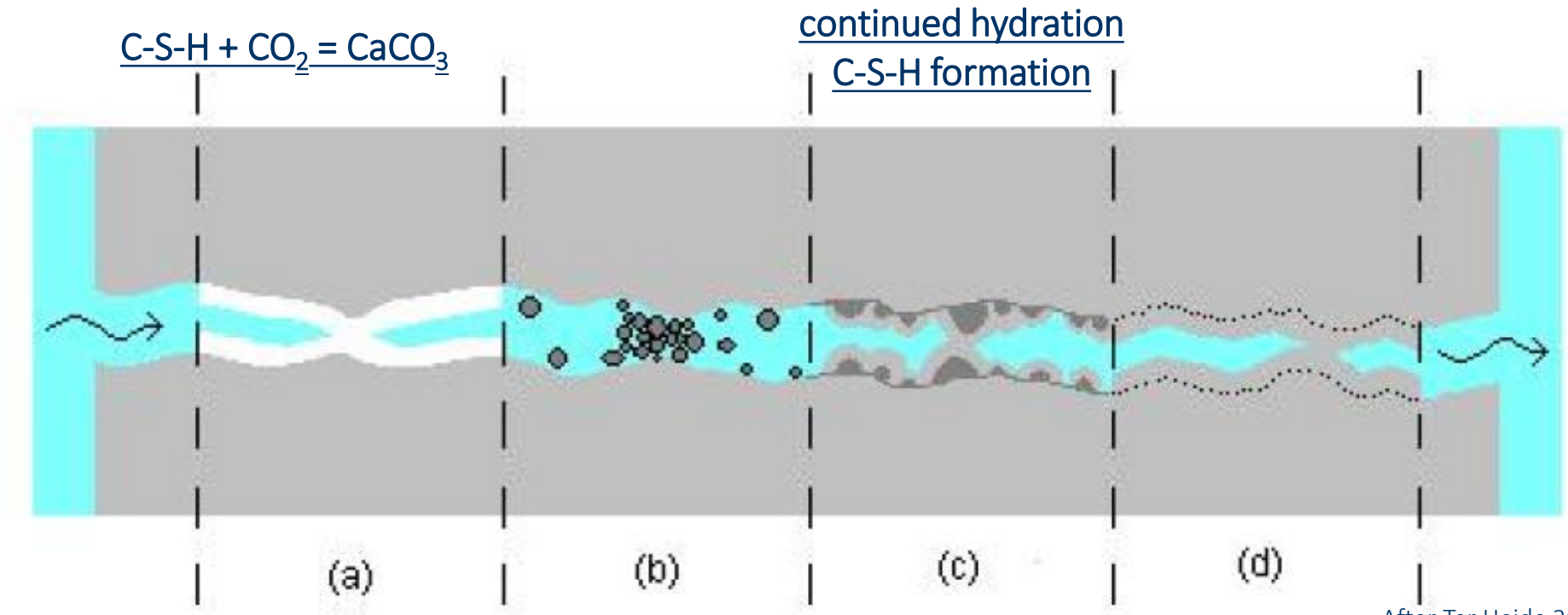


	limit sectional analysis	500°C isotherm method
	minimum F_s	minimum F_s
cast-in-situ solution	1.00 (7 h)	0.99 (7 h)
pre-cast solution	1.12 (6 h)	1.03 (6 h)

Self-healing in residual conditions

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

(Neville)

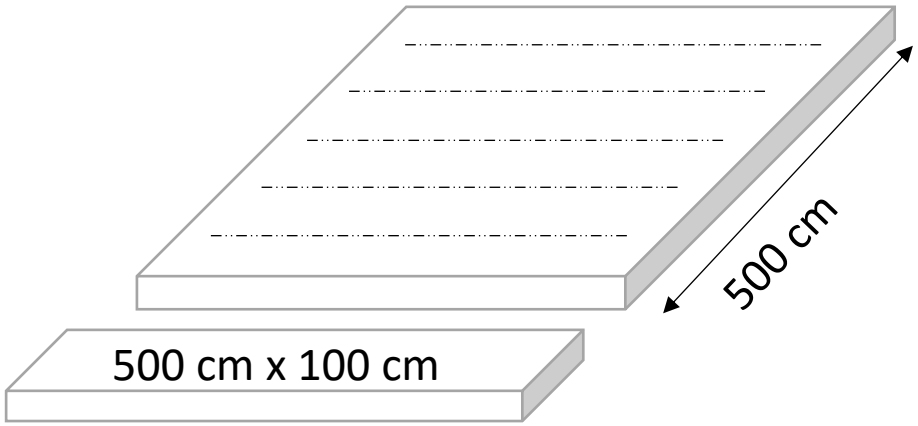


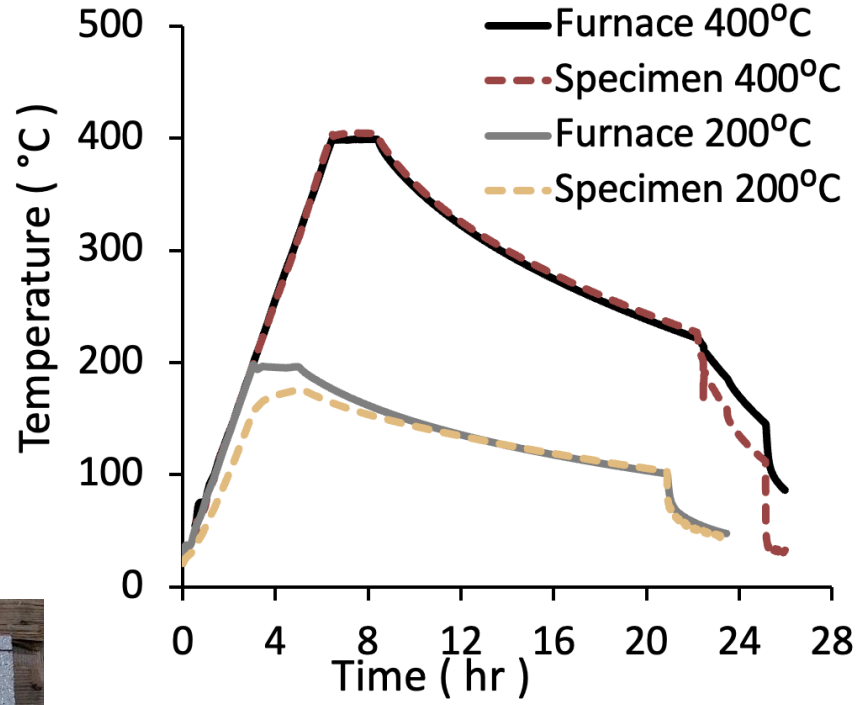
After Ter Heide 2005

Experimental campaign: mix design

Mix composition of the investigated Rinfor Grout Col ® UHPC

Constituent	Dosage (kg/m³)
Cement (CEM I + CEM II)	700
Siliceous sand 0-5 mm	1210
Microsilica and reactive filler	130
Polypropylene fibers (lf = 6 mm)	0.6
Steel fibers (lf = 20 mm)	100
Superplasticizer	30
Crystalline admixture Penetron Admix ®	0.9% by weight of cement
Water/cement ratio	0.29





Experimental campaign: testing plan

high-temperature mechanical property tests

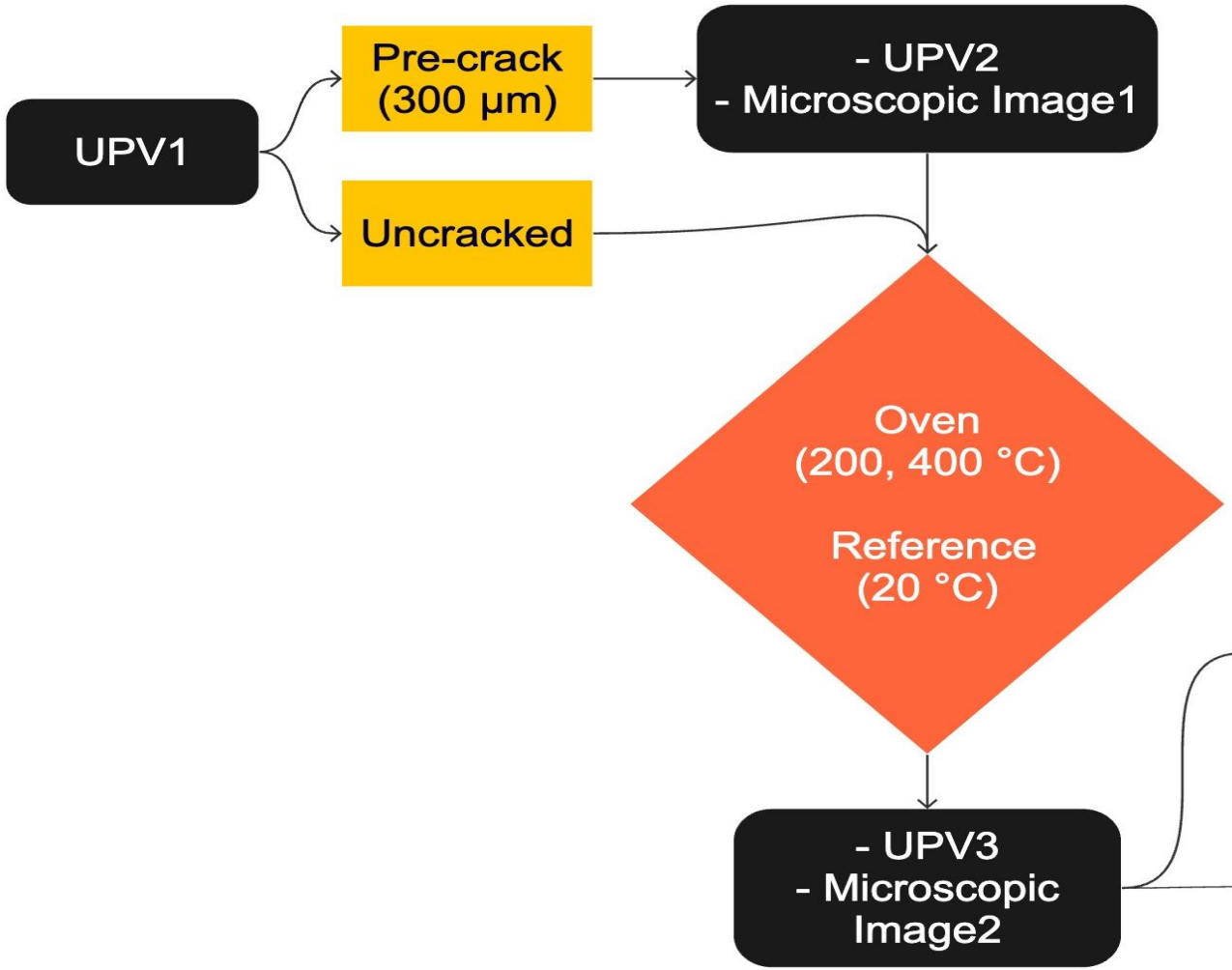
Series	Specimens	Condition	T [°C]	After exposure
REF	5	Uncracked	20	Flexural test
REF″	3	Pre-cracked	20	Self-healing
REF-6mo.	2	Uncracked	20	Flexural test after 6 months
T200	3	Uncracked	200	Flexural test
T200′	3	Pre-cracked	200	Flexural test
T200″	3	Pre-cracked	200	Self-healing
T400	3	Uncracked	400	Flexural test
T400′	3	Pre-cracked	400	Flexural test
T400″	3	Pre-cracked	400	Self-healing

Self-healing condition: Specimens were submerged in tap water for 6 months

′ – Pre-cracked

″ – Pre-cracked + self-healing

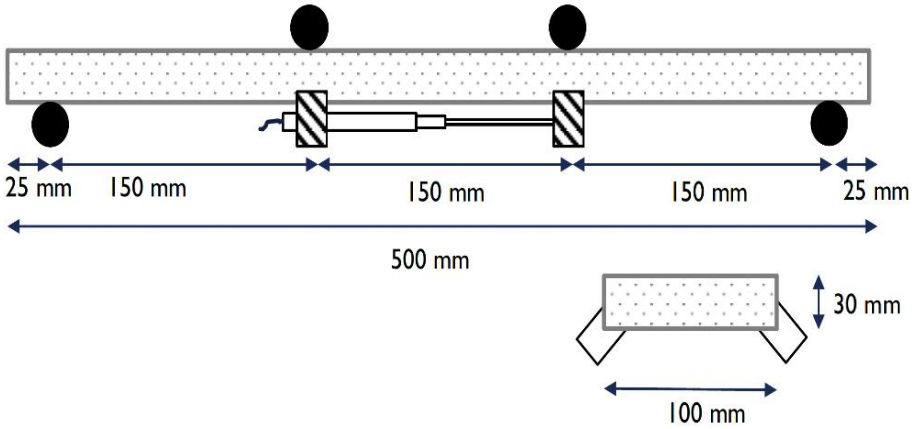
Experimental campaign: testing plan

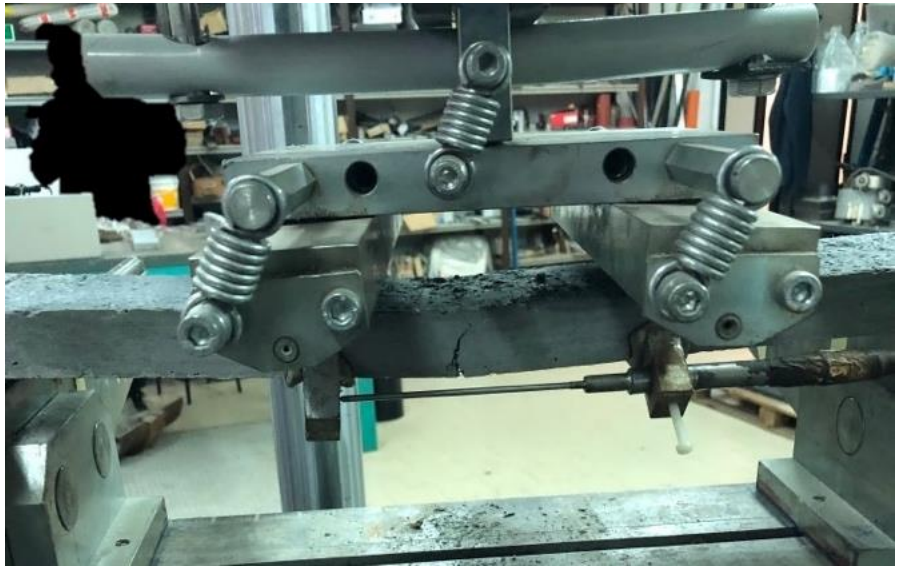


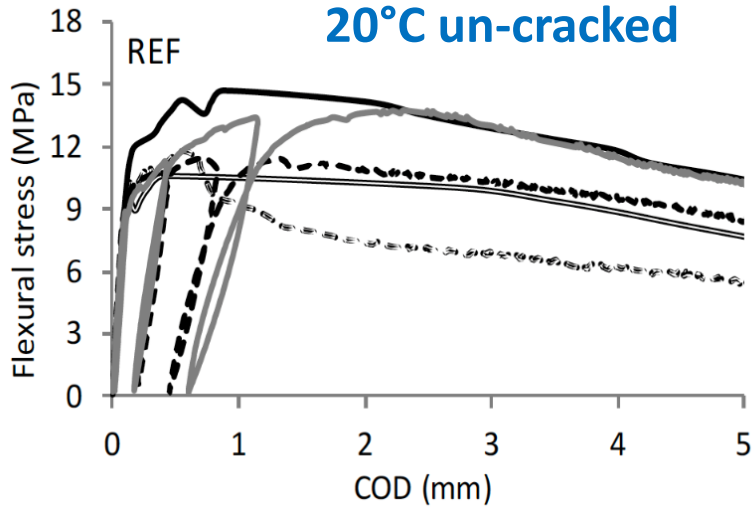
Heating rate: 1 °C/minute
Steady state time: 2 hours
Cooling time: 24 hours at lab condition

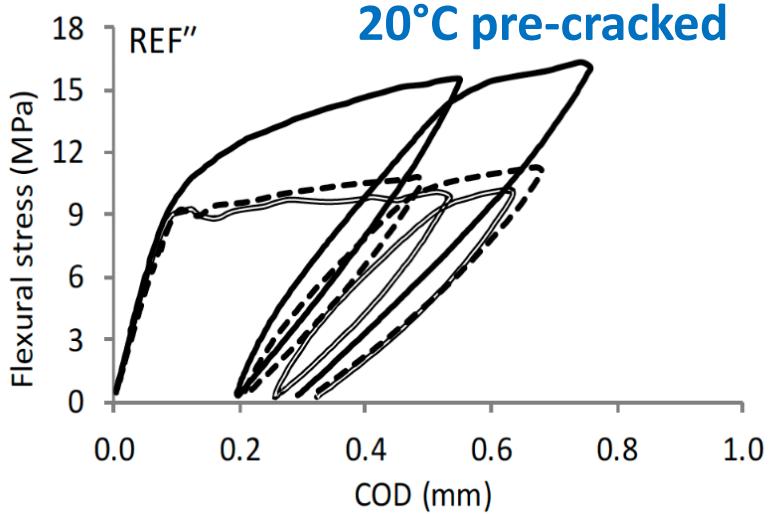
Flexural test loading rate: 15 µm/s

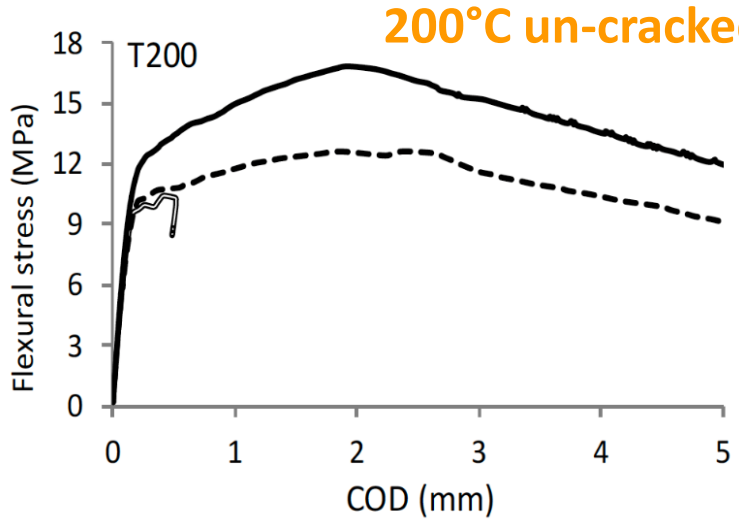
Performance of UHPC after exposure: 4PBT

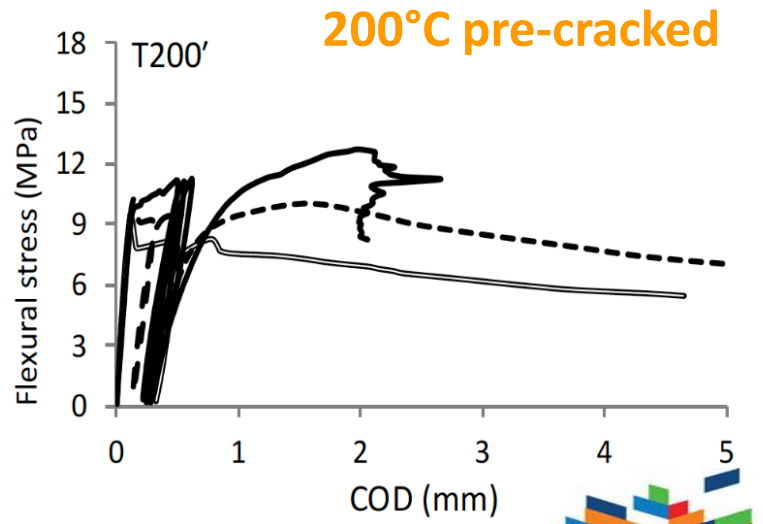




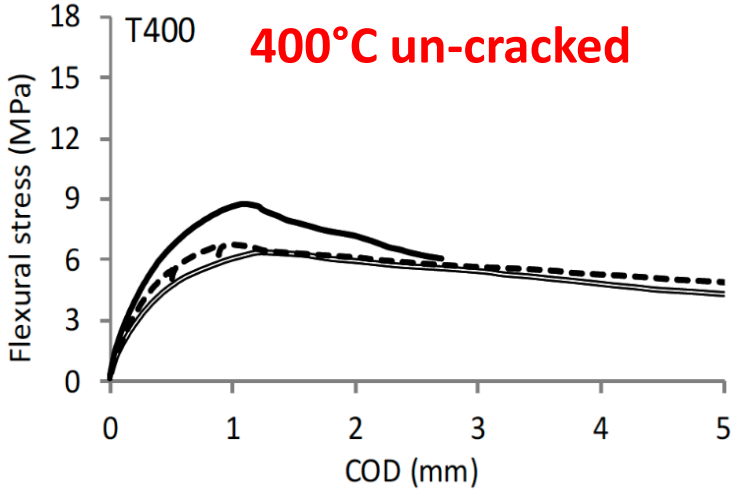


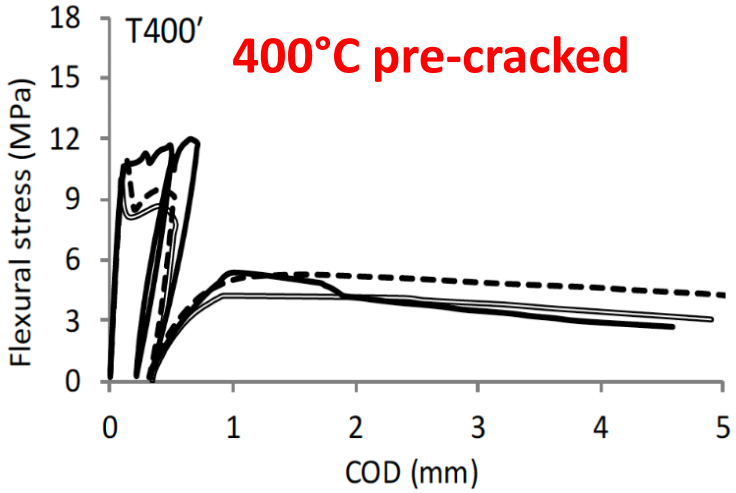


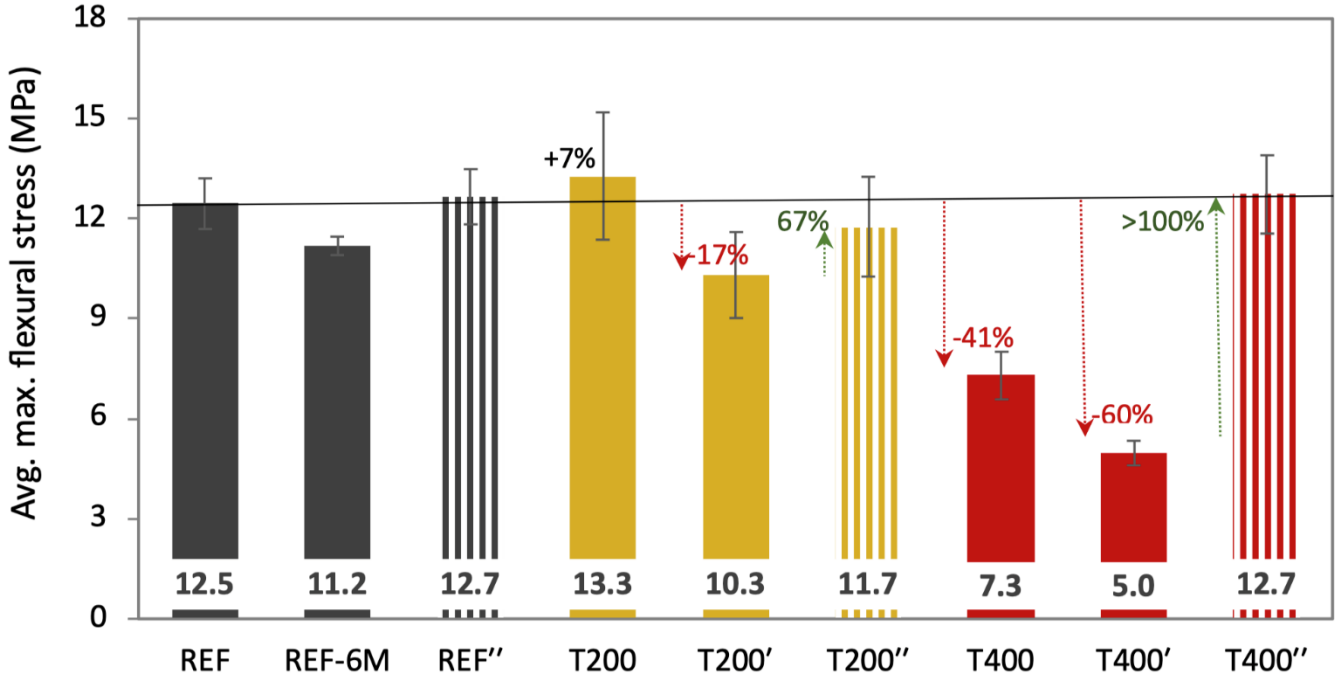




Performance of UHPC after exposure: 4PBT

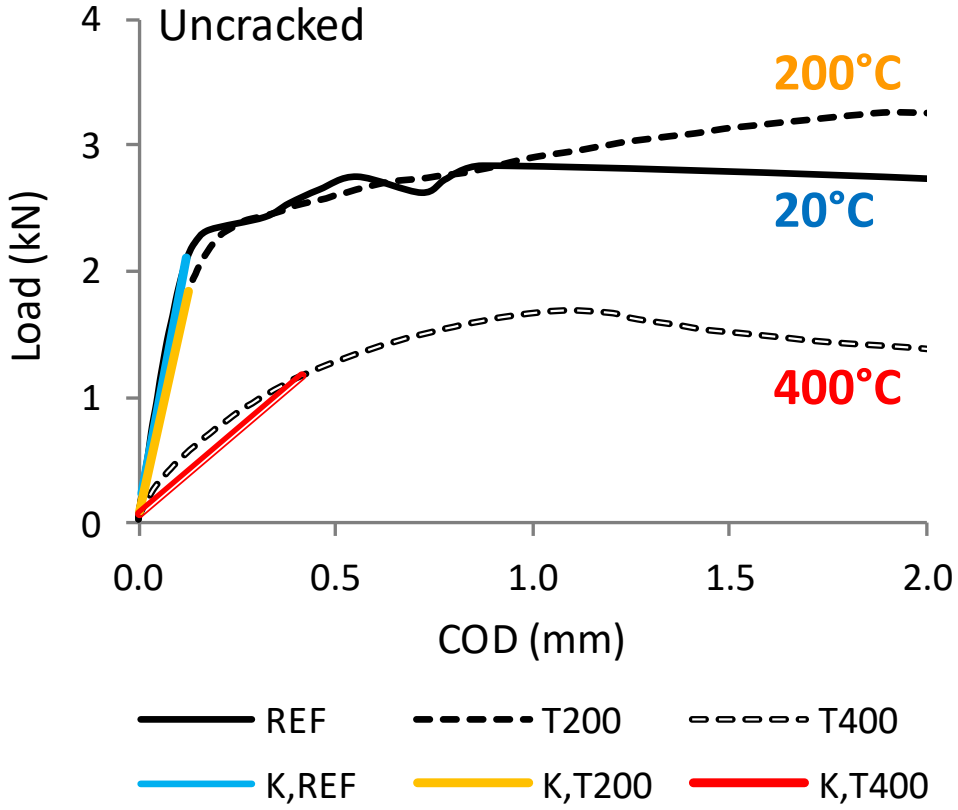


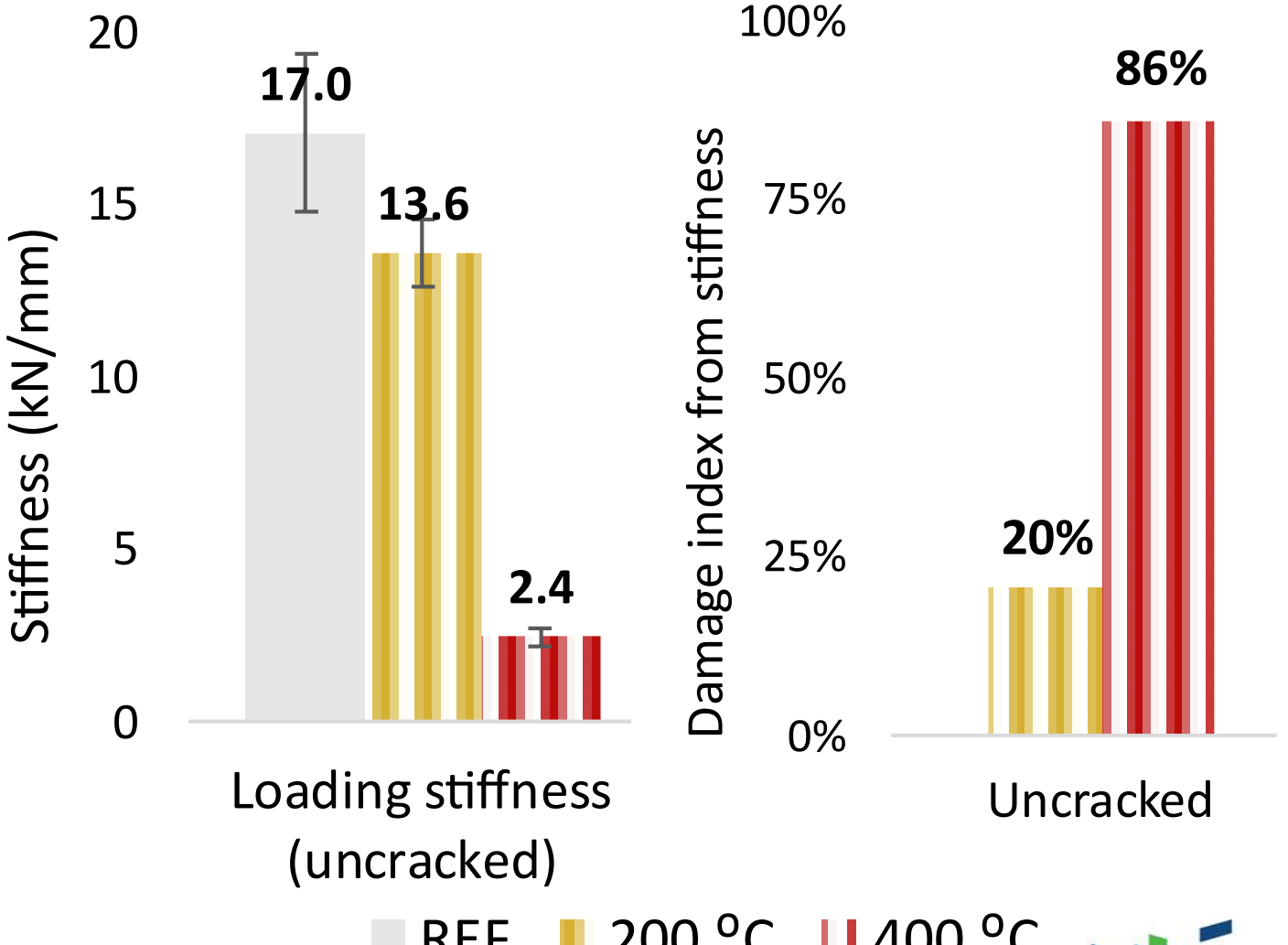




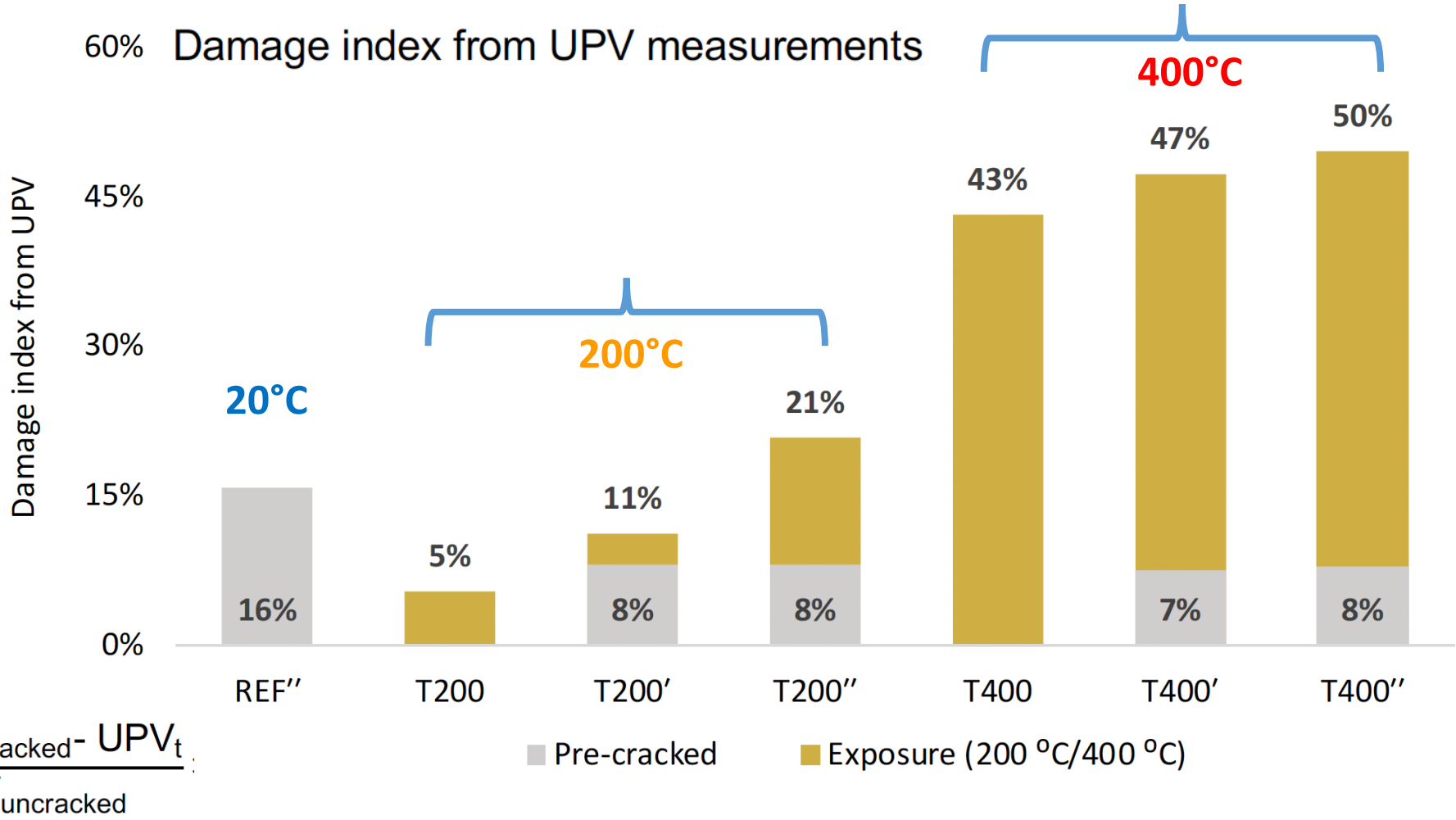
REF – Reference specimen tested at the beginning of the experiment
REF-6mo. - Reference specimen tested at the end of the experiment
T200 – Uncracked + exposed to 200 °C
T200' – Pre-cracked + exposed to 200 °C
T200" - Pre-cracked + exposed to 200 °C + self-healing

Performance of UHPC after exposure: flexural stiffness





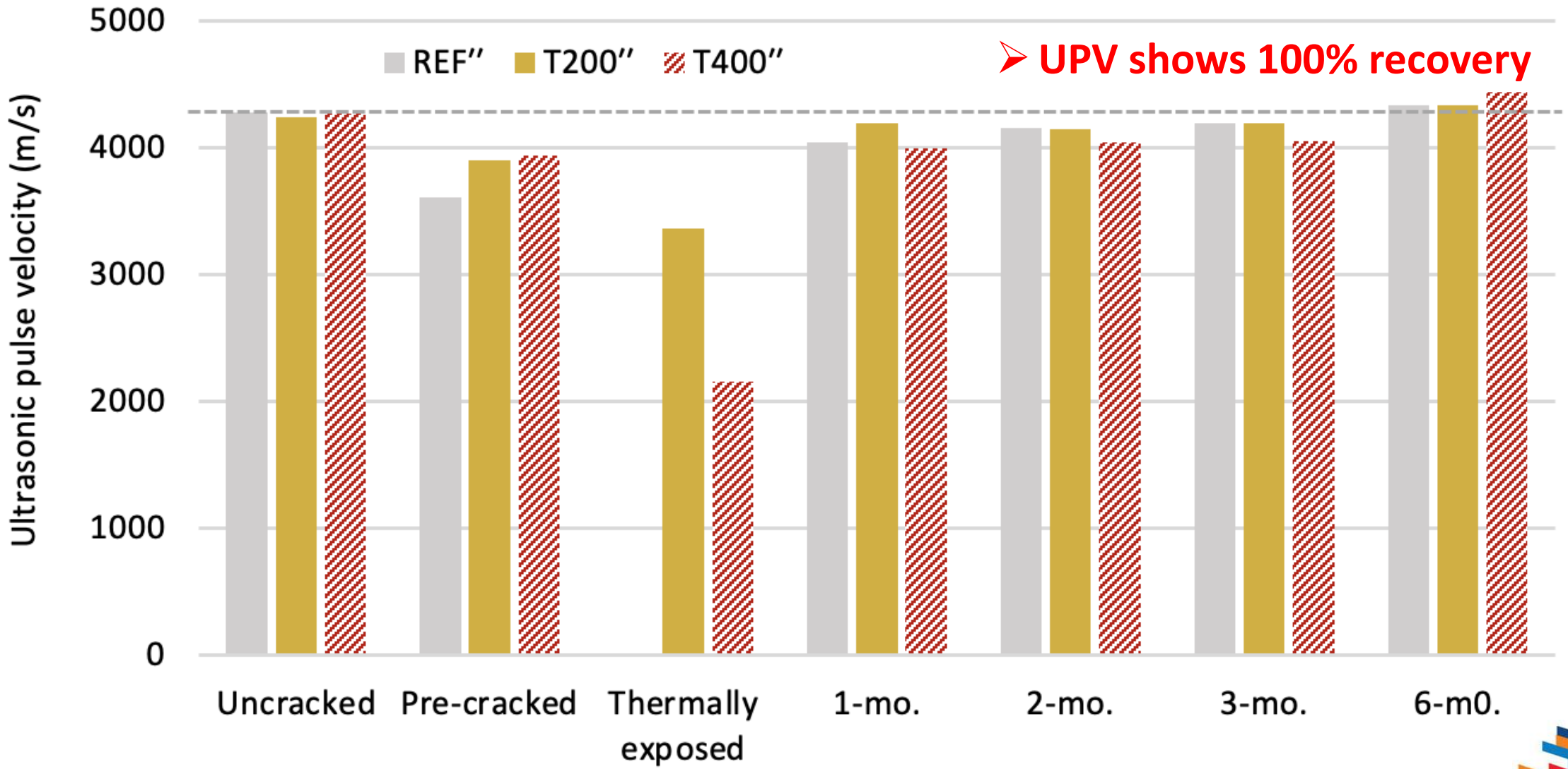
Performance of UHPC after exposure: UPV



$$\text{Damage index from UPV} = \frac{UPV_{uncracked} - UPV_t}{UPV_{uncracked}}$$

(Subscript t refers to the time of mechanical or thermal damage at which the UPV has been taken)

Self-healing performance: Ultrasonic pulse velocity



➢ **UPV shows 100% recovery**

Crack evolution

20°C

Optical microscopic images

200°C

400°C

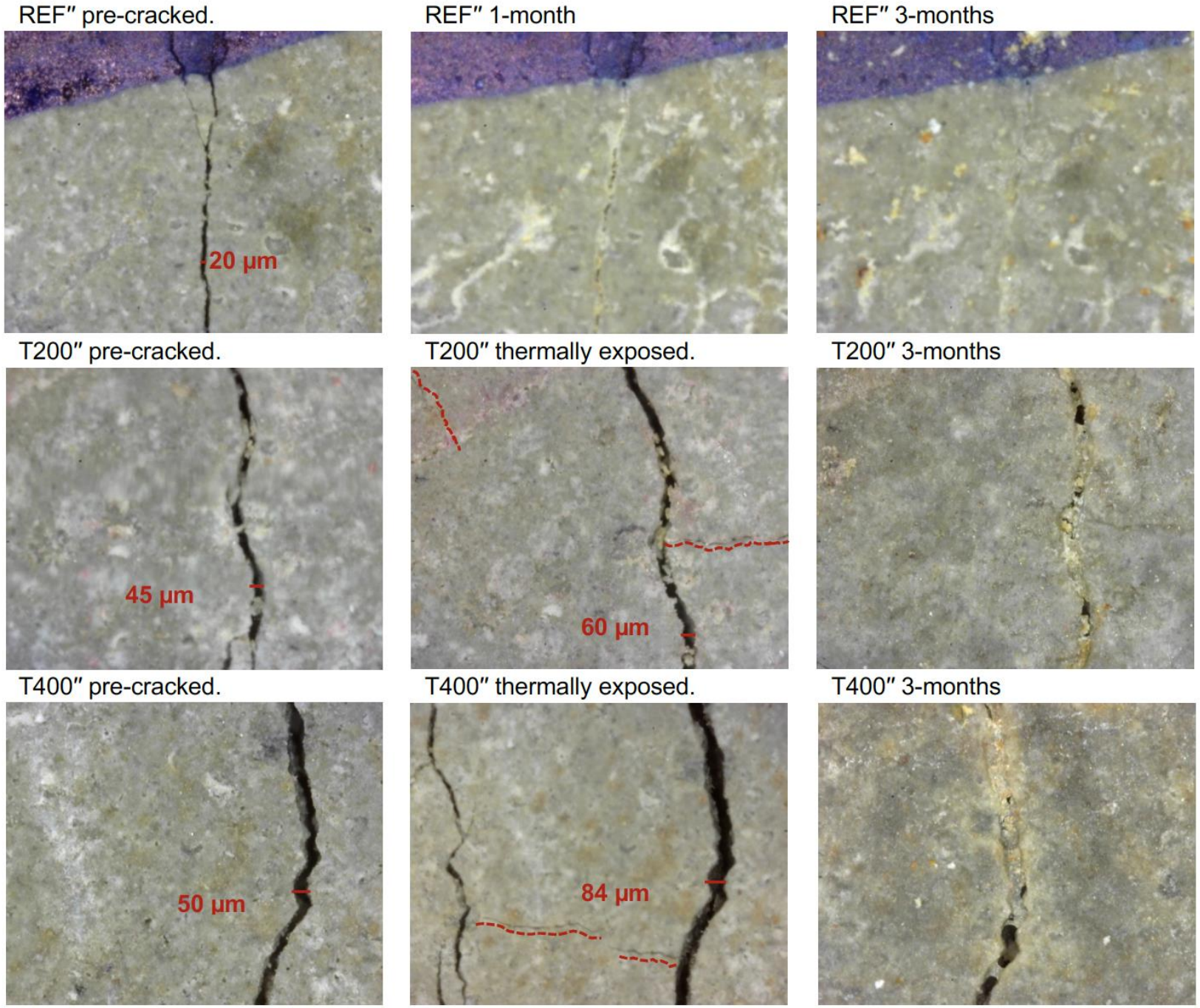
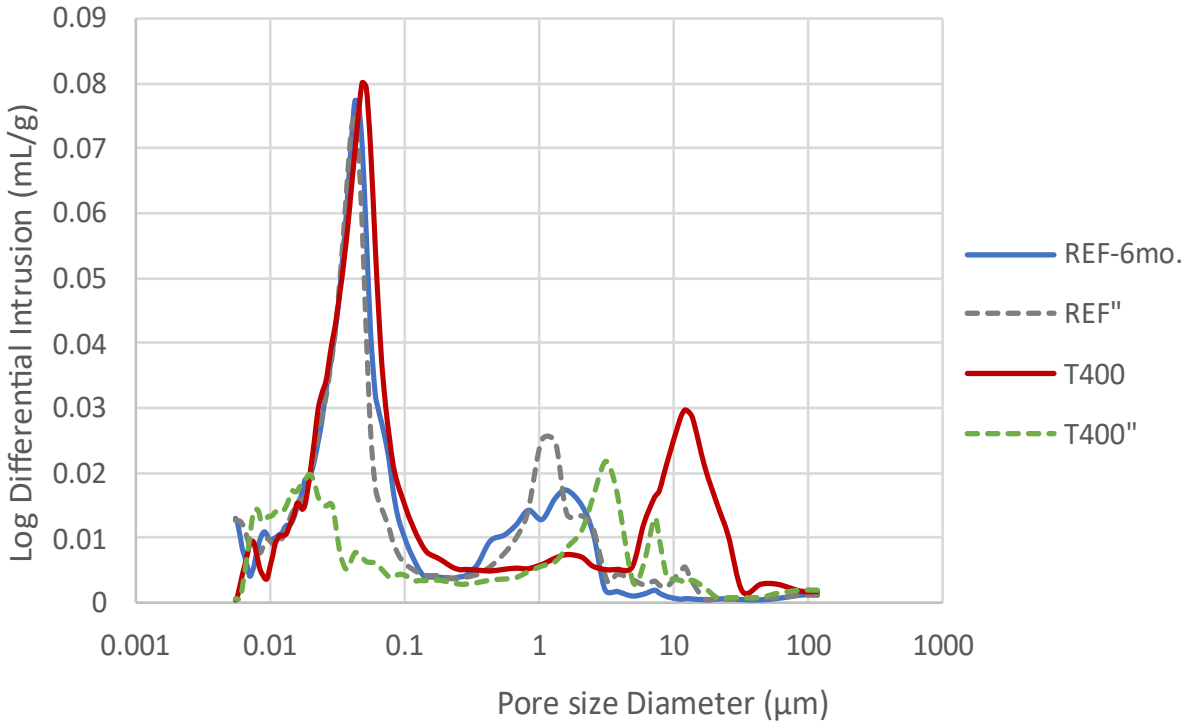
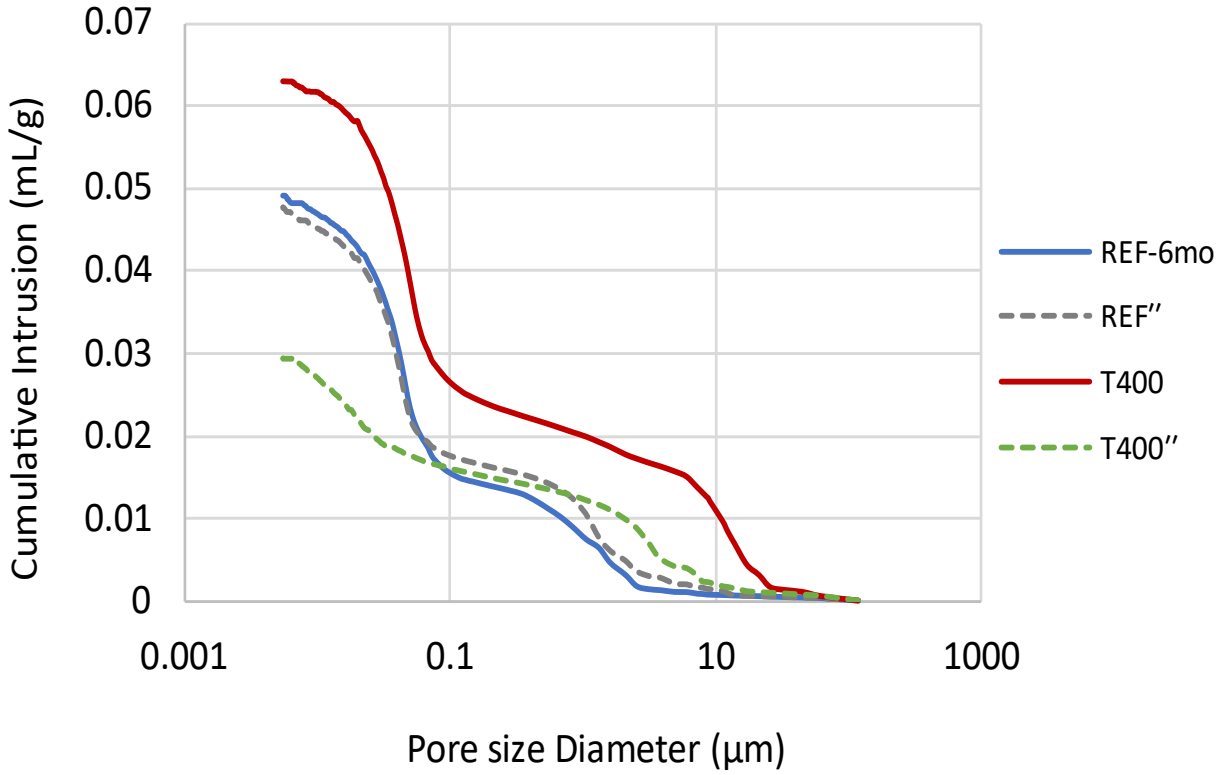


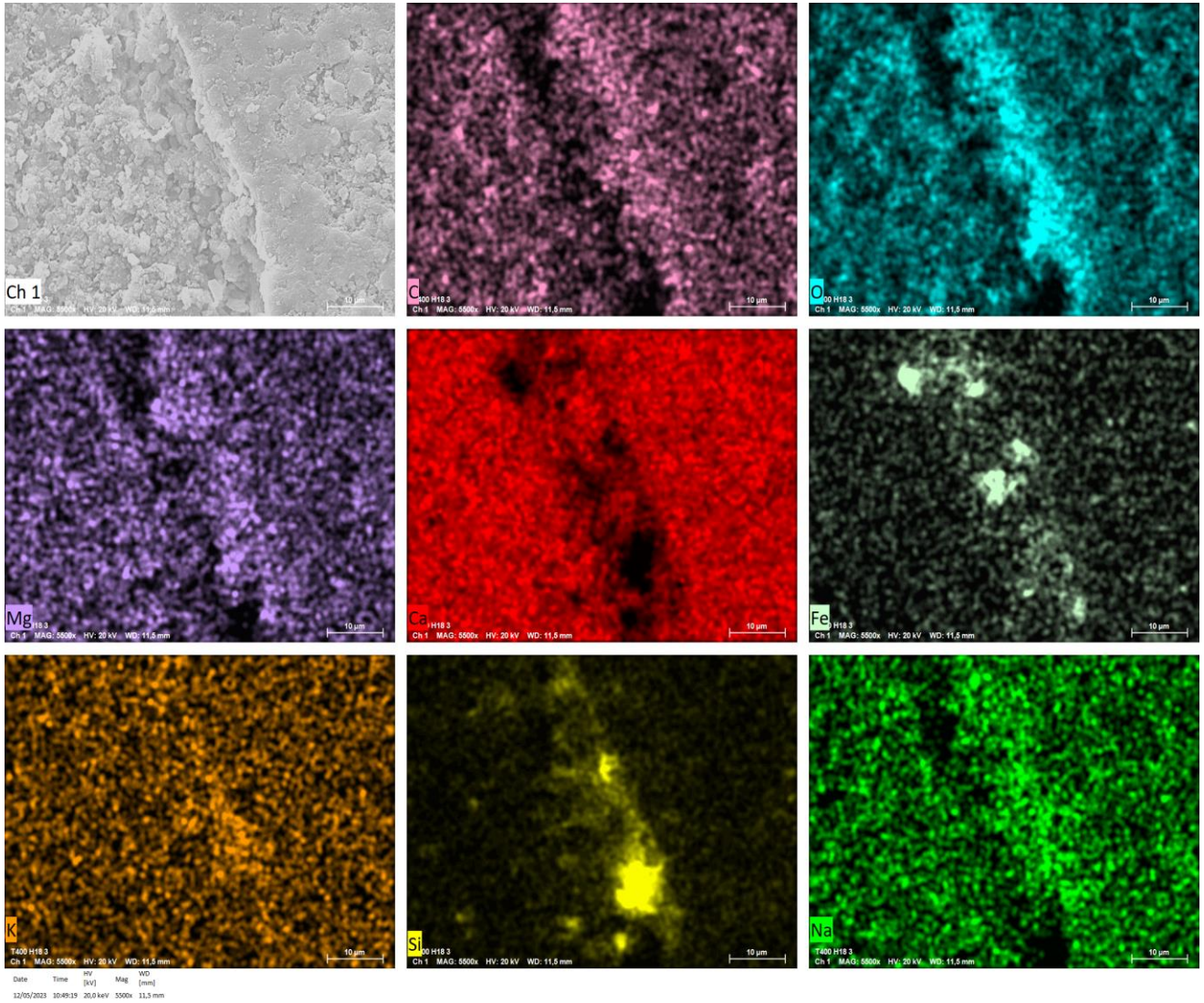
Figure 9: Microscopic images of REF″, T200″ and T400″

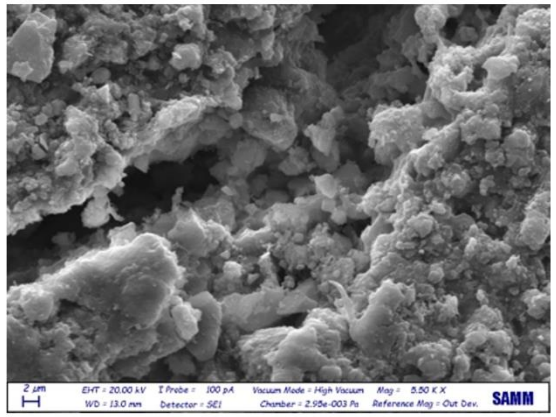
Pore size distribution

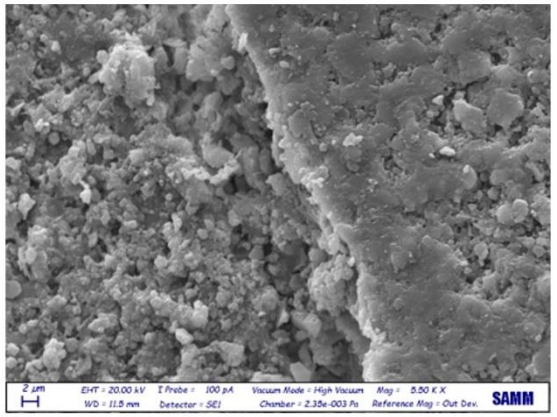




SEM



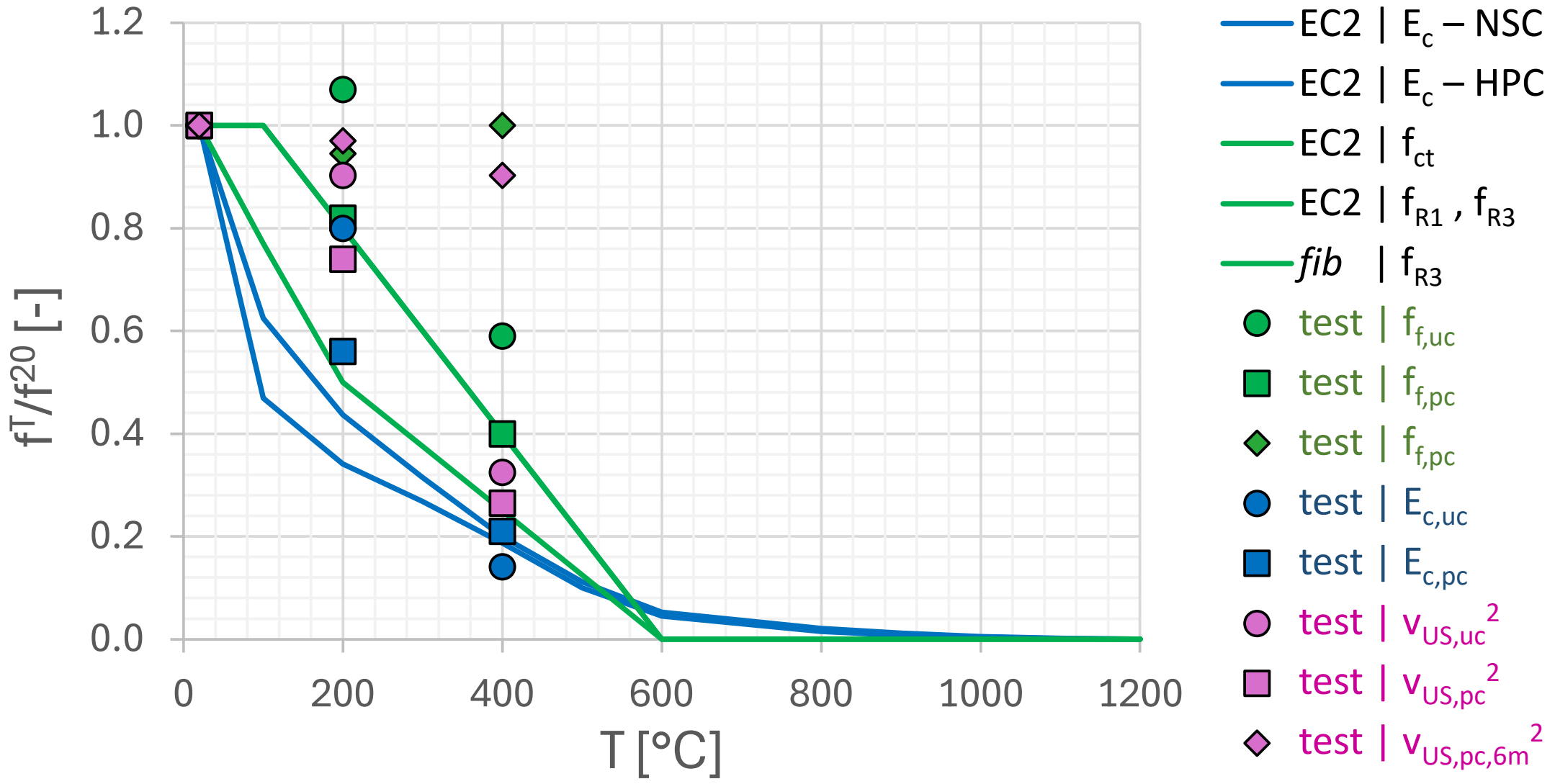




SEM-EDS element composition for T400‘‘

(color codes: pink-carbon, blue-oxygen, purple-magnesium, red-calcium, light green-iron, orange-potassium, yellow-silica, green-sodium)

Comparison with Standards



Conclusions

- The **crack width** for the specimens **ranged from a few micrometers to 100 µm following pre-cracking**. At the end of three months healing, the surface crack width was **partially closed**.
- The uncracked specimens exposed to **200 °C** did not exhibit any reduction in flexural strength, while the pre-cracked specimens lost 17% in strength.
- For the uncracked specimens exposed to **400 °C**, **the damage index for flexural strength** was 41%, and for pre-cracked specimens, it was **60%.**
- The **damage index for UPV** in uncracked specimens exposed to 400 °C was 43-47%**.** In contrast, the damage index for uncracked specimens exposed to 200°C was only 5%, (much lower than the damage due to pre-cracking). However, the specimens that were allowed to heal showed that the majority of the **damages was healed within one month**.
- **MIP** demonstrates **more than 50% reduction** in cumulative porosity of the specimens exposed to 400 °C after 6 months of healing, this should be the reason behind complete flexural strength recovery.
- **TGA** indicated a **partial recovery** of calcium-silicate-hydrates during submersion for the specimens exposed to 400°C. **SEM-EDX** showed that cracks in the specimens exposed to 400°C and subsequently healed were filled with calcium-based products. Additionally, **XRD** analysis revealed identical hydrated phase patterns for the reference specimens and those exposed to 400°C and healed.

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Thank You for the Kind Attention

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POLITECNICO MILANO 1863 | DIPARTIMENTO DI INGEGNERIA CIVILE E AMBIENTALE

Thank you for the kind attention

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