Early age fracture behaviour of Self Compacting SFRC for tunnel retrofitting: material characterization and structural transient design verification

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Statement of the problem

EUR 5 bn: cumulated investments in heavy rehabilitation work on existing tunnels (equal to around 300 km estimated at an average cost of 15-20MEUR/km) estimated in 2022-26

HIGHWAYS

1,500 km: Italian Tunnelling network (#1 in Europe)

1,000 km: more than 20 yrs old and need heavy maintenance

500 km: risk of collapse [2]

[2] *industry estimates*

210 Tunnels under watch: high risk of collapse [3]

[3] *MIT/CSLP*

RAILWAYS

1,240 km: built in 1870-1920 [2]

1,000 km: 70% of total railways tunnels not concrete [2]

Statement of the problem

a lack of critical infrastructures in heavy populated and industrialized areas in Italy, generates as a loss in the GDP of the same area of **36,000 Eur/km/day** (Università Carlo Cattaneo)

Every year road interruptions and traffic congestion delays cost an average of > EUR 3500/household (ASCE)

Current «state of art» tunnel retrofitting

SCRAPING

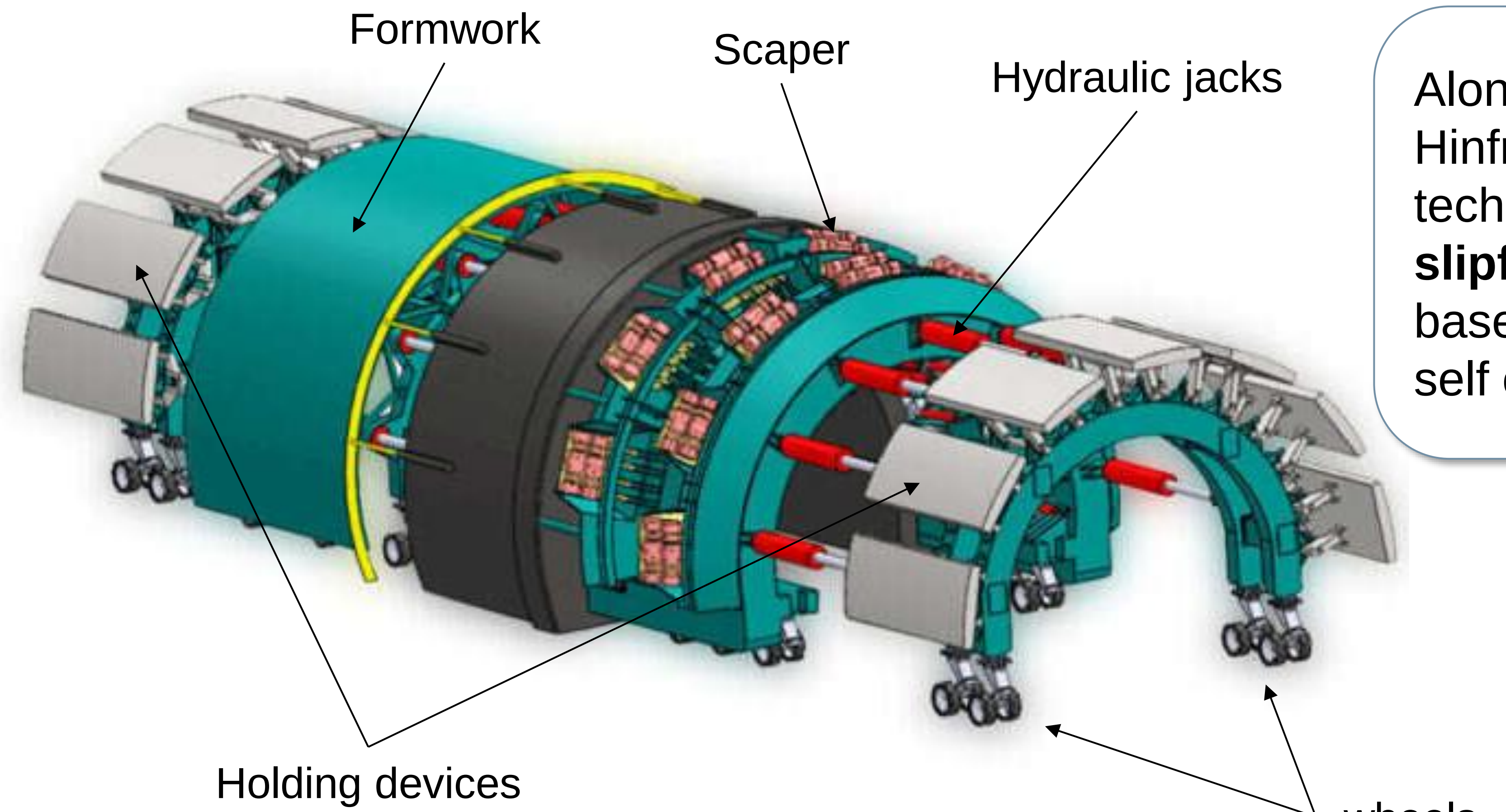
TEMPORARY WORKS

Current «state of art» tunnel retrofitting

NEW LINING – CAST IN PLACE

NEW LINING – PARTIALLY PRECAST

“Horizontal slipforming” solution



Along with the start-up company Hinfra we have been developing a technology based on **horizontal slipforming** of **tunnel** linings, based of “fast strength gaining” self compacting FRC

HINFRA™ The Large Scale Digital Concrete Extrusion Project

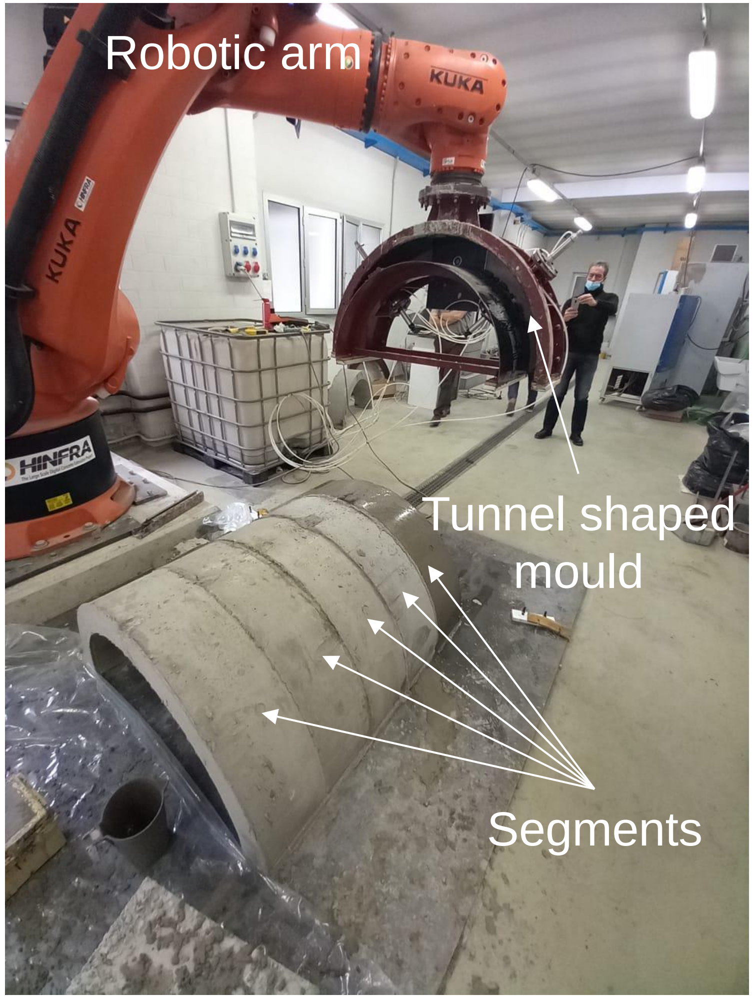
eTLR EXTRUDED TUNNEL LINING REGENERATION

Patented technology*

**Ref. UIBM No.102020000032327 “Metodo automatizzato e treno di lavorazione per il rivestimento gallerie”*

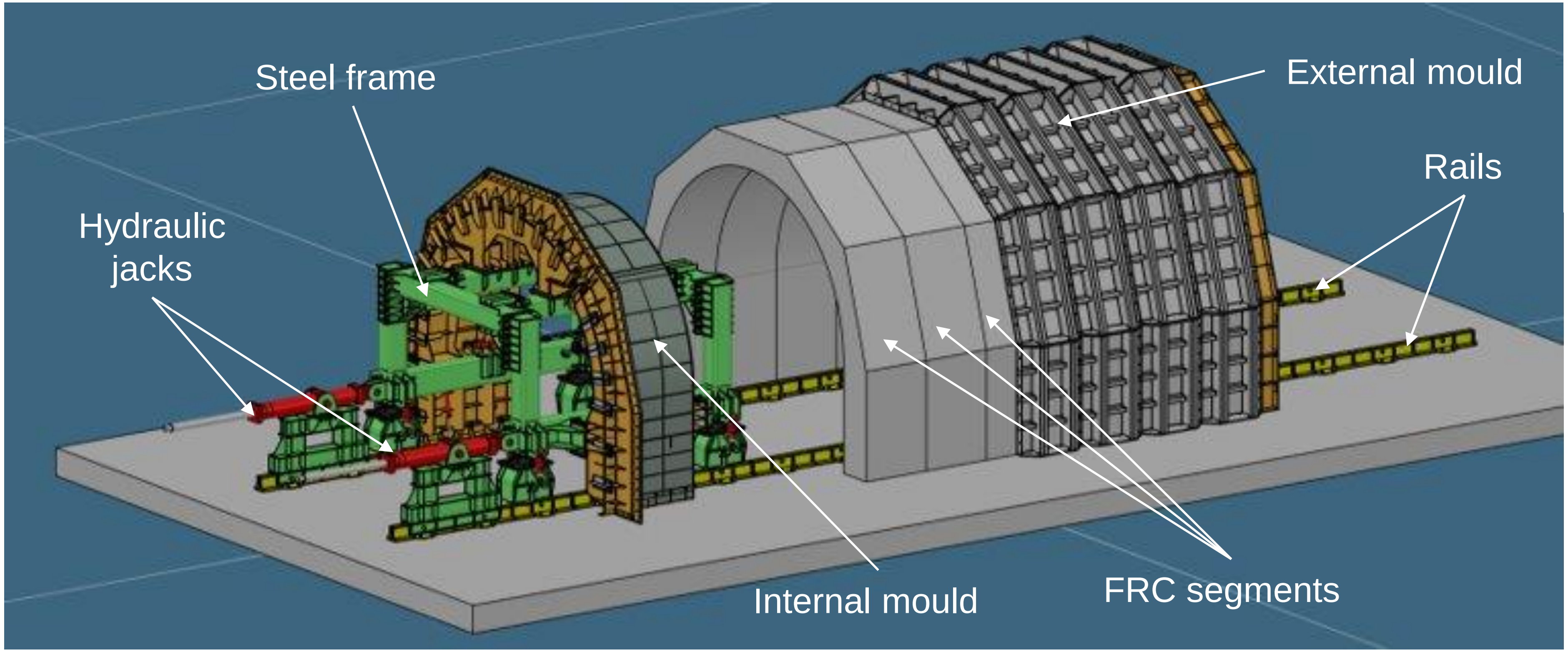
Small Scale Validation

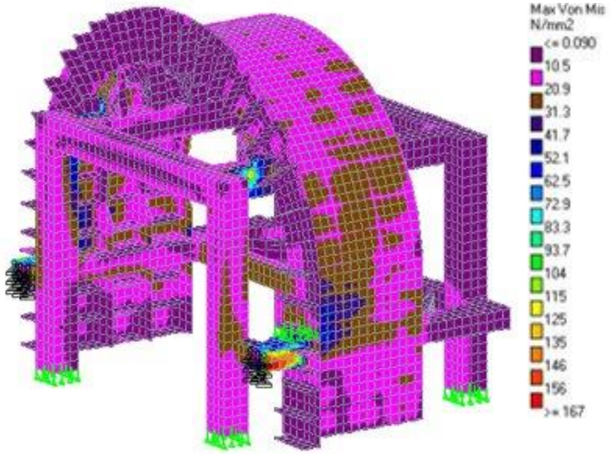
Preliminary small scale extrusions have been done by means of a **robotic arm** to validate the feasibility of the technology.



Full Scale Validation

“quasi full scale” mock-up validation on test - site



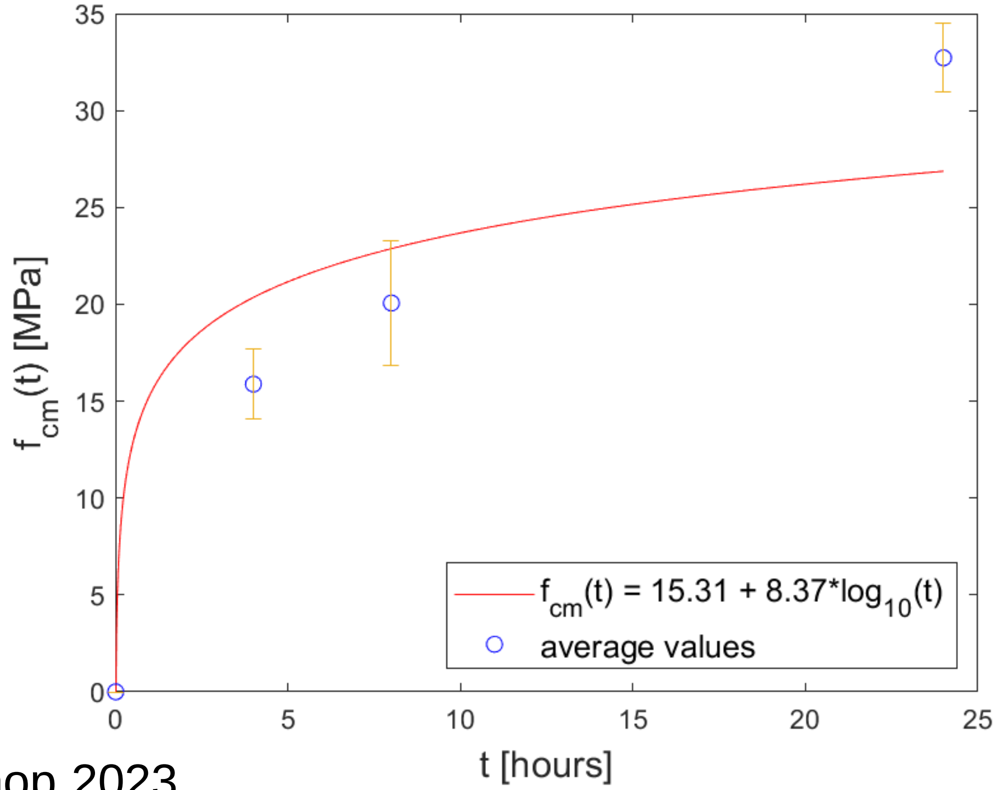


Process and material requirements

Material is **pumped** up to the key of the internal mould, from which it flows down to the bottom. As soon as the mould is filled and concrete has achieved a sufficient level of strength, the system moves, slip-forming **SFRC** tunnel segments.

«Early age» mechanical characterization

Due to the presence of CSA in the binder composition the concrete is characterized by a very **fast strength gain**.



Ferrara et al., ACI-fib FRC workshop 2023

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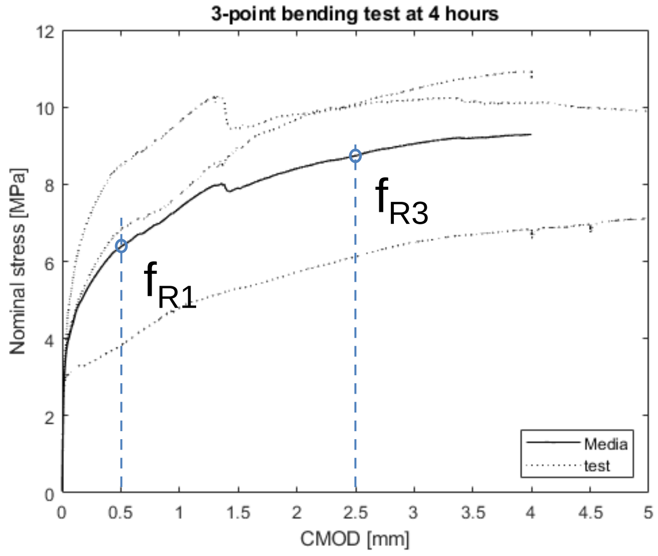
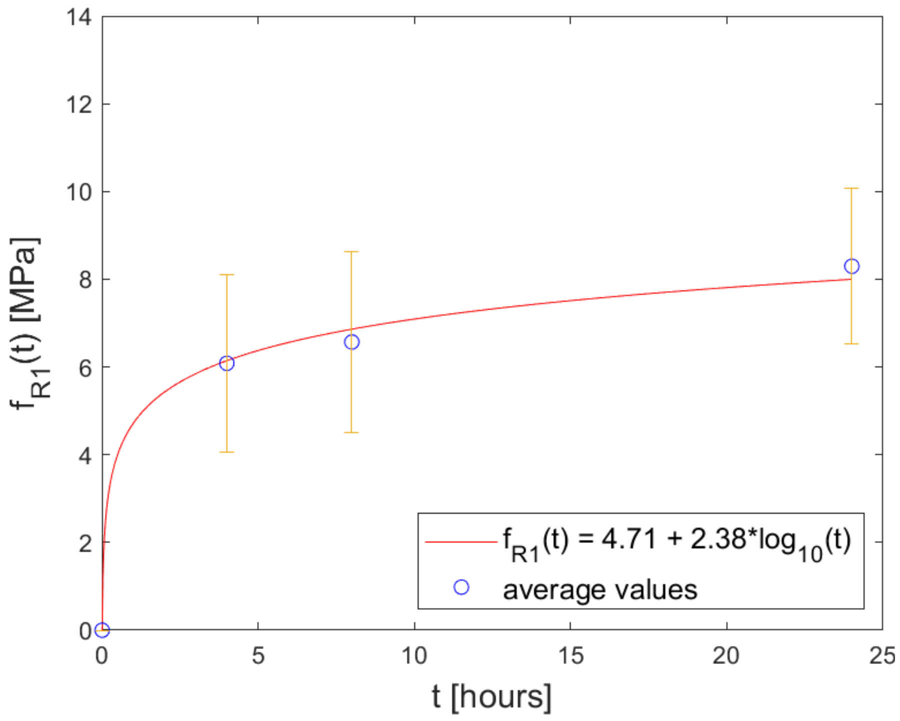
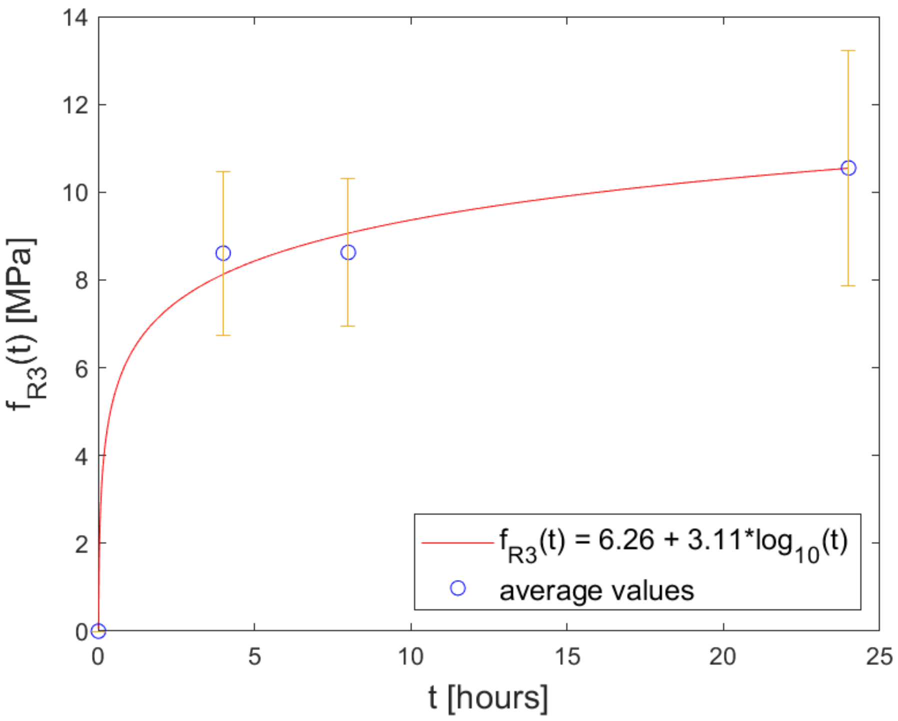


Class 3e at 4h
Class 4e at 8h
Class 6d at 24h





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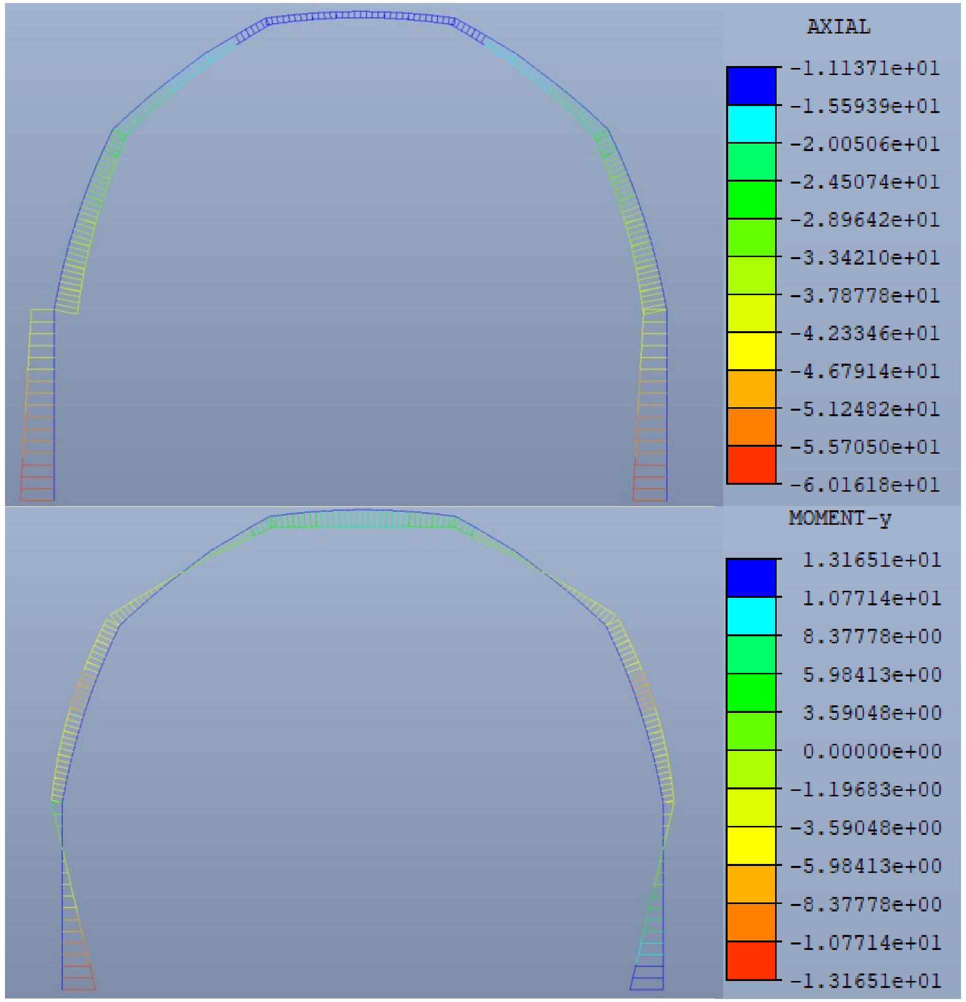
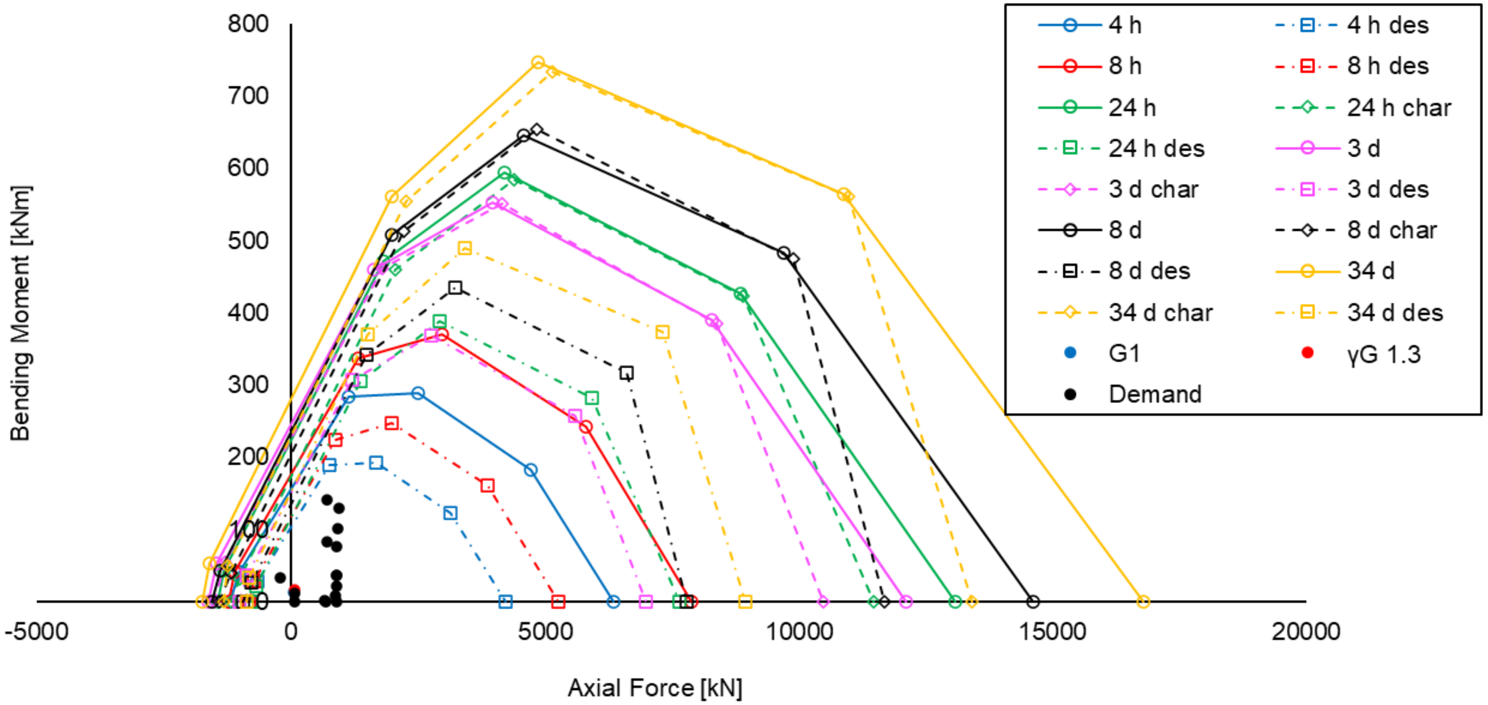
«Eage» structural design





At 4h safety guaranteed for self-weight as well as for accidental failure of the existing lining (transmitting all the actions to the new one)

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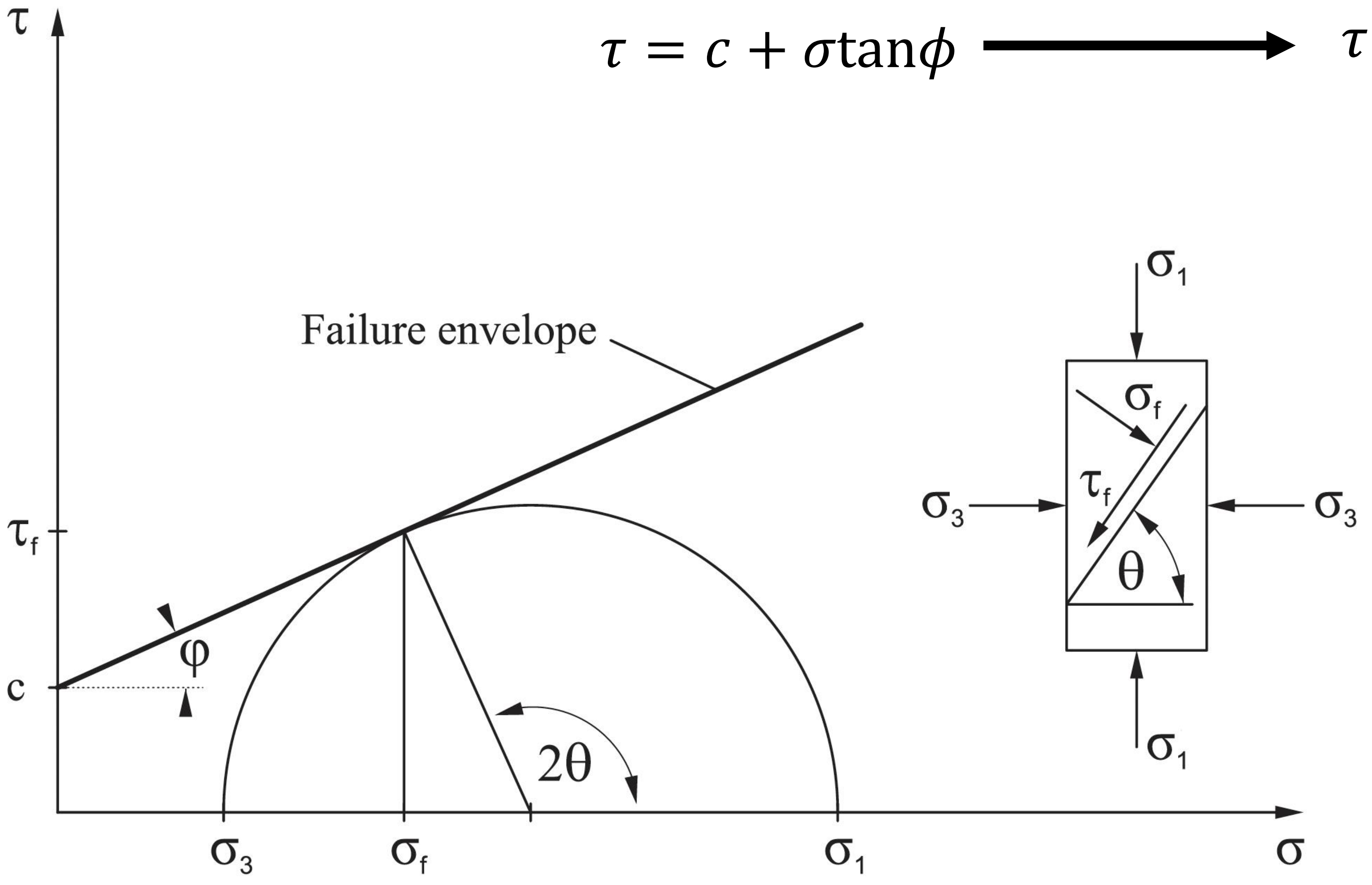
«Very early age» modelling/characterization



$$\tau = c + \sigma \tan\phi \longrightarrow \tau(t) = c(t) + \sigma \tan(\phi(t))$$

Material
- 600 g of binder
- 1400 g of aggregate (max diameter 4mm)
- 210 g of water
- 11.7 g of superplasticizer
- 0.9 g of retarder (in case)

	Unconfined uniaxial compression test (UUCT)	Direct shear test (DST)
Age [min]	45, 60, 75	45, 60, 75
Confinement pressure [kPa]	–	0.44, 11.36, 21.55
Number of samples per set	3	3
Total number of samples	9	27

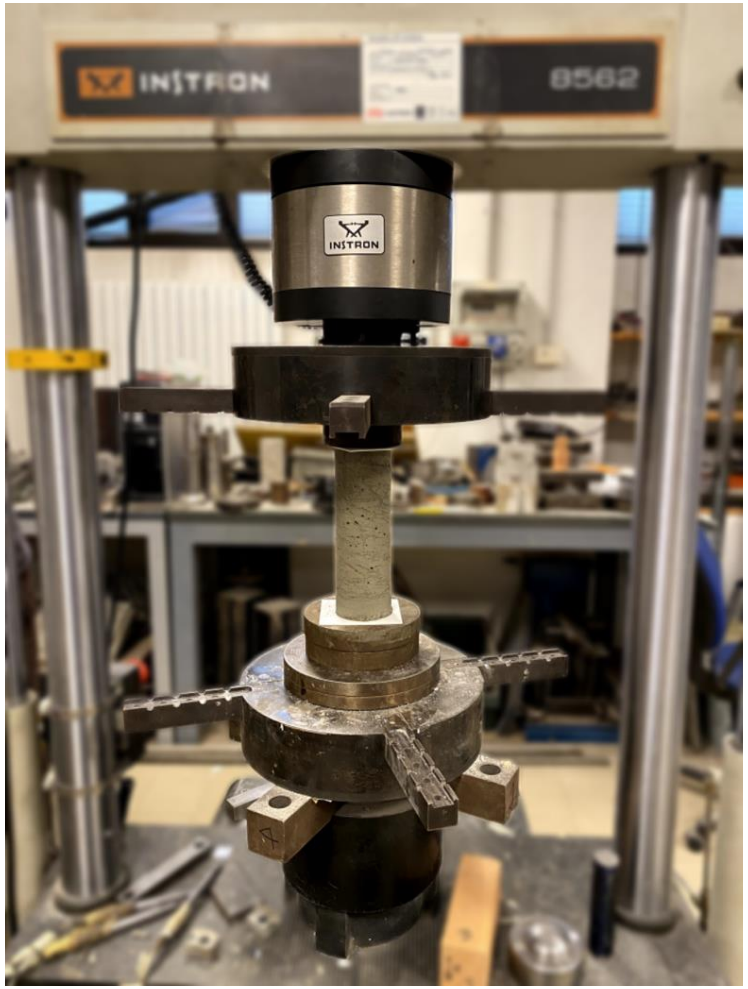
Table 1: Summary of experimental program for the mix without retarder

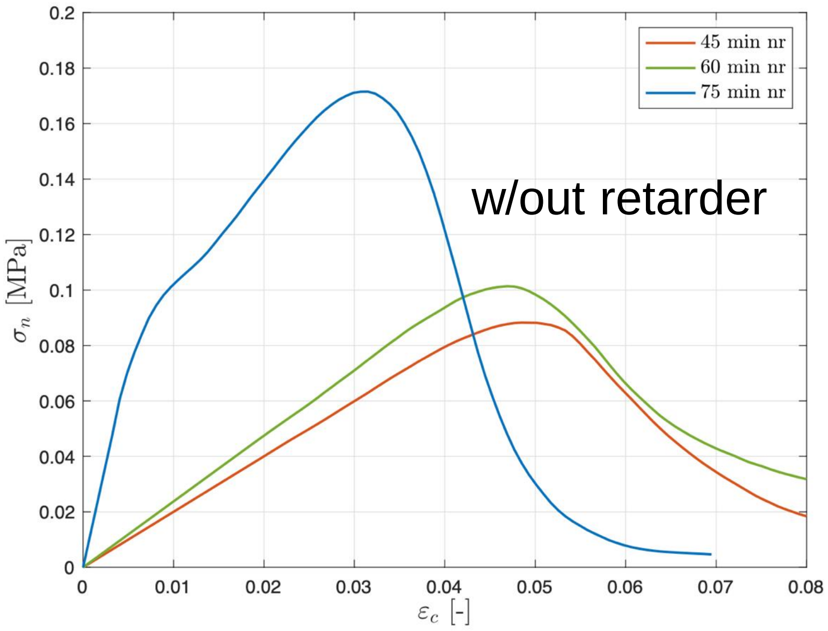
	Unconfined uniaxial compression test (UUCT)	Direct shear test (DST)
Age [min]	120	120
Confinement pressure [kPa]	–	0.44, 11.36, 21.55
Number of samples per set	3	3
Total number of samples	3	9

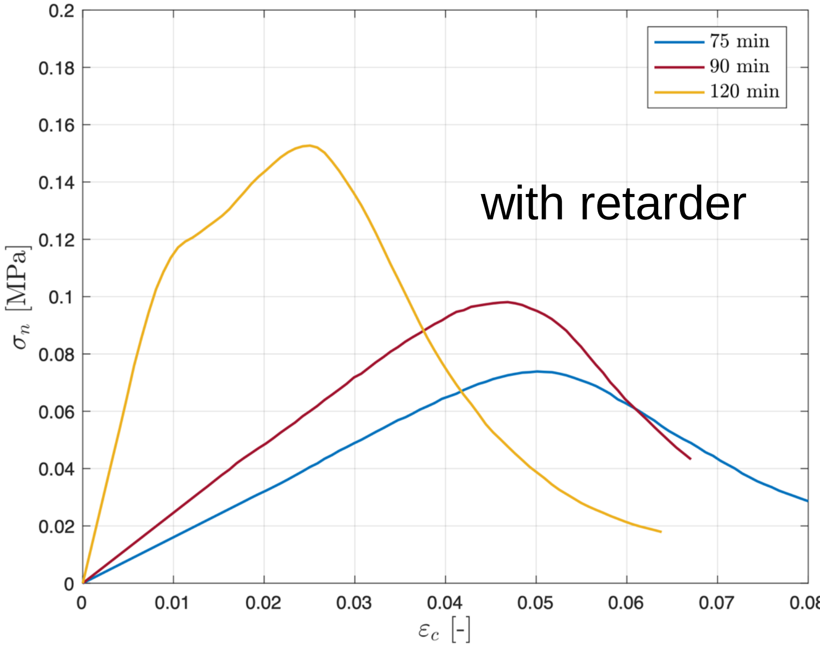
Table 2: additional tests for the mix with retarder (0.9 g/l)

A. Marcucci PhD thesis, unpublished results

«Very early age» characterization







Age [min]	E [MPa]	$\sigma_{max}[MPa]$	$\varepsilon_{max}[-]$
45	2.001	0.088	0.0490
60	2.375	0.101	0.0474
75	14.887	0.172	0.0314

Age [min]	E [MPa]	$\sigma_{max}[MPa]$	$\varepsilon_{max}[-]$
75	1.603	0.074	0.0498
90	2.459	0.098	0.0466
120	13.284	0.153	0.0251

A. Marcucci PhD thesis, unpublished results

«Very early age» characterization

(a) Failure C-45-3nr

(b) Failure C-60-2nr

(c) Failure C-75-2nr

A. Marcucci PhD thesis, unpublished results

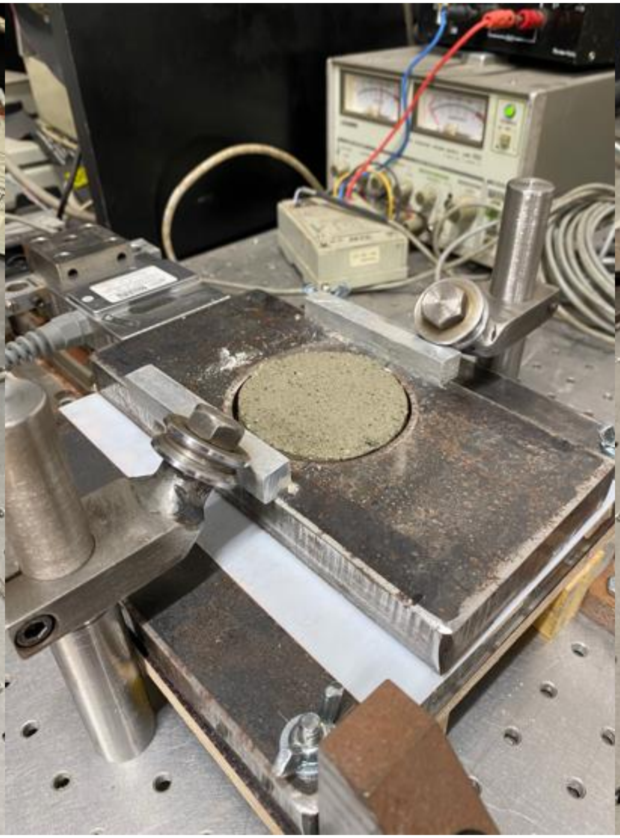
«Very early age» characterization

with normal stress

w/out normal stress

1° level

2° level

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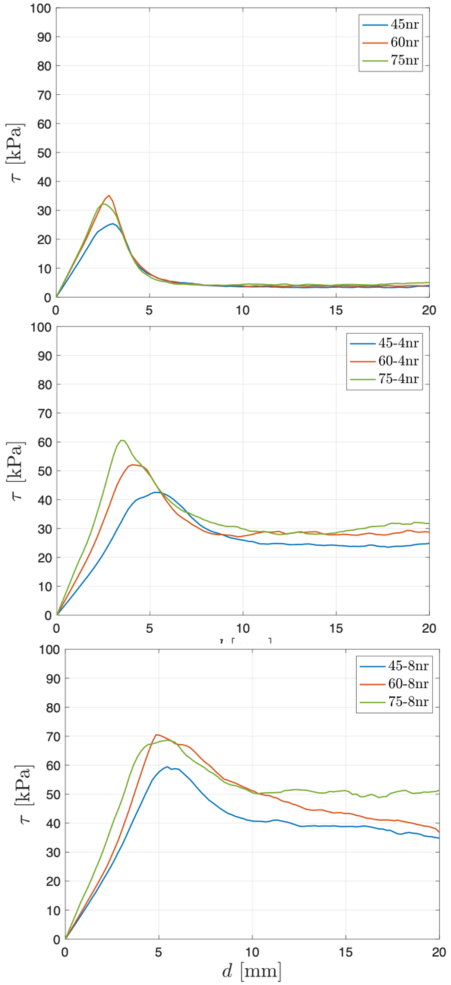
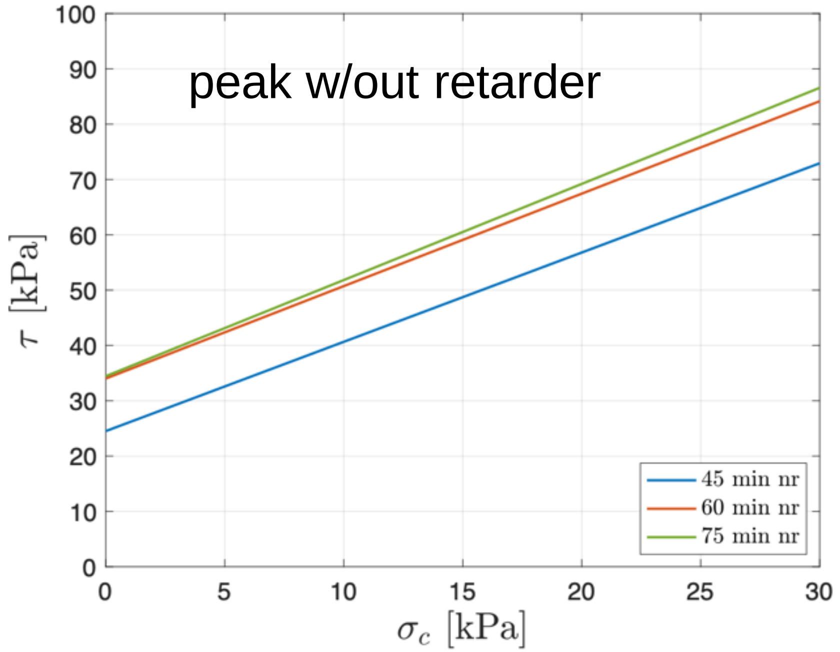
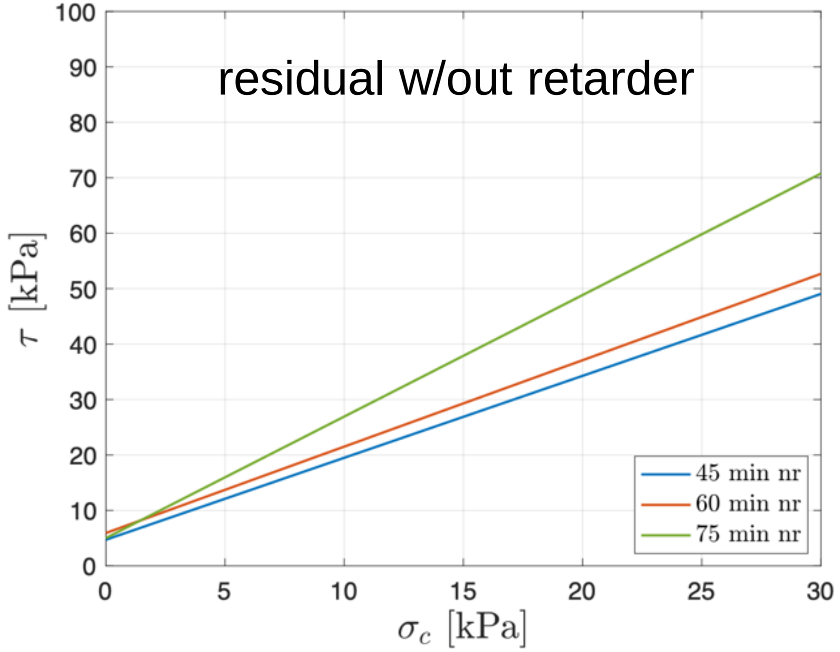


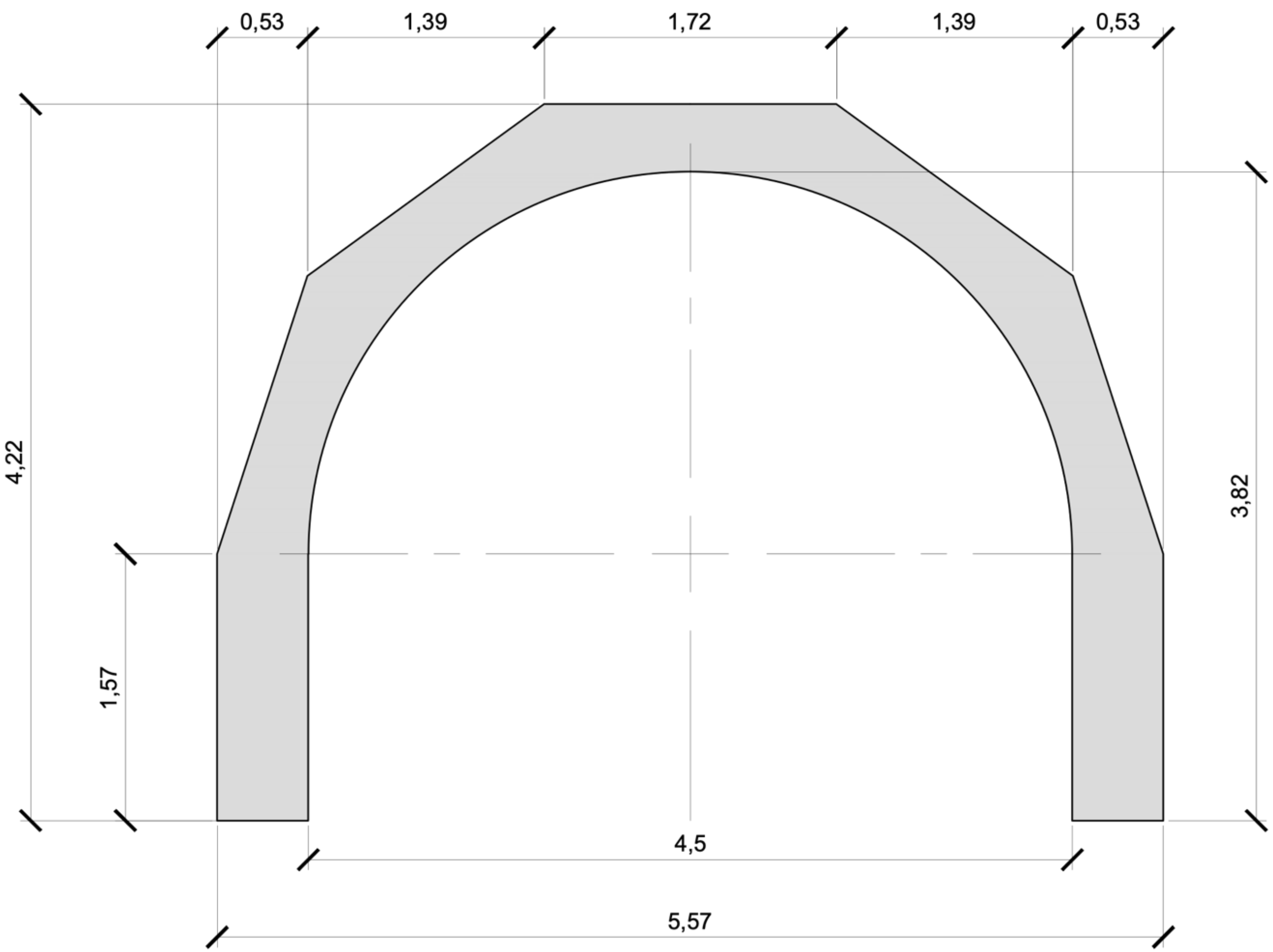


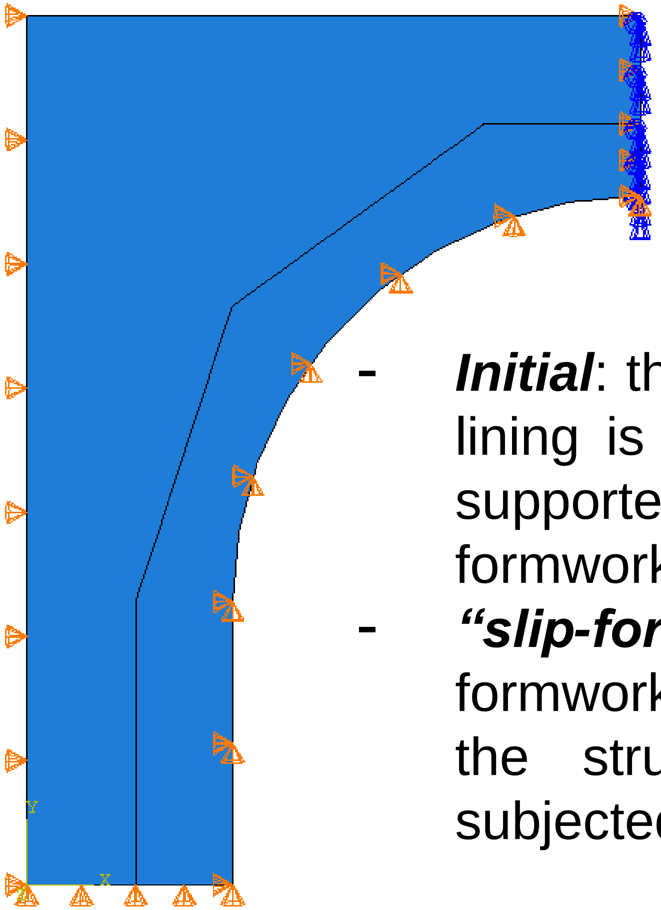


Age [min]	$\phi_p[°]$	$c_p[kPa]$	$\phi_r[°]$	$c_r[kPa]$
45	58.22	24.52	55.92	4.70
60	59.10	34.02	57.31	5.92
75	60.08	34.45	65.48	5.00

A. Marcucci PhD thesis, unpublished results

«quasi-full» scale mock-up modelling





- ***Initial***: the tunnel's structural lining is completed and still supported by the lower formwork
- ***"slip-forming"***: the formwork is removed and the structural element is subjected to its own weight

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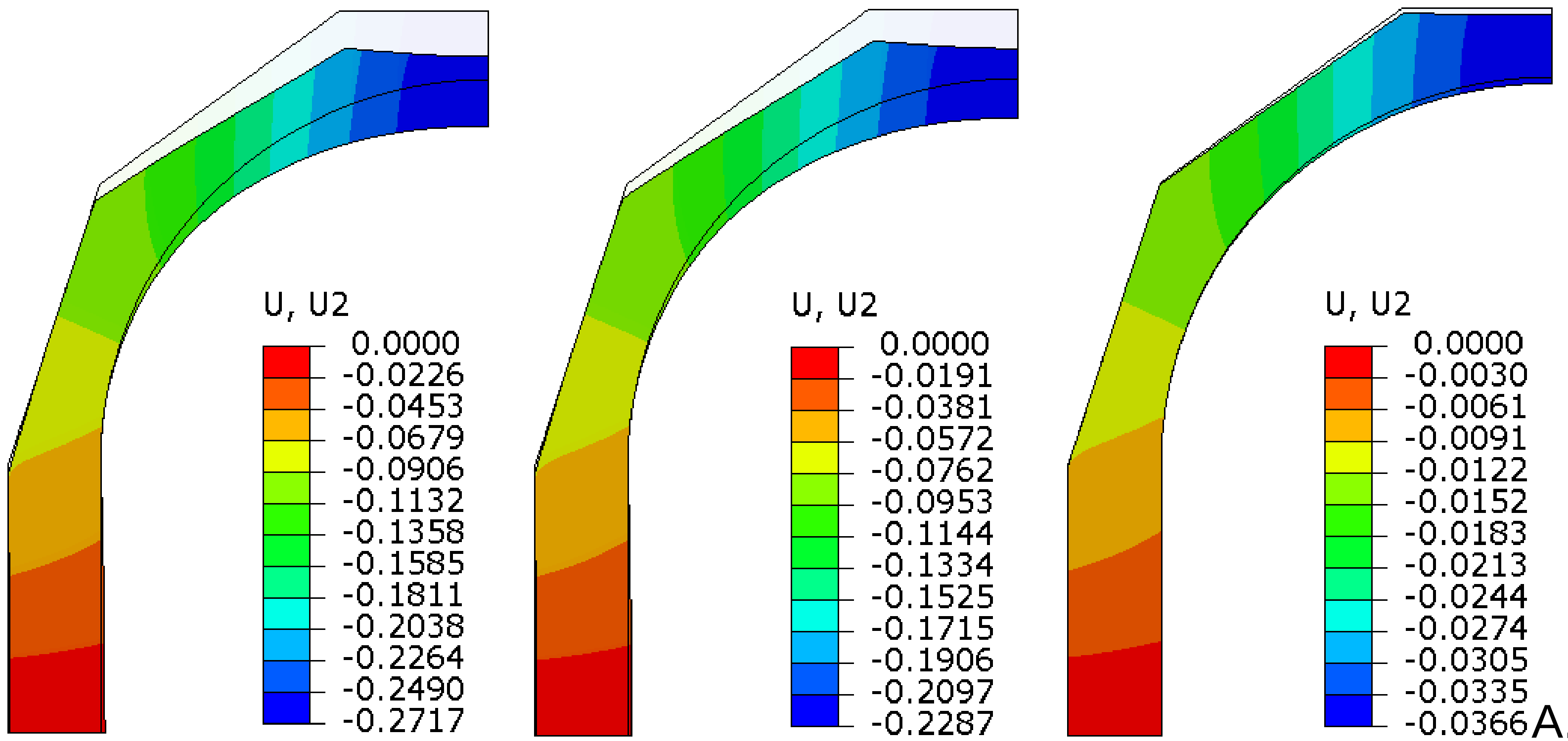
«quasi-full» scale mock-up modelling

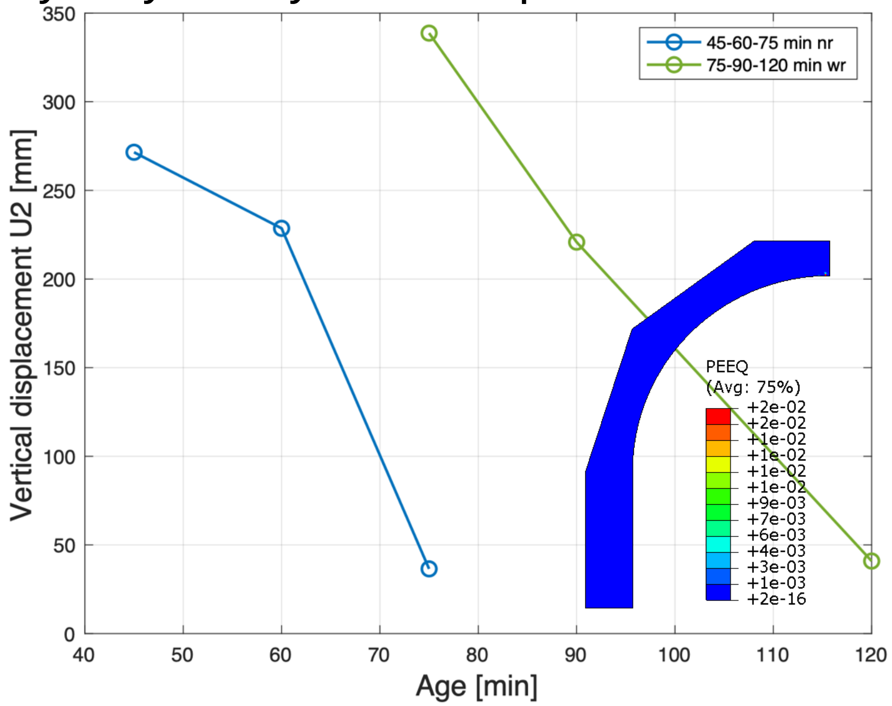
When can we slip-form?

Displacement still not compatible with functionality

Strains only very locally exceeds plastic threshold

45 min | 60 min | 75 min





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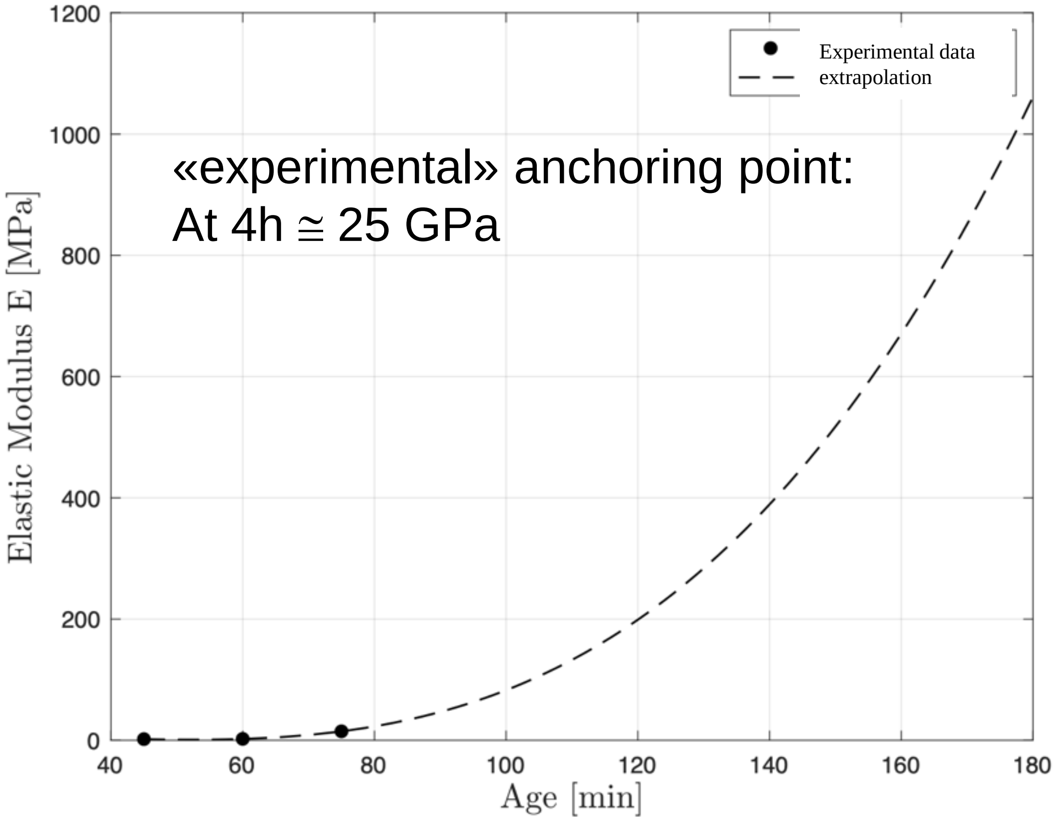
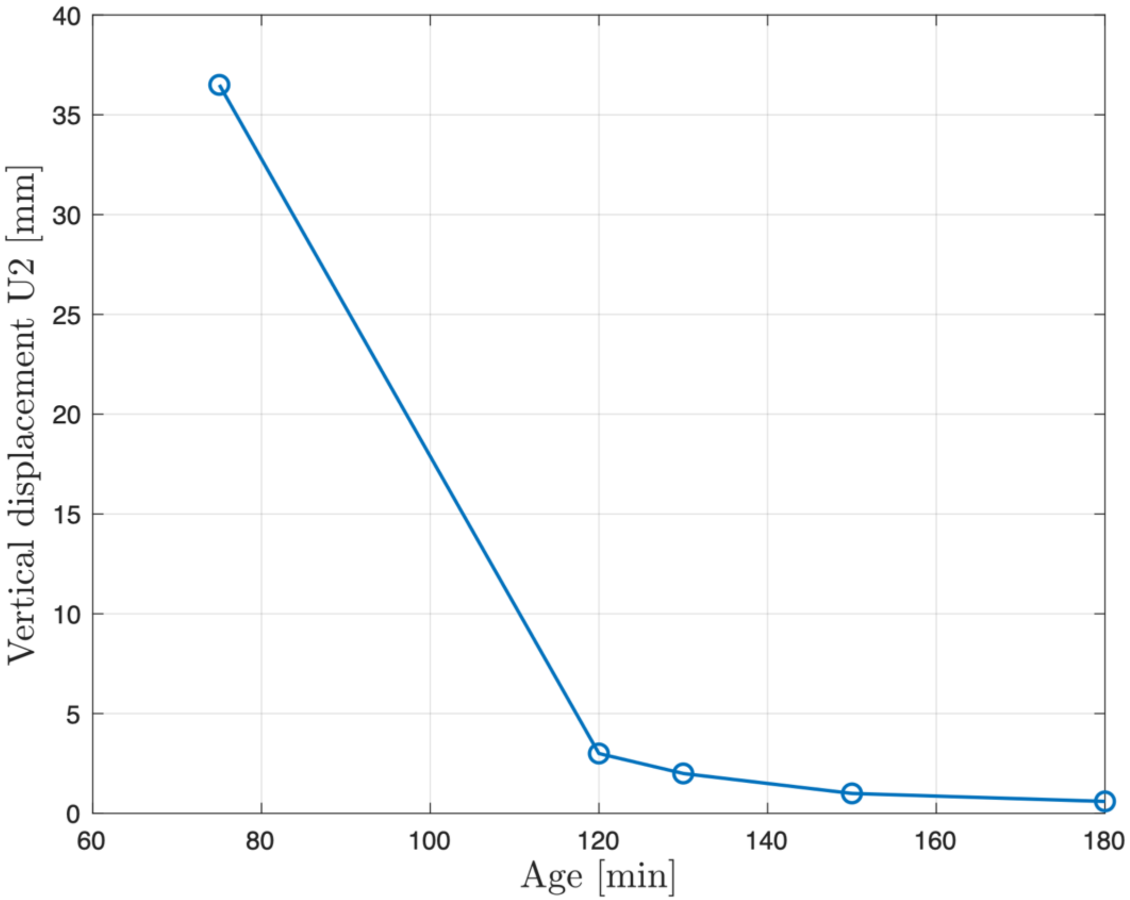
«quasi-full» scale mock-up modelling

When can we slip-form?
Extrapolate model parameters





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Conclusions

- The SFRC adopted in the innovative solution has excellent mechanical properties, which allow for the stability of the tunnel lining since the very early ages enhancing the overall productivity of the maintenance intervention.
- A dedicated experimental campaign has been designed and performed to identify the Mohr-Coulomb model parameters to describe the material behaviour in the very early ages (from ½ to 4 h)
- The Mohr-Coulomb model has been successfully employed to simulate the «slip-forming» transient design situation (tunnel lining subjected to its own weight) and identify the optimal «time frame» considering functionality and productivity requirements

Thank you for your attention!

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PON RICERCA E INNOVAZIONE 2014 - 2020

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