UNIVERSITY OF BRESCIA
Department of Civil Engineering, Architecture, Environment, Land Planning and of Mathematics
PhD Course in:
CIVIL AND ENVIRONMENTAL ENGINEERING

EXPERIMENTAL STUDY OF FLY ASH-BASED GEOPOLYMER CONCRETE: STRUCTURAL APPLICATIONS

Linda Monfardini, PhD Student
l.monfardini001@unibs.it

GEOPOLYMERCAMP


Brescia

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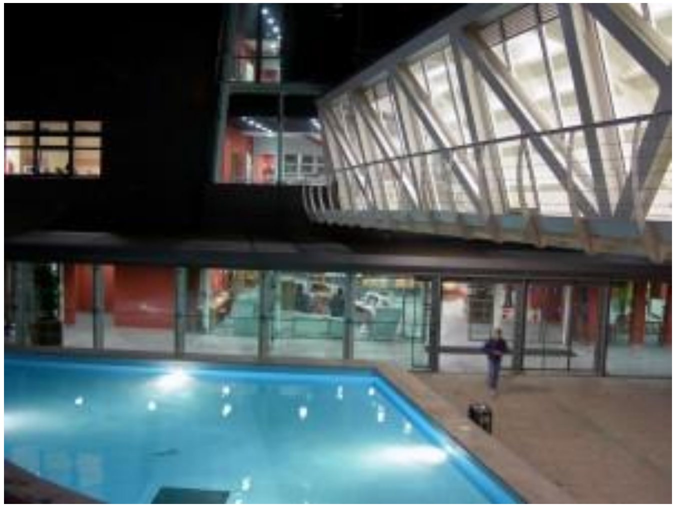
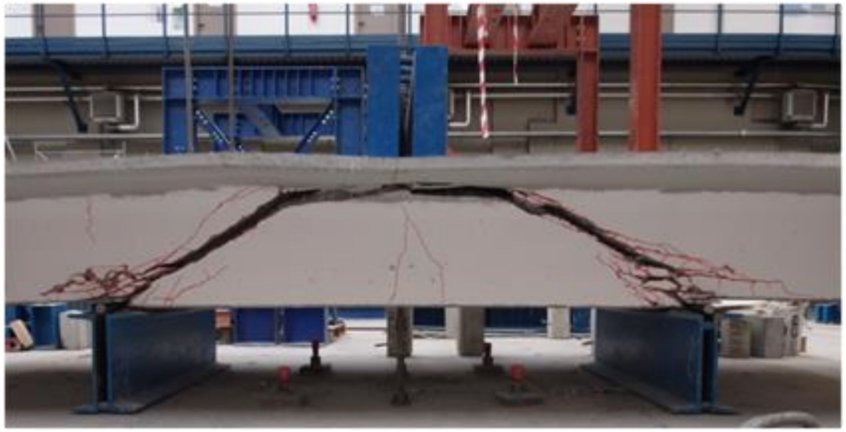
University of Brescia
Faculty of Engineering



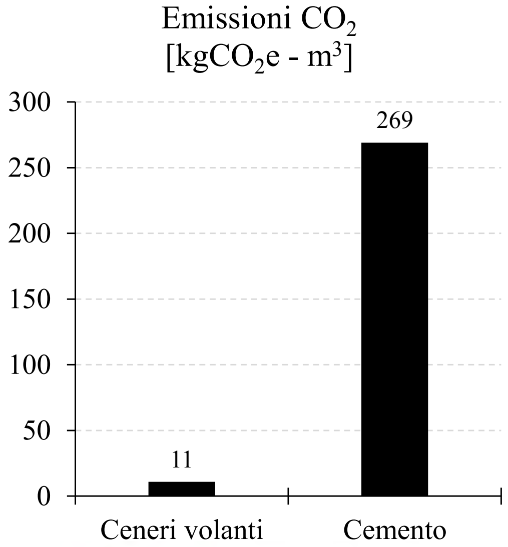


“Pietro Pisa” Testing Lab

Concrete: one of the most used material in the world

Because of PORTLAND CEMENT, concrete production has a significant effect on global warming and CO_2 emissions

Louise K. Turner, Frank G. Collins, *"Carbon dioxide equivalent (CO_2-e) emissions: a comparison between geopolymer and OPC cement concrete"*.



1 ton Cement ≈ 1 ton CO_2

NEED OF ECO-FRINEDLY MATERIAL

GEOPOLYMER CEMENT/CONCRETE

ADVANTAGES

- Cement free

Reduction of CO_2 emissions

- Use of fine dust derived from industrial processes

Reuse of waste materials

- Good mechanical and durability properties

ECO-FRIENDLY MATERIAL

STRUCTURAL APPLICATIONS

Retrofitting of existing structures

Precast structures

University of Queensland's Global Change Institute, Australia

Geopolymer mortar

Self compacting geopolymer concrete

Fiber reinforced geopolymer concrete

OUTLINE

STEP 1: MIX DESIGN

- Study of the optimal mix design
- Analysis of curing parametres

STEP 2: MATHERIAL CHARACTERIZATION

- Compressive strenght
- Young’s Modulus
- Stress-strain relationship
- Analysis of Modulus of Rupture (MOR)

STEP 3: FULL-SCALE TESTS

- Two full-scale beams tested under four point loading system

CONCLUSIONS

STEP 1: MIX DESIGN

ALUMINOSILICATE SOURCE	Metakaolin, Slag	**Class F Fly Ash** **(ASTM C618-78)**
ALKALINE SOLUTION	Potassium Hydroxide + Potassium Silicate	**Sodium Hydroxide** **(8M)** + **Sodium Silicate** **(WR=2** **Conc. 44%)**
AGGREGATES	**Fine and Coarse aggregates** **(Maximum size=10 mm)**	

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CLASS F FLY ASH:

FLY ASH USED BY UNIBS

Total $SiO_2 = 56\%$

$Al_2O_3 = 28\%$

$SiO_2+Al_2O_3 = 84\ \%$

$SiO_2/Al_2O_3 \approx 2$

$CaO = 2\%$

$Fe_2O_3 = 5.5\ \%$

LOI = 2.8 %

SUPERPLASTICIZER

NO CONTRIBUTION IN TERMS OF WORKABILITY

Structural applications
Si:Al = 2

J.Davidovits, *High-alkali cements for 21st century concretes*, in "Concrete technology, past present and future", Proceedings of V. Mohan Malhotra symposium, Ed. P. Kumar Metha, ACI SP-144, 1994, pp. 383-397.

LOI:
It should be less than 5%→
Inhibition of reaction

Low content of CaO→ Avoid fast setting

J. Davidovits, M. Izquierdo, X. Querol, D. Antennucci, H. Nugteren, V. Butselaar-Orthlieb, C. Fernández-Pereira, Y. Luna, *The European Research Project GEOASH: geopolymer cement based on European coal fly ashes*, Technical Paper #22, Geopolymer Institute Library, www.geopolymer.org, 2014.

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MIX DESIGN & CURING PARAMETRES

Materials	[kg/m³]
Coarse Aggregate (6-10 mm)	1201
Sand	647
Tot. Aggregates	**1848**
Class F Fly Ash	408
Sodium Hydroxide 8 M	41
Sodium Silicate	103
Extra H_2O	35
Total	**2435**

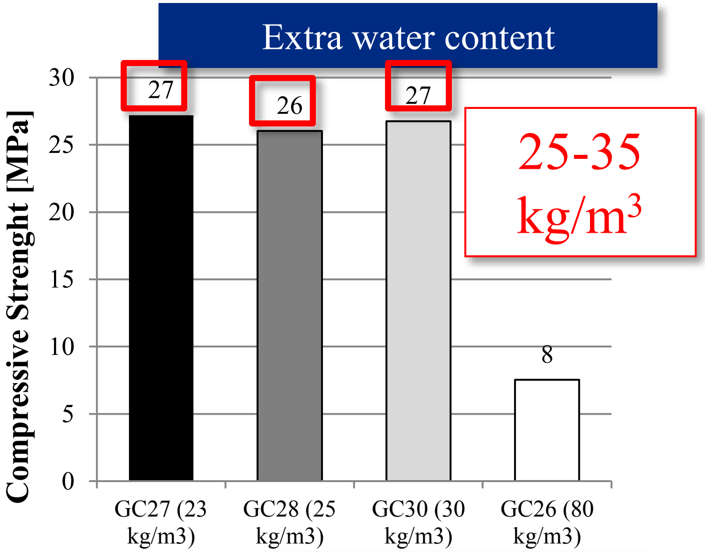
Aggregates: 80% by mass

Coarse Aggregate/Sand = 2

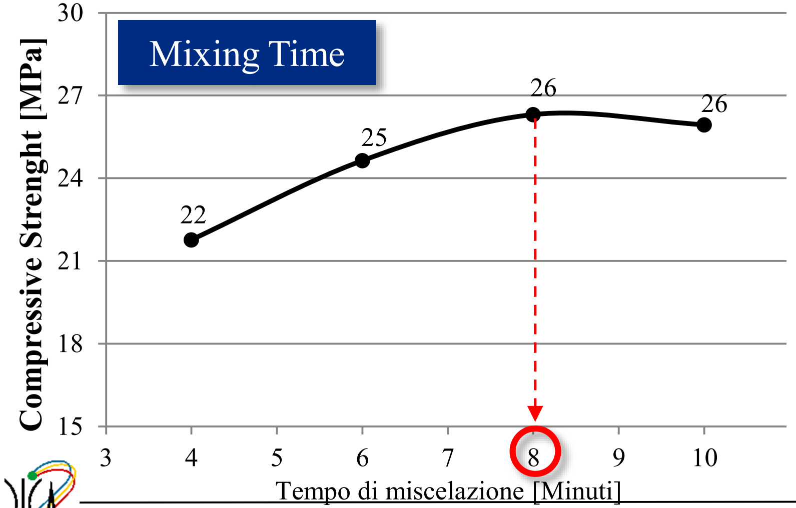
Silicate/ Hydroxide= 2.5

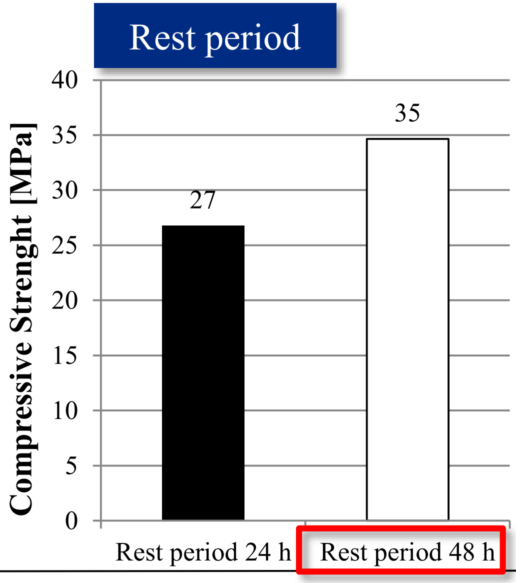
Alakaline Solution/Fly ash=0.35

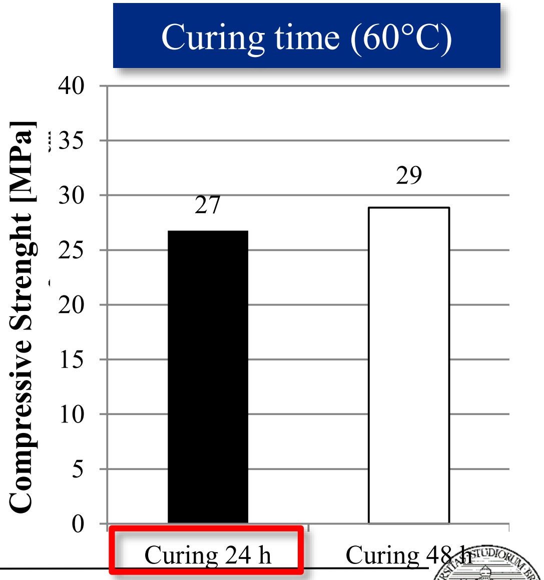
Liquid/Fly Ash = 0.44


Extra water content

25-35 kg/m^3


Mixing Time


Rest period


Curing time (60°C)

Linda Monfardini - l.monfardini001@unibs.it

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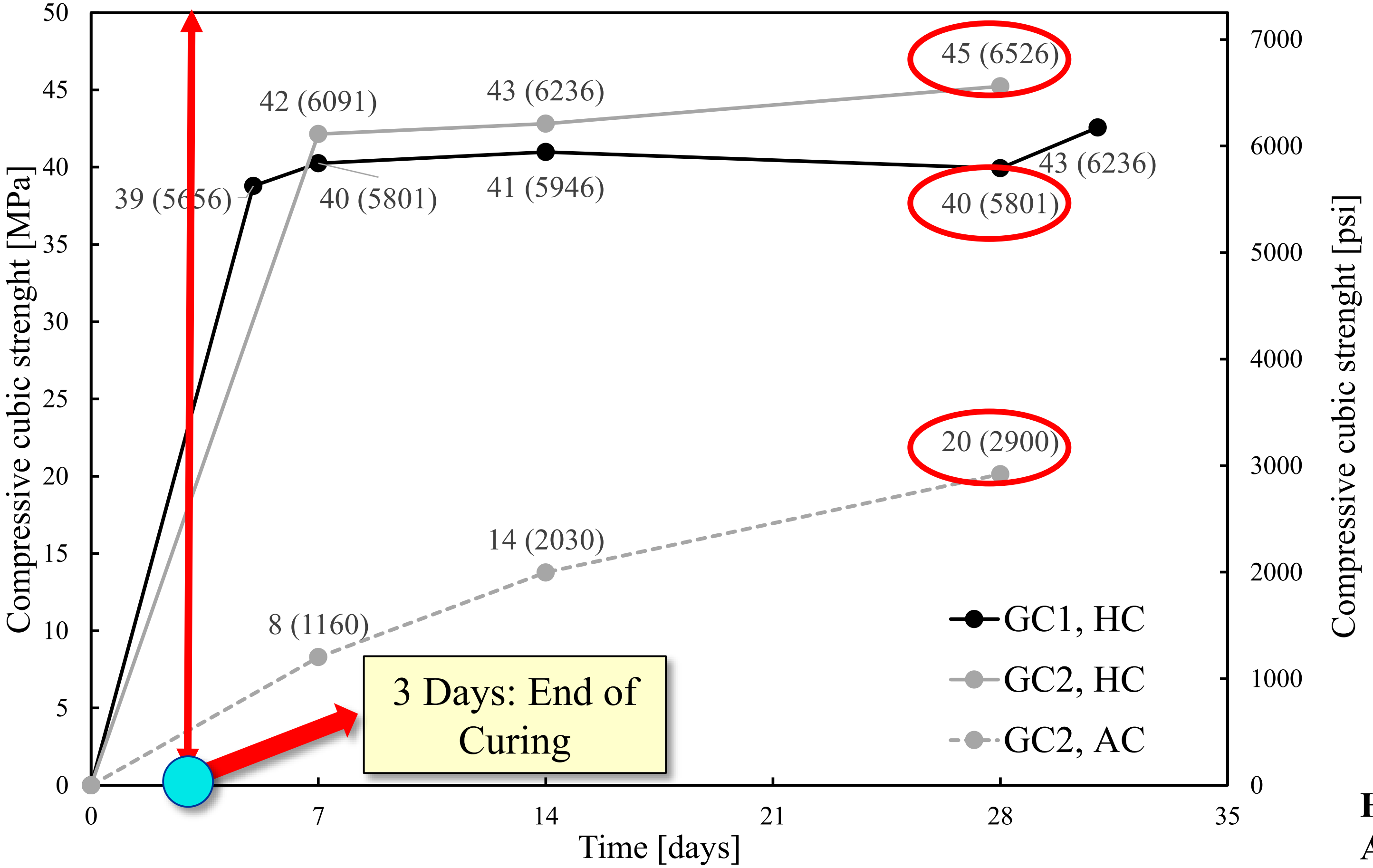
STEP 2: MATERIAL CHARACTERIZATION
CUBIC COMPRESSIVE STRENGHT



$f_{cm}=0.83\ R_{cm}$

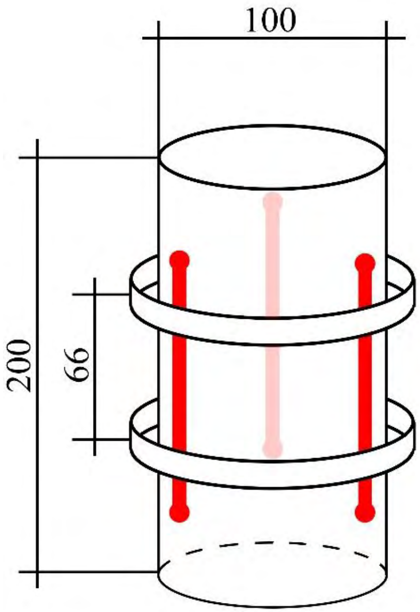
Cylinder compressive strength:

33-37 MPa

HC:Heat Curing
AC: Ambient Curing

STEP 2: MATERIAL CHARACTERIZATION YOUNG'S MODULUS

UNI 6556



EXPERIMENTAL RESULTS

BEAM 1 GC1	BEAM 2 GC2
24 GPa	25 GPa

ANALYTICAL RESULTS

For ordinary concrete, Eurocode 2 recommends the following relation:

$$E_{cm} = 22000\left(\frac{f_{cm}}{10}\right)^{0.3}$$

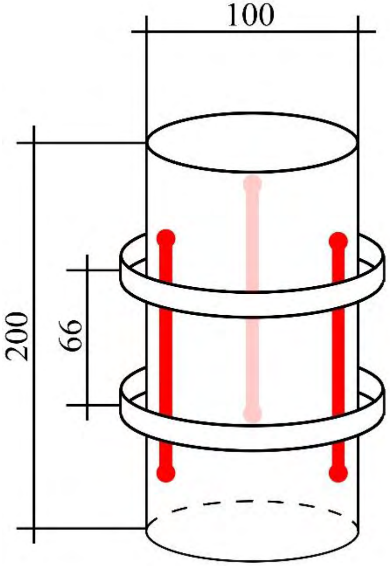
Maximum Aggregate size = 10 mm

$$\mathbf{E_{cm} = 31\text{-}\ 32.5\ GPa}$$

STEP 2:
STRESS-STRAIN RELATIONSHIP

UNI 6556

Test run in stroke control



ANALYTICAL FORMULAS

THORENFELDT et al.

$$\sigma_c = f_{cm} \cdot \frac{\varepsilon_c}{\varepsilon_{cm}} \cdot \frac{n}{n-1+(\varepsilon_c/\varepsilon_{cm})^{nk}}$$

$n = 0{,}8+(f_{cm}/17)$

$k = 0{,}67+(f_{cm}/62)$, se $\varepsilon_c/\varepsilon_{cm}>1$

$k = 1$, se $\varepsilon_c/\varepsilon_{cm} \leq 1$

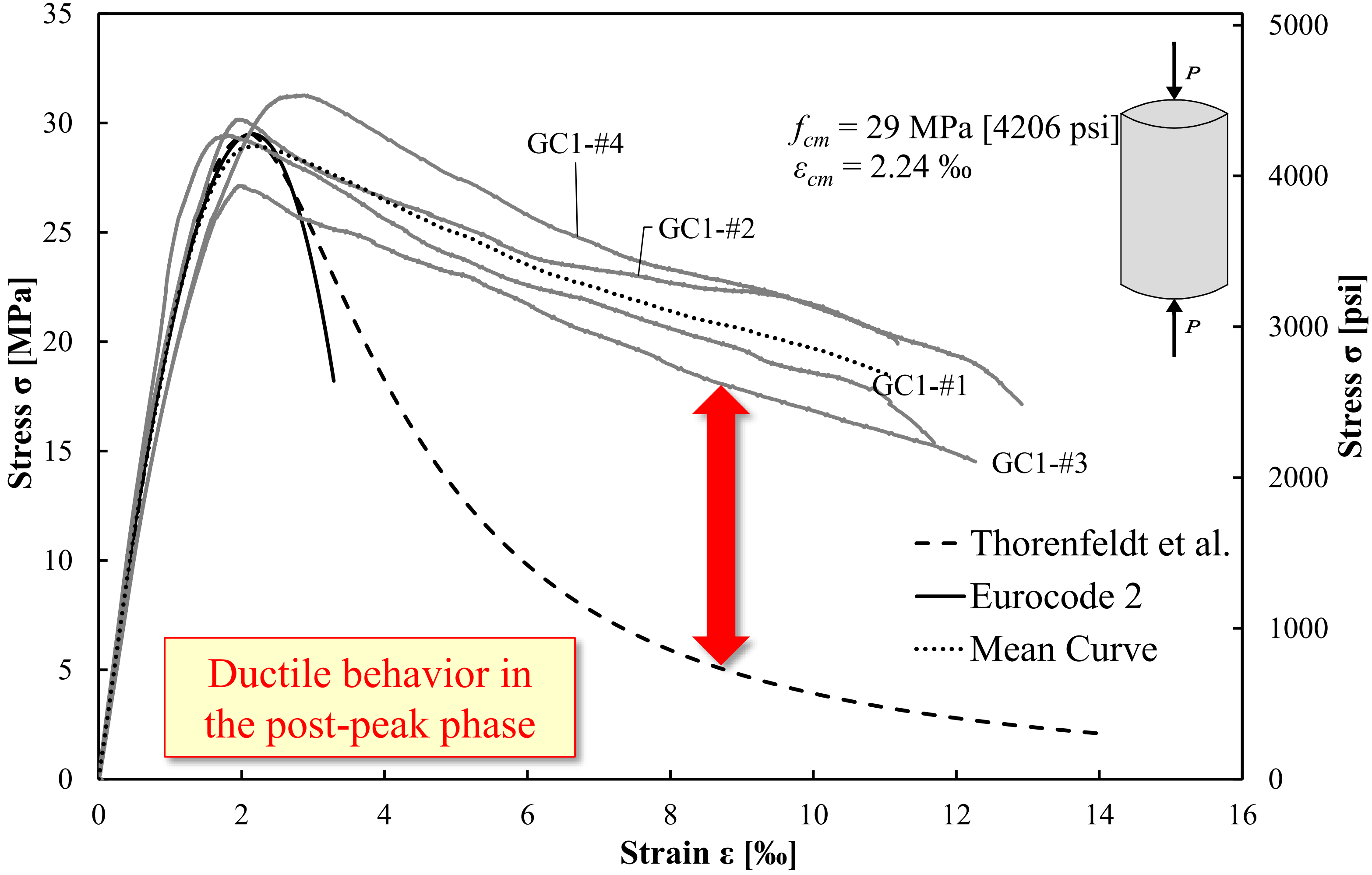
EUROCODE 2

$$\sigma_c = f_{cm} \cdot \frac{k\eta - \eta^2}{1+(k-2)\cdot\eta}$$

$\eta = \varepsilon_c/\,\varepsilon_{cm}$

$k = 1{,}05 \cdot E_{cm} \cdot |\varepsilon_{cm}| / f_{cm}$

STEP 2: STRESS-STRAIN RELATIONSHIP

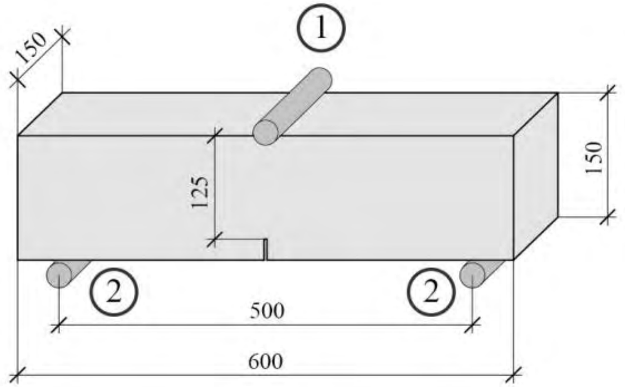


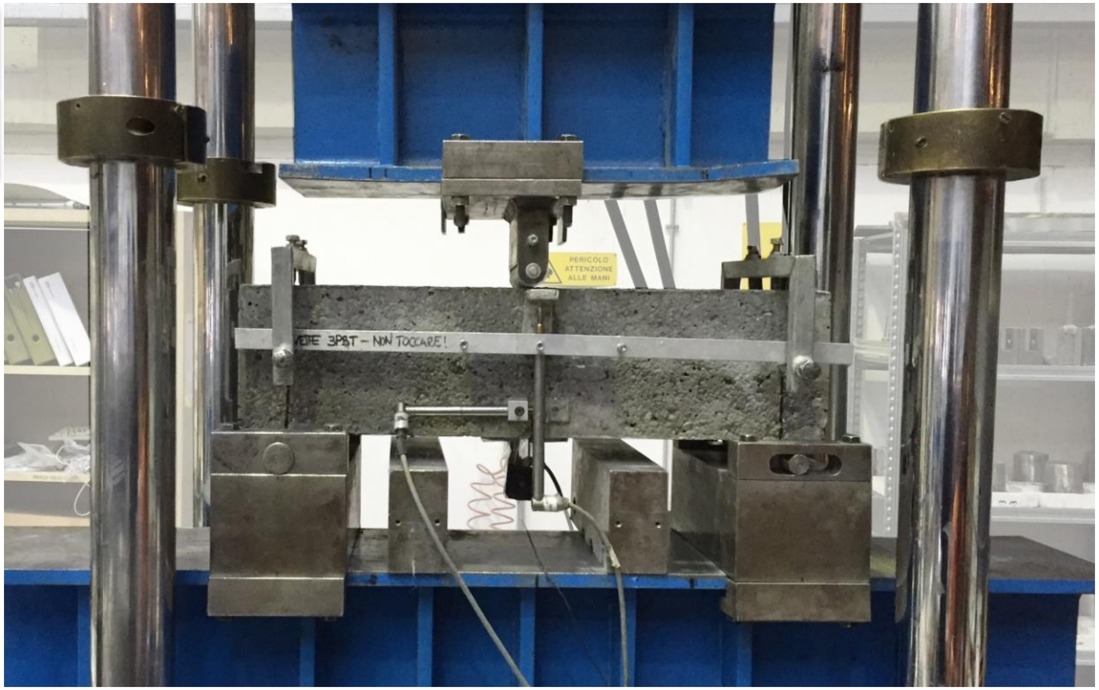
Ductile behavior in the post-peak phase

STEP 2: MODULUS OF RUPTURE (MOR)

MODULUS OF RUUTURE

UNI EN 14651



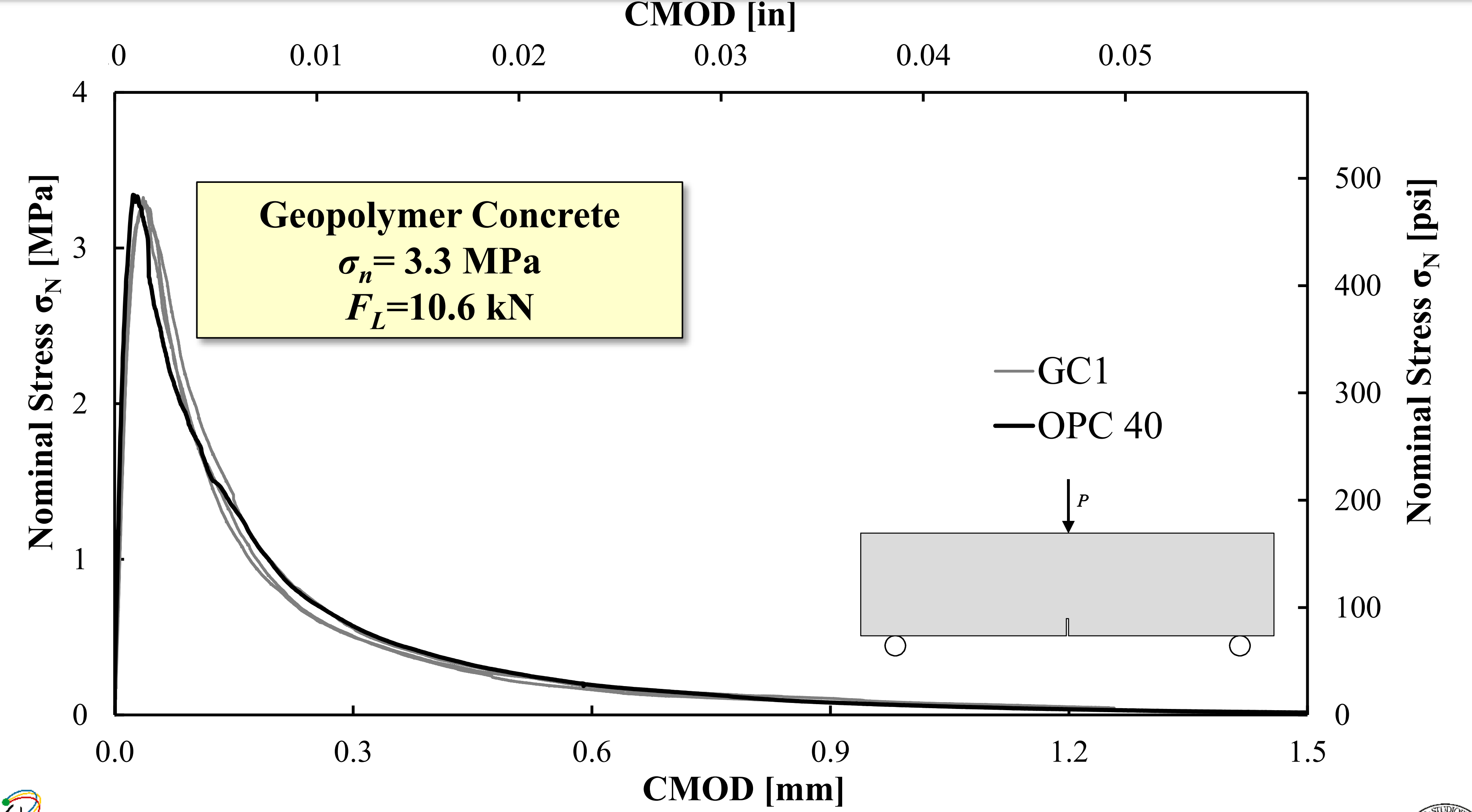


Goal:

Indirect analysis of tensile strenght

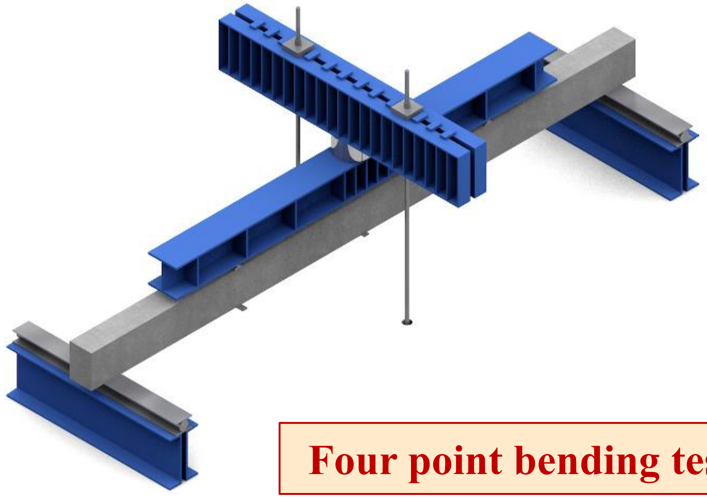
- CMOD (*Crack Mouth Opening Displacement*)
- 2 CTOD (*Crack Tip Opening Displacement*)
- 2 MPD (*Mid Point Displacement*)

STEP 2: MODULUS OF ROPTURE

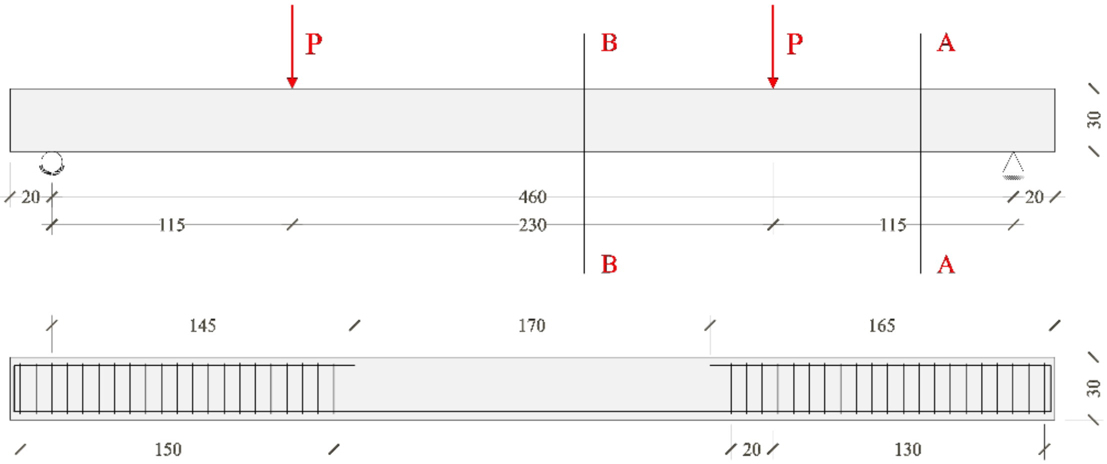


Geopolymer Concrete
σ_n= 3.3 MPa
F_L=10.6 kN

STEP 3: FULL-SCALE TESTS



Four point bending test



$A_s = 4.02$ cm^2

$A'_s = 0$

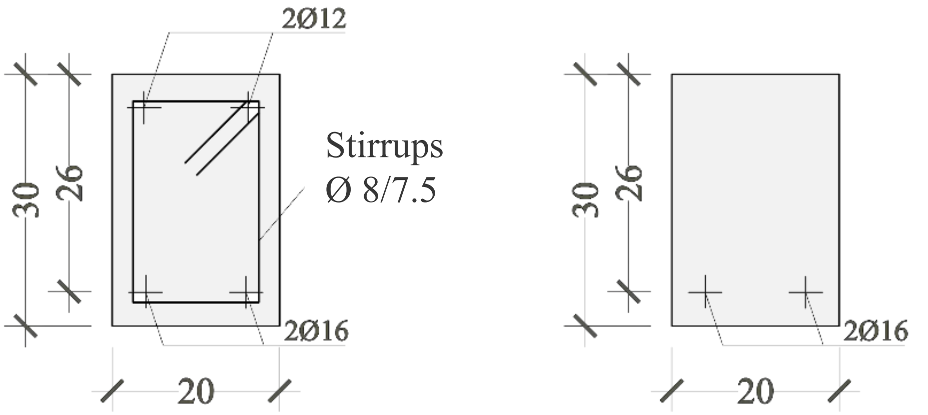
$\rho_l = 0.77$ %

$\rho_v = 0.67$ %

$f_{sy} = 545$ MPa

$\sigma_{st,max,es} = 260$ MPa

$A_{st} = 0.50$ cm^2

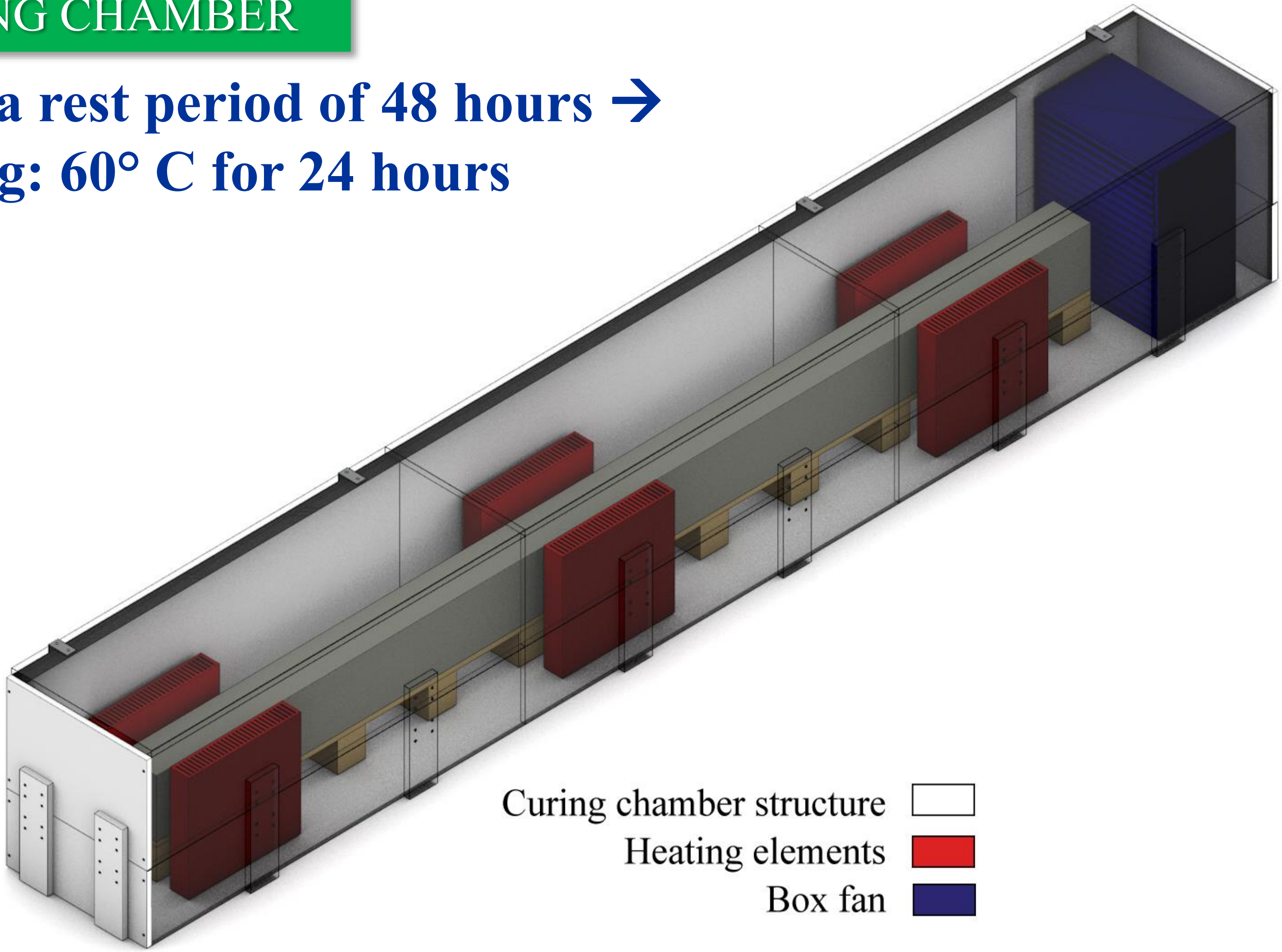


$M_u = 0.9 \cdot d \cdot A_s \cdot f_{sy} = 51$ kNm

$P_u = 2\,M_u / a = 89$ kN

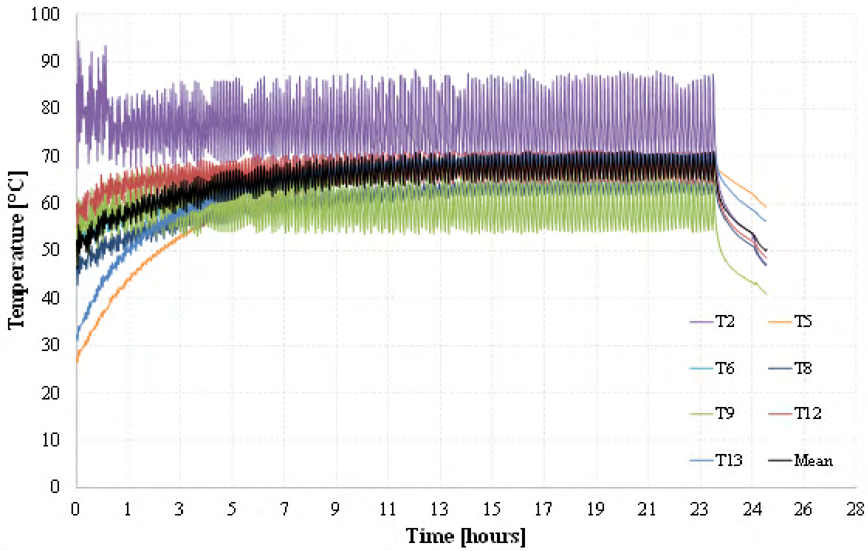
CURING CHAMBER

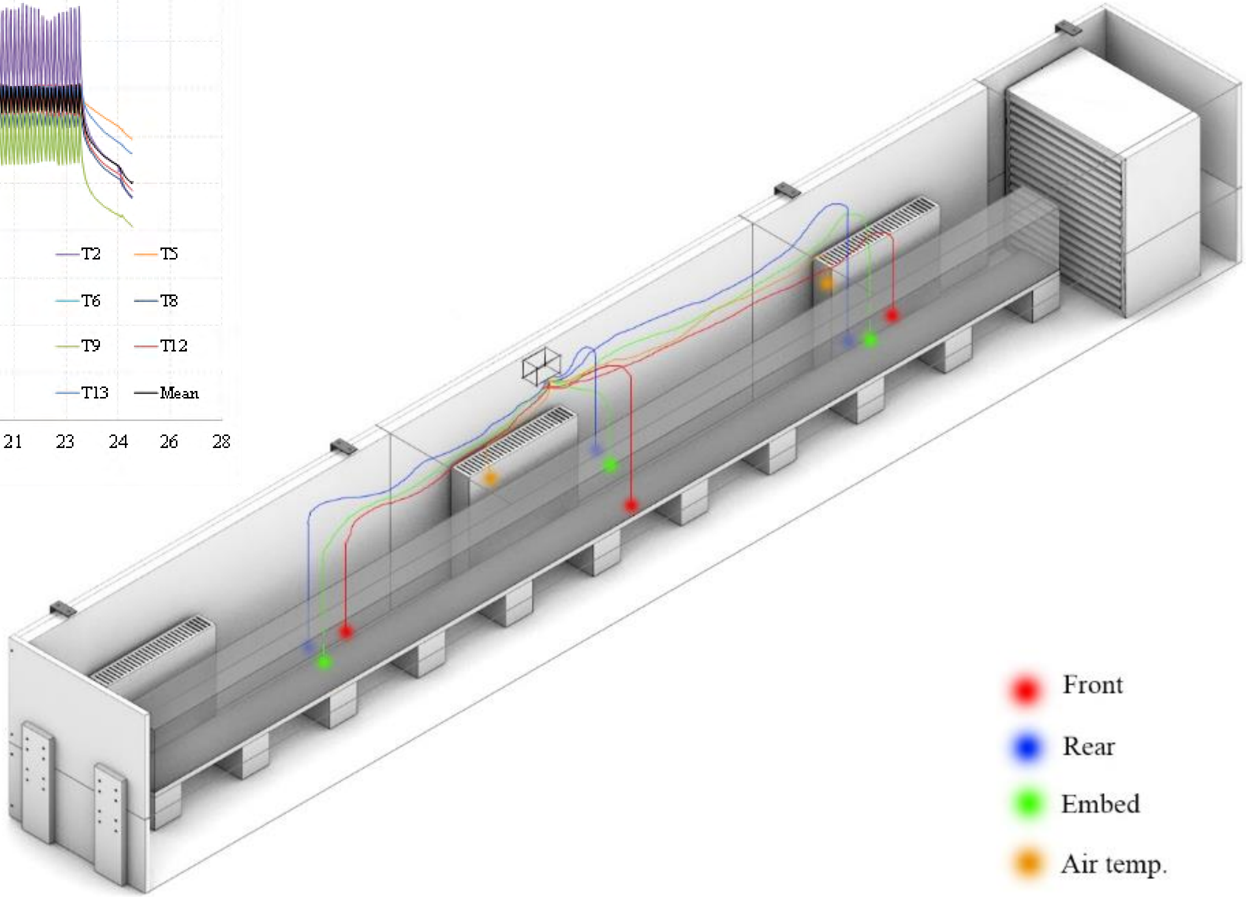
After a rest period of 48 hours →
Curing: 60° C for 24 hours



Linda Monfardini - l.monfardini001@unibs.it

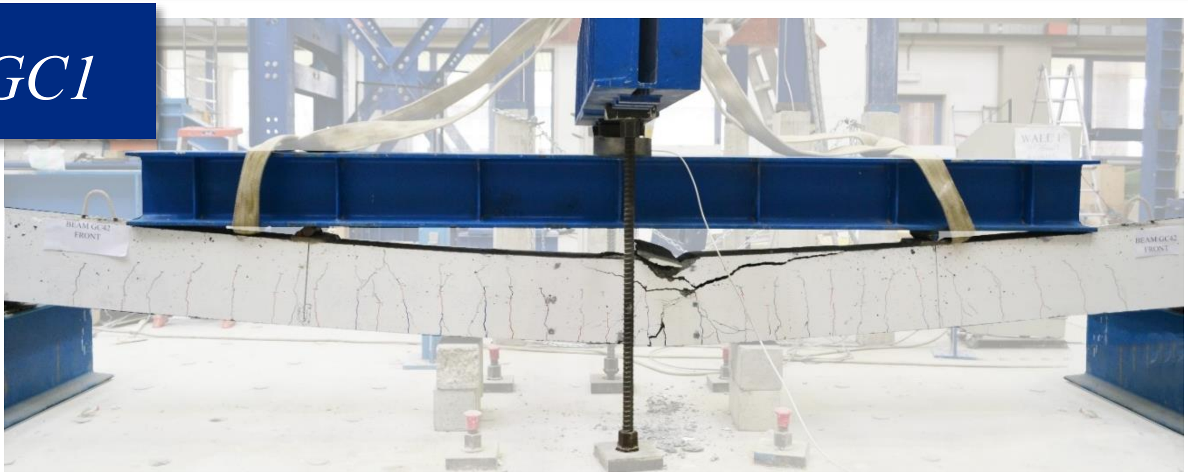
TEMPERATURE MONITORING





COMPARISON OF RESULTS

Beam GC1



Test Day:

31 days

$P_u = 95\ kN$

$\delta_u = 156\ mm$

$E = 24\ GPa$

Beam GC2

Test Day:

8 days

$P_u = 92\ kN$

$\delta_u = 127\ mm$

$E = 25\ GPa$

LOAD-DISPLACEMENT

$P_{u,GC1}$ = 95 kN

$P_{u,GC2}$ = 92 kN

$\delta_{u,GC1}$ = 156 mm

$\delta_{u,GC2}$ = 127 mm

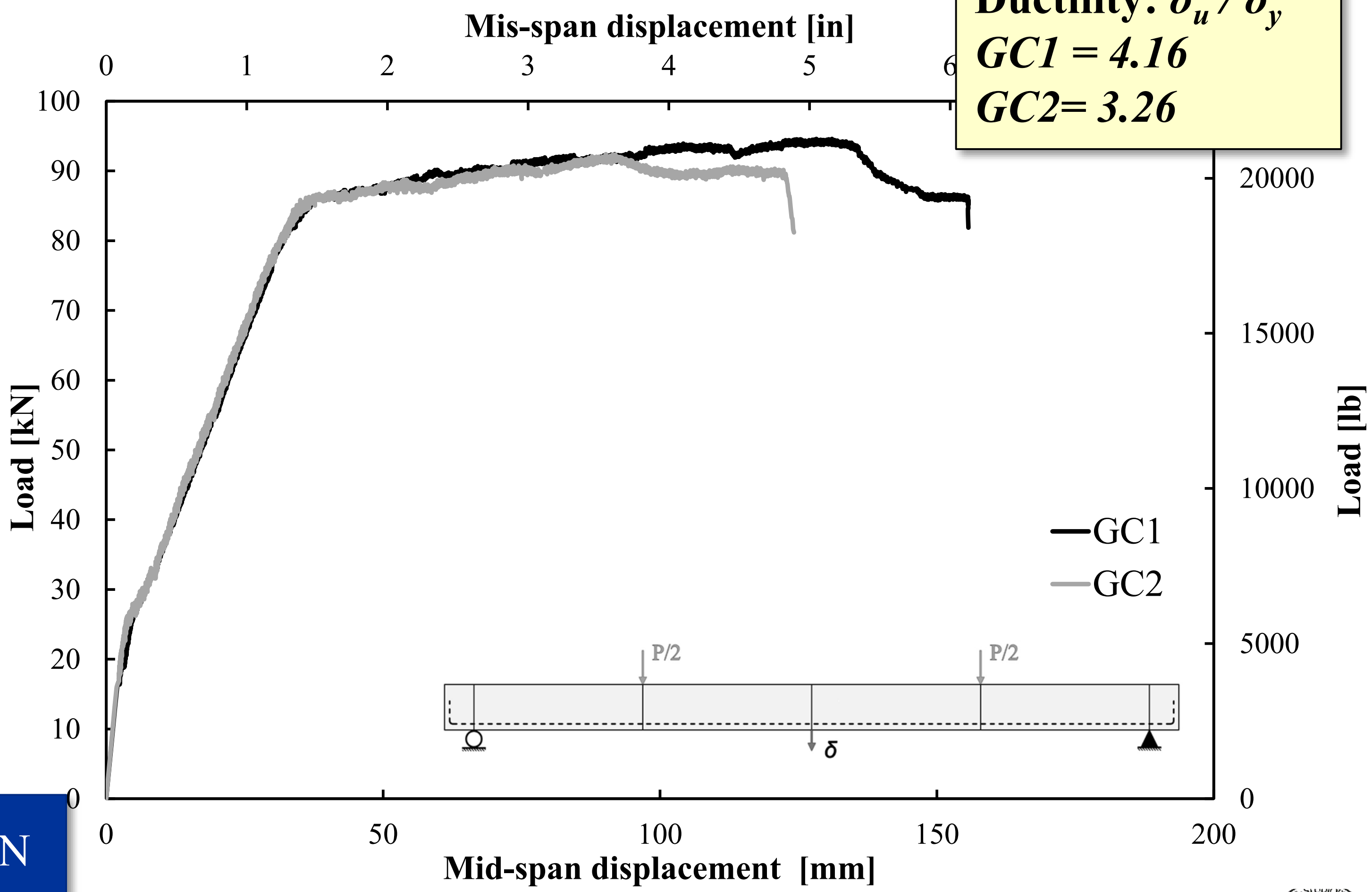
$P_{y,GC1}$ = 85 kN

$P_{y,GC2}$ = 86 kN

$\delta_{y,GC1}$ = 37 mm

$\delta_{y,GC2}$ = 38 mm

$P_{u,\,predicted}$ = 89 kN



Ductility: δ_u / δ_y

GC1 = 4.16

GC2= 3.26

CRACK PATTERN

Beam GC1

Experimental result

$S_{rm} = 102$ mm

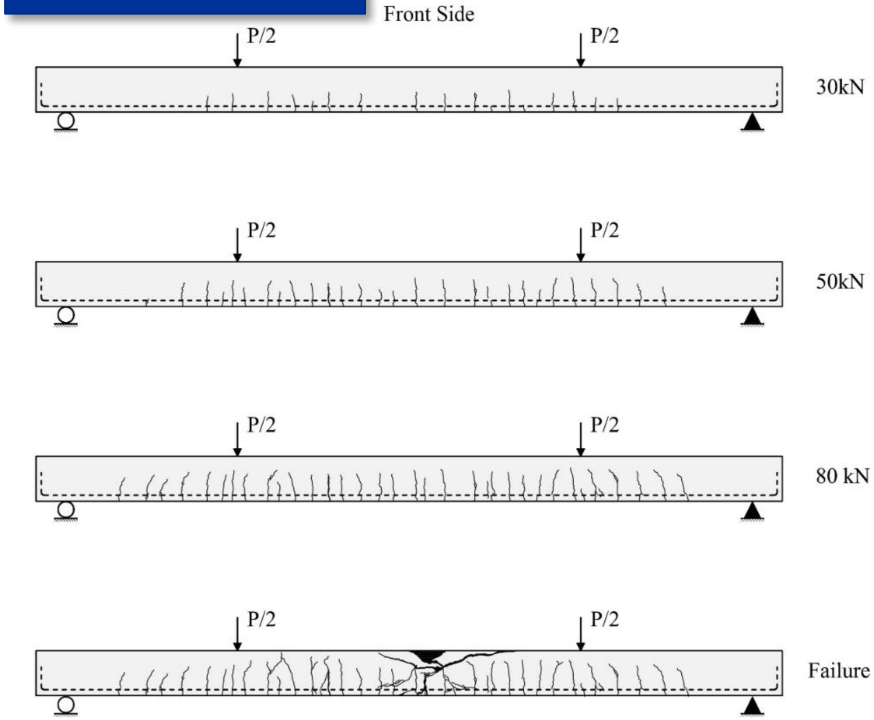
(1) $S_{rm} = 2 \cdot \left(c + \frac{s}{10}\right) + k_1 \cdot k_2 \cdot \frac{\varphi}{\rho_{eff}} = 115\ mm$ (MC1978)

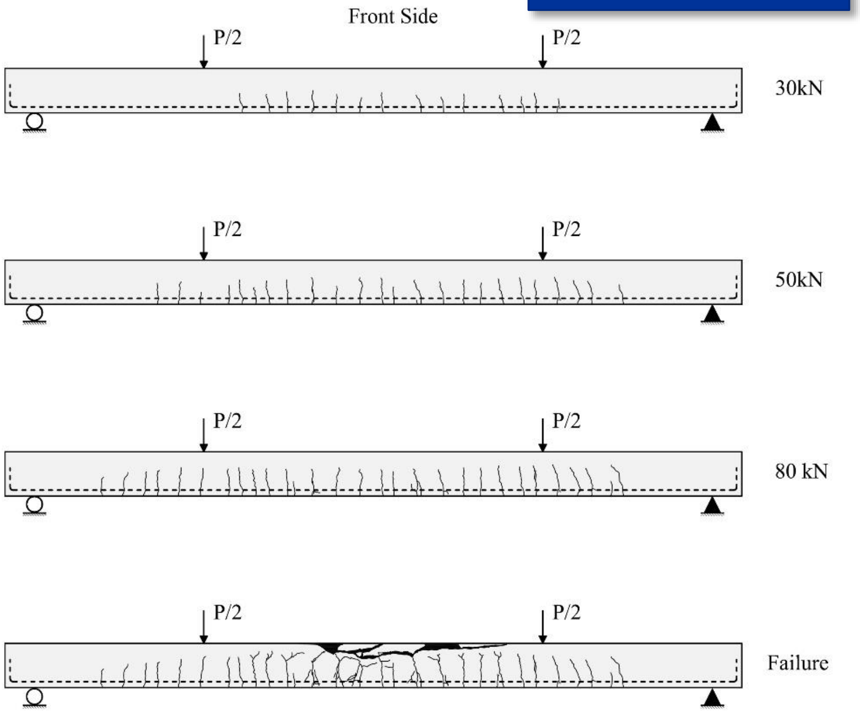
(2) $S_{rm} = \frac{2}{3} \cdot \frac{\varphi}{3{,}6 \cdot \rho_{eff}} = 108\ mm$ (MC1990)

Baem GC2

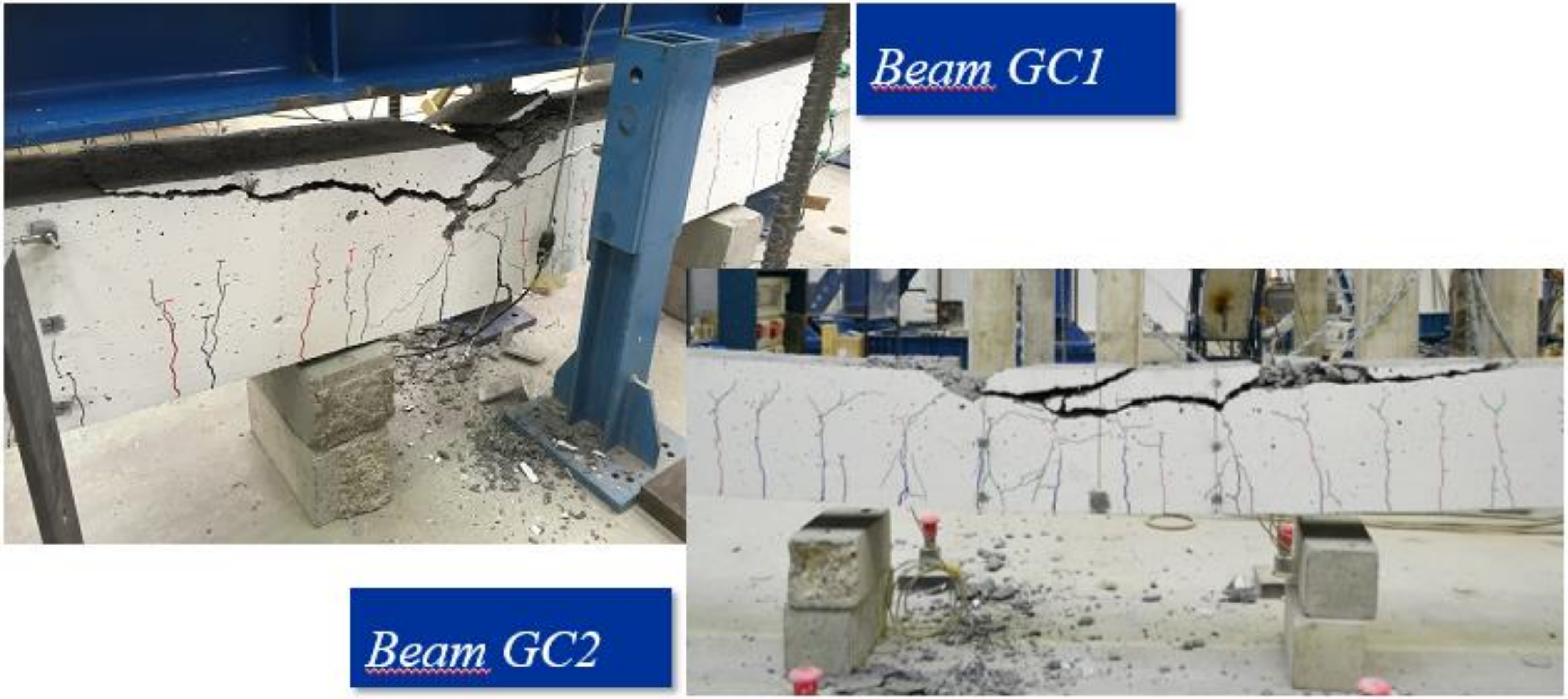
Experiental result

$S_{rm} = 113$ mm





COLLAPSE



Beam GC1

Beam GC2

CONCLUSIONS

- Compression strength had a limited increase in time after the heat curing;
- Experimental Young’s modulus is lower than ordinary concrete;
- Constitutive law: in pre-peak phase, a trend similar to analytical formulas proposed for ordinary concrete. In post-peak response GC presented a more ductile behavior;
- MOR tests pointed out a rather brittle behavior coincident to ordinary concrete;
- Despite difference in testing time, flexural behavior of full-scale beams did not show differences in terms of ultimate load; on the contrary there are minor difference in terms of ultimate displacement and ductility;
- As expected for ordinary concrete, full-scale beams reached failure because of concrete crushing with yielded steel;
- Experimental mean crack spacing fits well with analytical formulas for ordinary concrete.

Linda Monfardini - l.monfardini001@unibs.it

Thank you for your kind attention!

University of Brescia, Italy