Sostenibilità delle strutture in calcestruzzo ad elevate prestazioni

Marianovella Leone

Dipartimento di Ingegneria dell'Innovazione

Università del Salento

ITALY aci CHAPTER

UNIVERSITÀ DEL SALENTO

L'Ateneo tra i due mari

SAIE BARI 7-9 Ottobre 2021

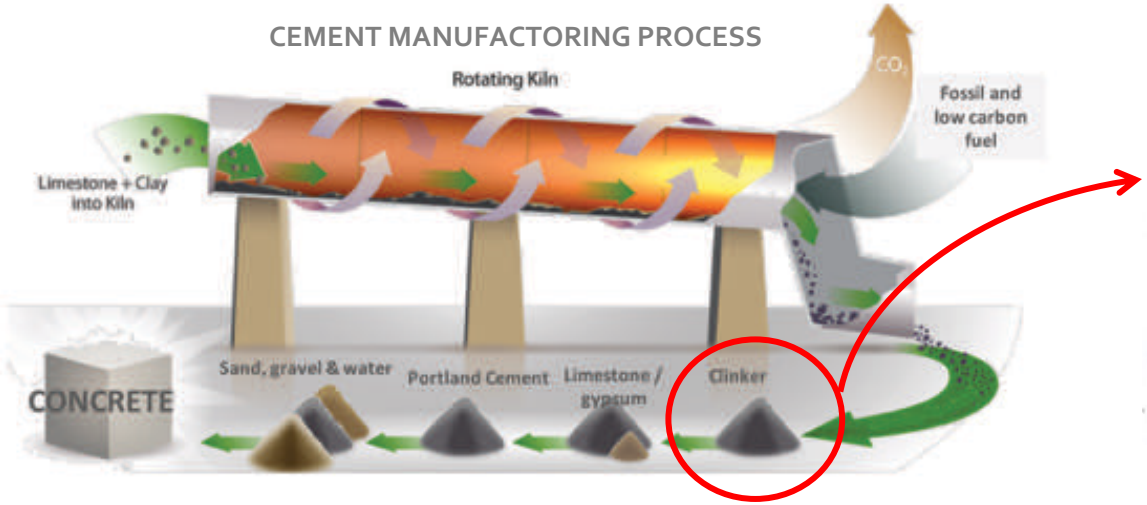
08 Ottobre 2021

OUTLINE SEMINARIO

- Calcestruzzi con leganti non cementizi
  - GEOPOLIMERI
  - SOLFOALLUMINOSI
- Calcestruzzi additivati con materiali da riciclo
  - Fibre in acciaio derivante da PFU
  - Gomma derivante de PFU

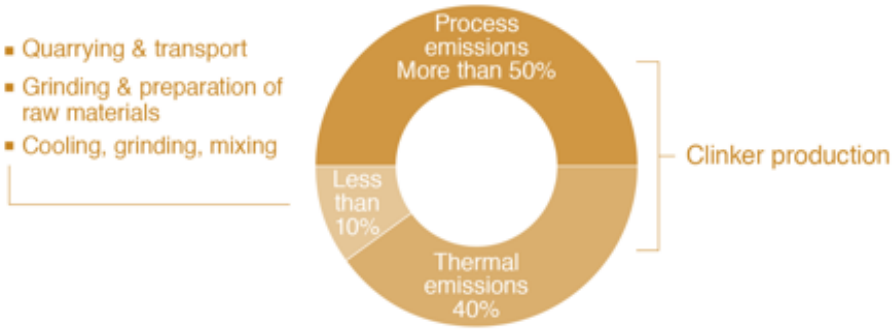
Calcestruzzi Geopolimerici

Why Geopolymer Concrete?



Replace clinker with geopolymer material

- About 8% of global CO_2 emissions come out from cement industry
- The production of clinker accounts for most of the CO_2 emissions of cement production



Why Geopolymer Concrete?

NATURAL:
- Kaolin
- Calcined clay

INDUSTRIAL WASTE:
- Silica fume
- Fly ash
- Ground Granulated Blast-Furnace Slag (GGBFS)

RAW MATERIALS

Catalytic liquid system is used as alkaline activator solution.

ACTIVATION

The activation requires no heat: CO_2 emissions are reduced up to **80%!**

FINAL PRODUCT

Great mechanical and structural properties

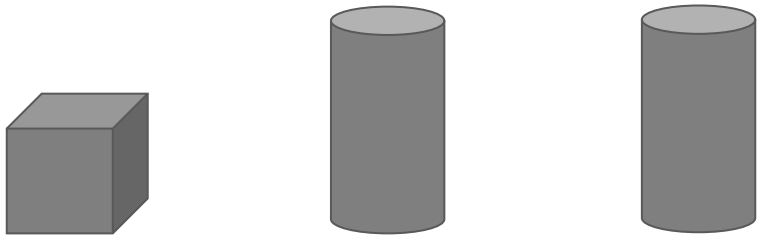
Excellent performances in terms of chemical and fire resistance

Experimental program

GPC MIX DESIGN

(defined in the previous phase of the project)

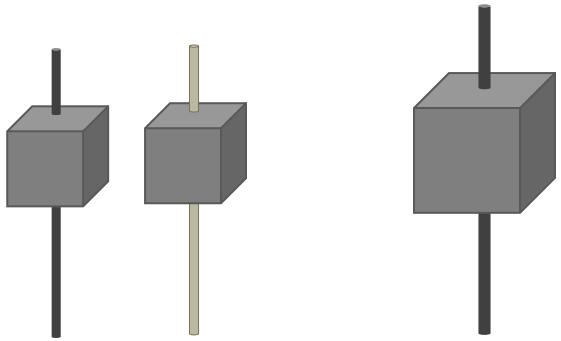
MECHANICAL CHARACTERIZATION



Compressive strength | Constitutive law | Modulus of Elasticity

PULL-OUT TESTS WITH STEEL AND GFRP BAR

ϕ12mm bar specimen



ϕ16mm bar specimen

Geopolymer concrete mix design

Components	Quantity
Ground Granulated Blast-Furnace Slag	224 kg/m3
Limestone and gypsum	128 kg/m3
Silica Fume	48 kg/m3
Ingessil (Activator solution)	170 kg/m3
Water	140 kg/m3
Additive (Plasticizer)	8 kg/m3
Sand	1092 kg/m3
Gravel	471 kg/m3

Workability tests

Casting	Slump	Workability class
Casting 1	26 cm	S_5
Casting 2	27 cm	S_5
Casting 3	25 cm	S5
Casting 4	27 cm	S_5

Modulus of Elasticity

UNI EN 12390-3

ELASTIC MODULUS	24312 MPa	CoV: 17%
PREVISION ACCORDING TO Eurocode 2	$E_{cm} = 22.000[(f_{cm})/10]^{0,3}$ 36005 MPa	

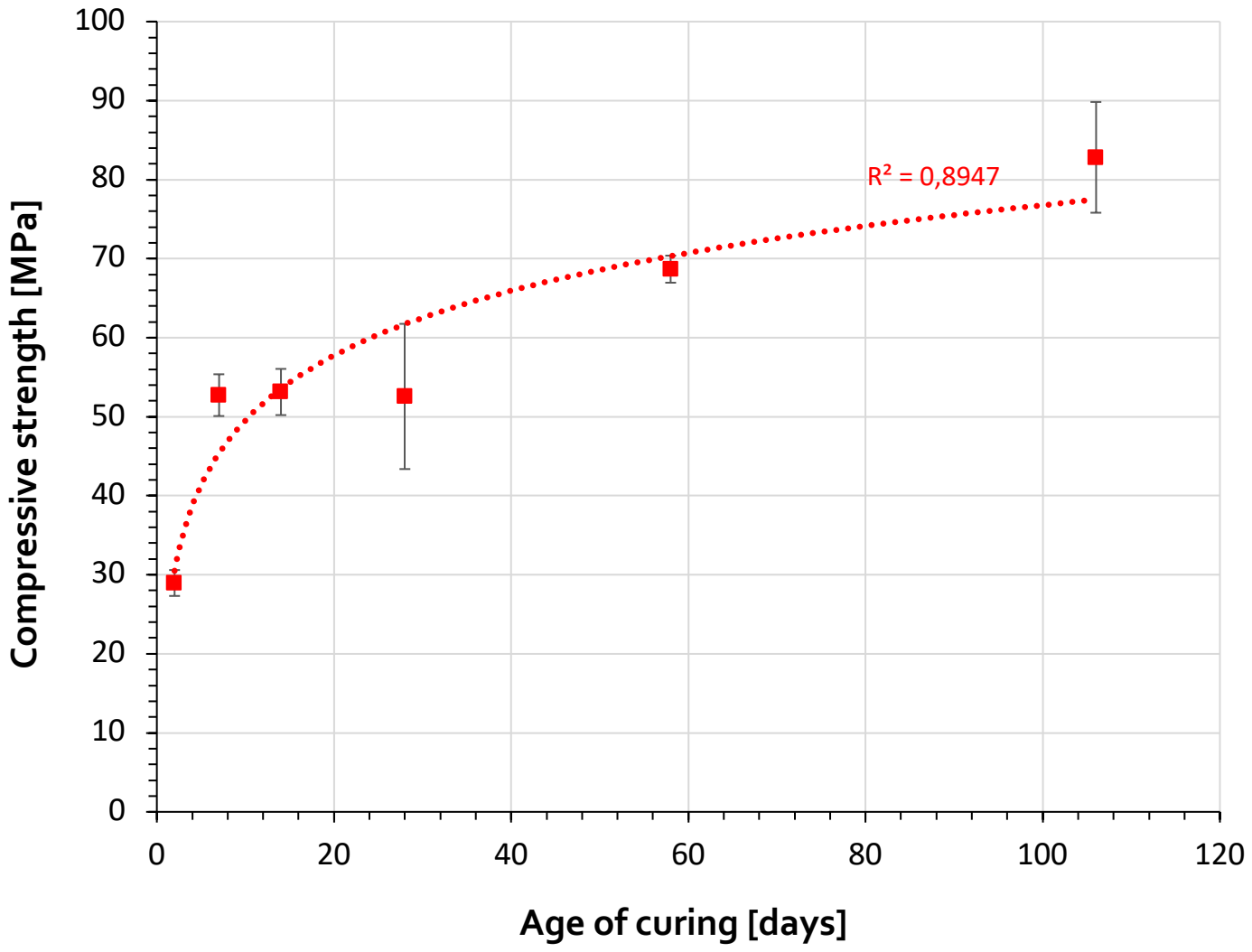
Compressive strength tests

UNI EN 12390-3

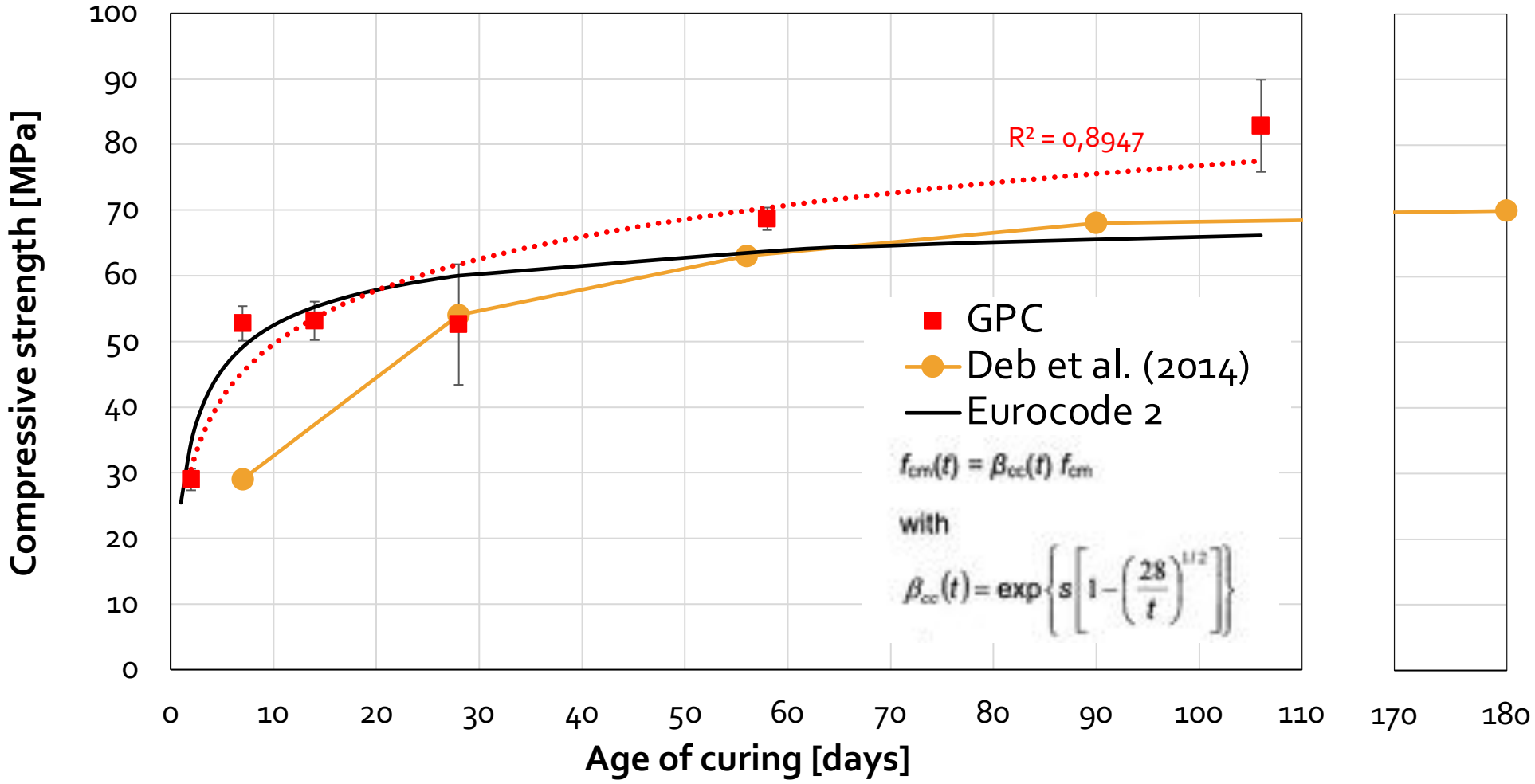
Age [days]	σ [MPa]	CoV
2	29,0	5,7%
7	52,7	5,0%
14	53,1	5,5%
28	**52,6**	**5,5%**
60	68,7	-
106	82,8	-

Compressive strength tests

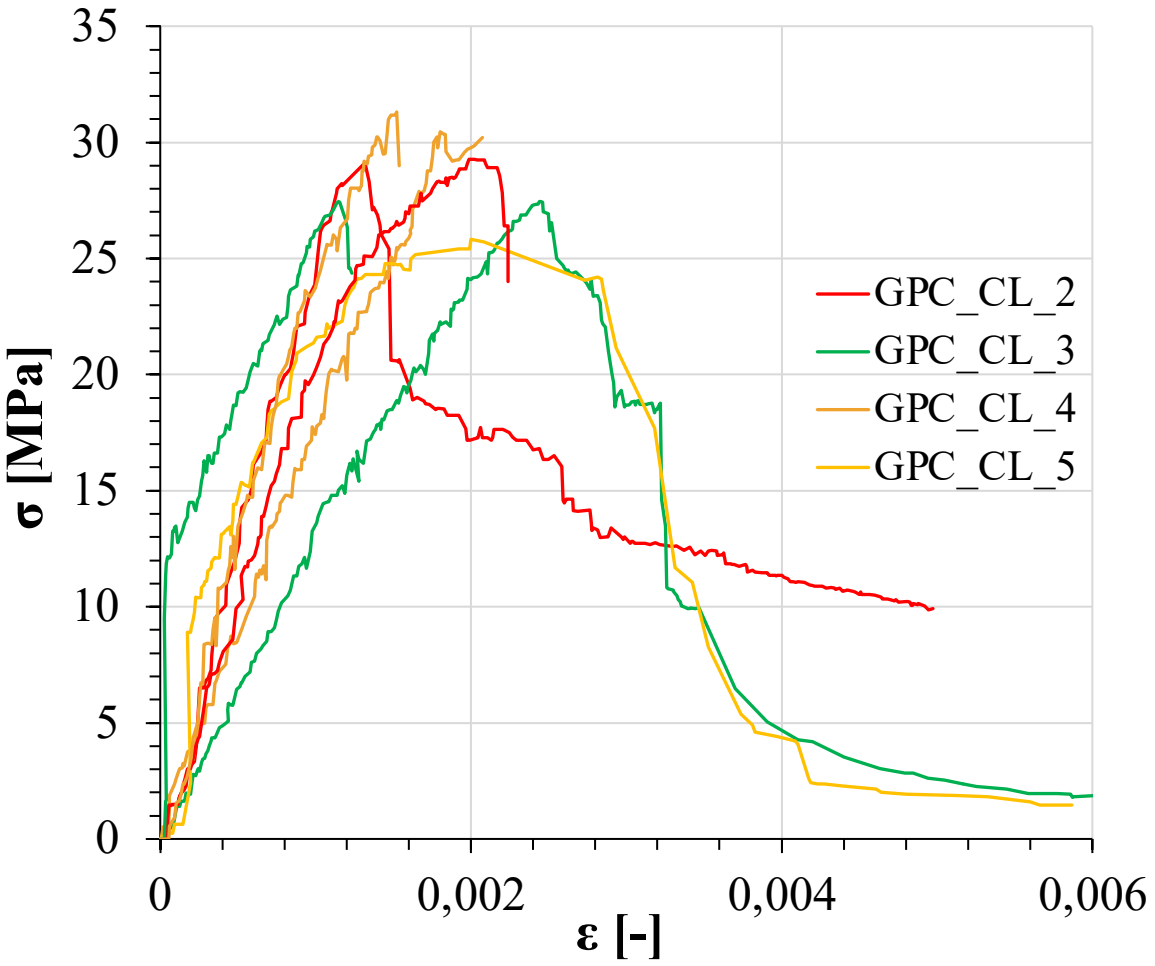
UNI EN 12390-3



Compressive strength evolution

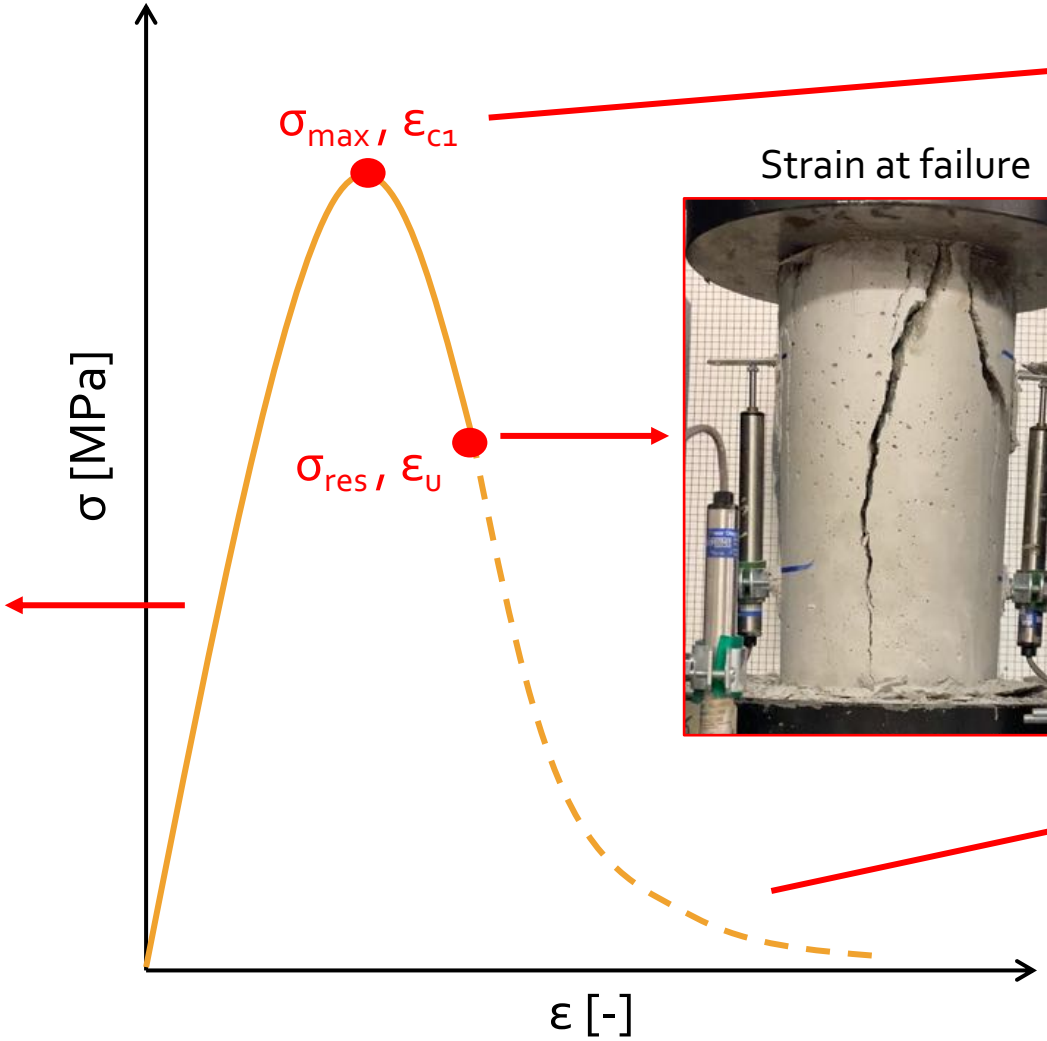


Constitutive law tests



Constitutive law

Elastic Stage

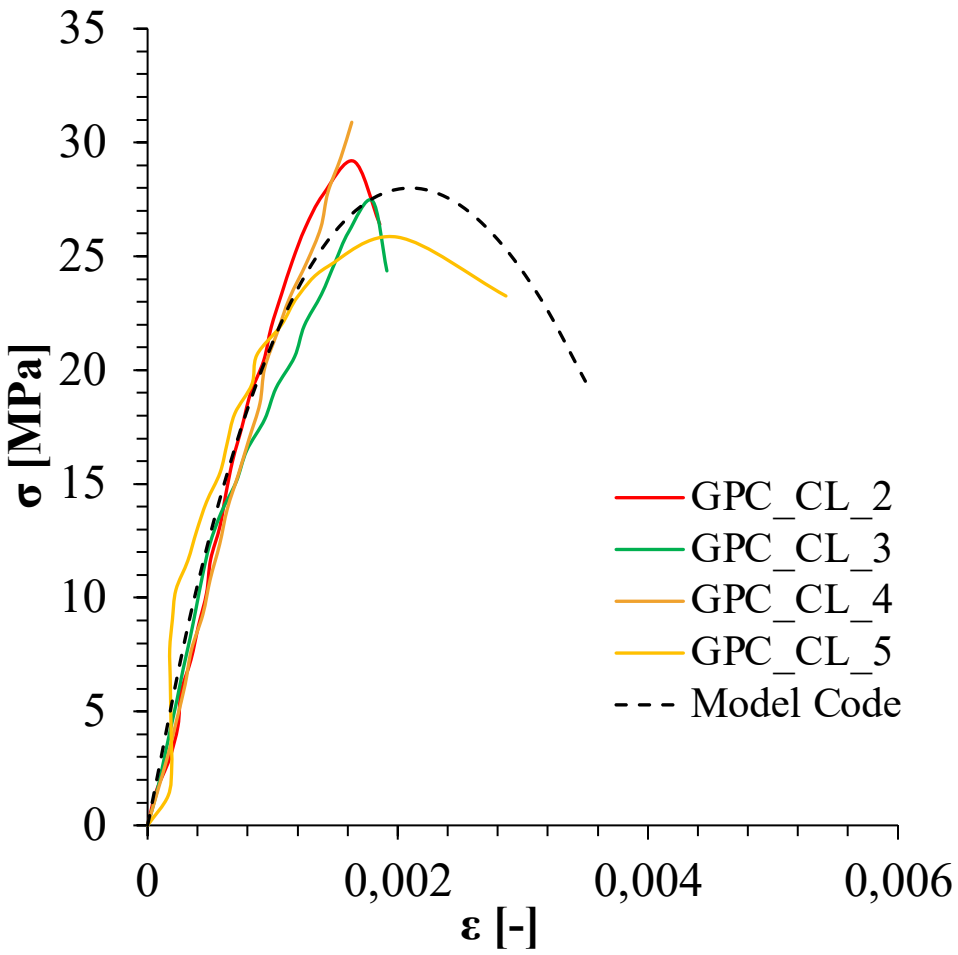


Strain at failure

Failure stage

Compressive strenght

Design constitutive law curves

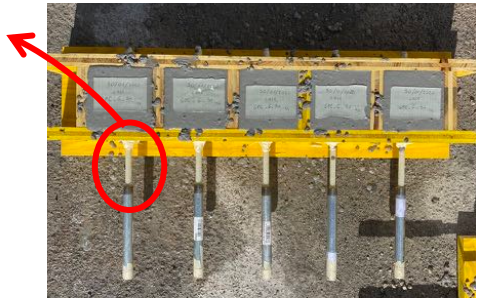


Specimen	f_c [MPa]	ε_{cu} [-]
GPC_CL_2	29,3	0,0018
GPC_CL_3	27,5	0,0019
GPC_CL_4	31,5	-
GPC_CL_5	25,8	~~0,0029~~
Average	**28,5** (CoV 7%)	**0,0019**

Pull-out test setup

RILEM Recommendations for the Testing and Use of Constructions Materials - RC 6 Bond test for reinforcement steel. 2. Pull-out test, 1983

Bar	Diameter	L_b	Number of samples
Steel	12mm	5ϕ	4
		2.5ϕ	5
	16mm	5ϕ	5
GFRP	12mm	5ϕ	5
		2.5ϕ	5



Comparison between steel and GFRP bar

Bar type	Sample id	Bond strength [MPa]	Average bond [MPa]
GFRP	GPC_GP_12_1	10.6	9.7 (CoV 14%)
	GPC_GP_12_2	7.7	
	GPC_GP_12_3	9.5	
	GPC_GP_12_4	9.4	
	GPC_GP_12_5	11.4	
Steel	GPC_P_12_2	26.2	25.5 (CoV 3%)
	GPC_P_12_3	24.9	
	GPC_P_12_4	25.4	
	GPC_P_16_2	21.0	22.0 (CoV 3%)
	GPC_P_16_3	22.5	
	GPC_P_16_4	22.0	
	GPC_P_16_5	22.7	

- The pull-out tests of GPC with steel bar and with GFRP were performed at different age of curing
- The GPC-steel bond strength values have been corrected by using the coefficient

$$\left(\frac{f_c}{f_{cREF}}\right)^{1/2}$$

Pull-out test Results

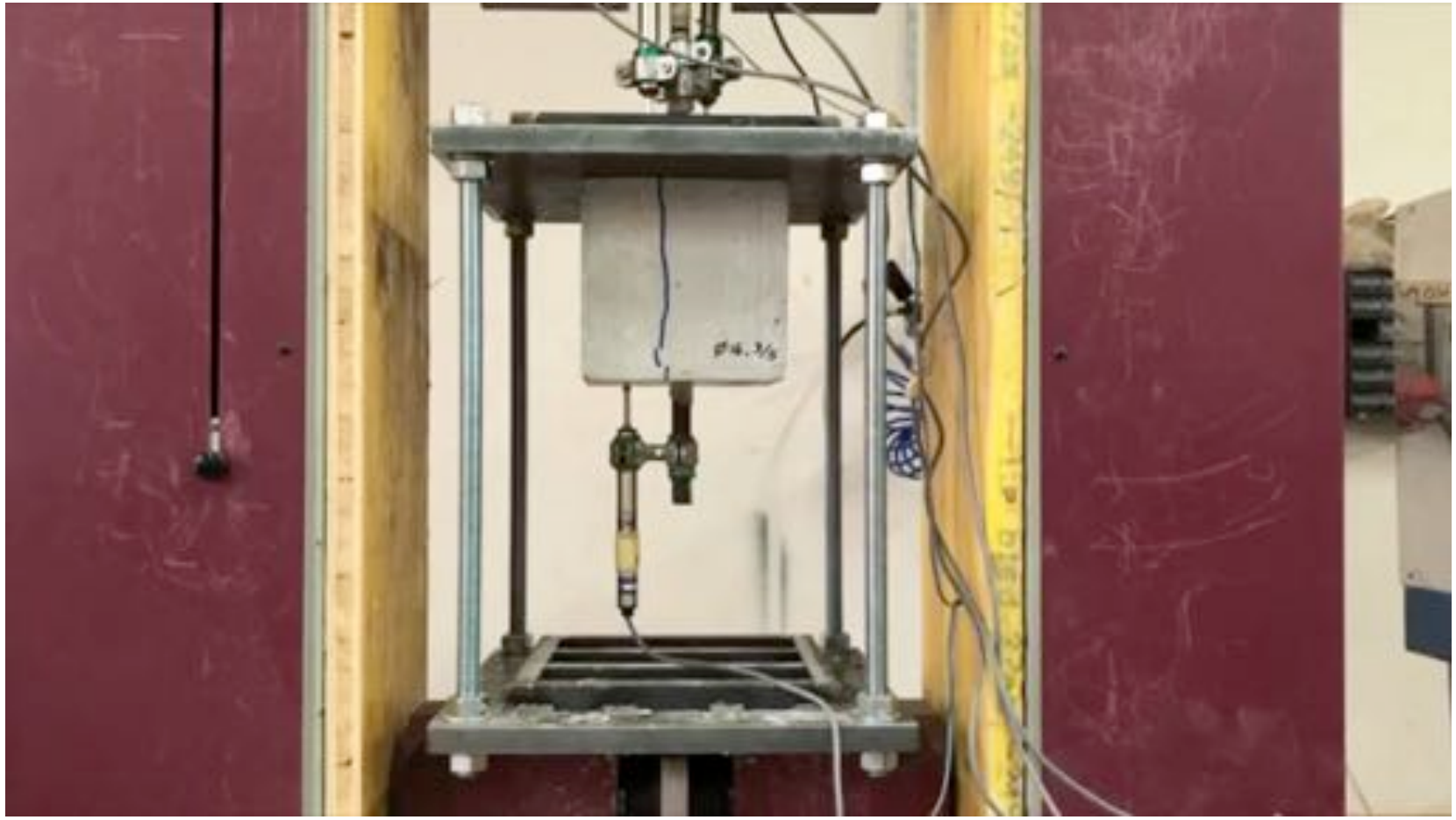
(ϕ12mm steel bar
ϕ12mm GFRP bar)

PULL-OUT FAILURE

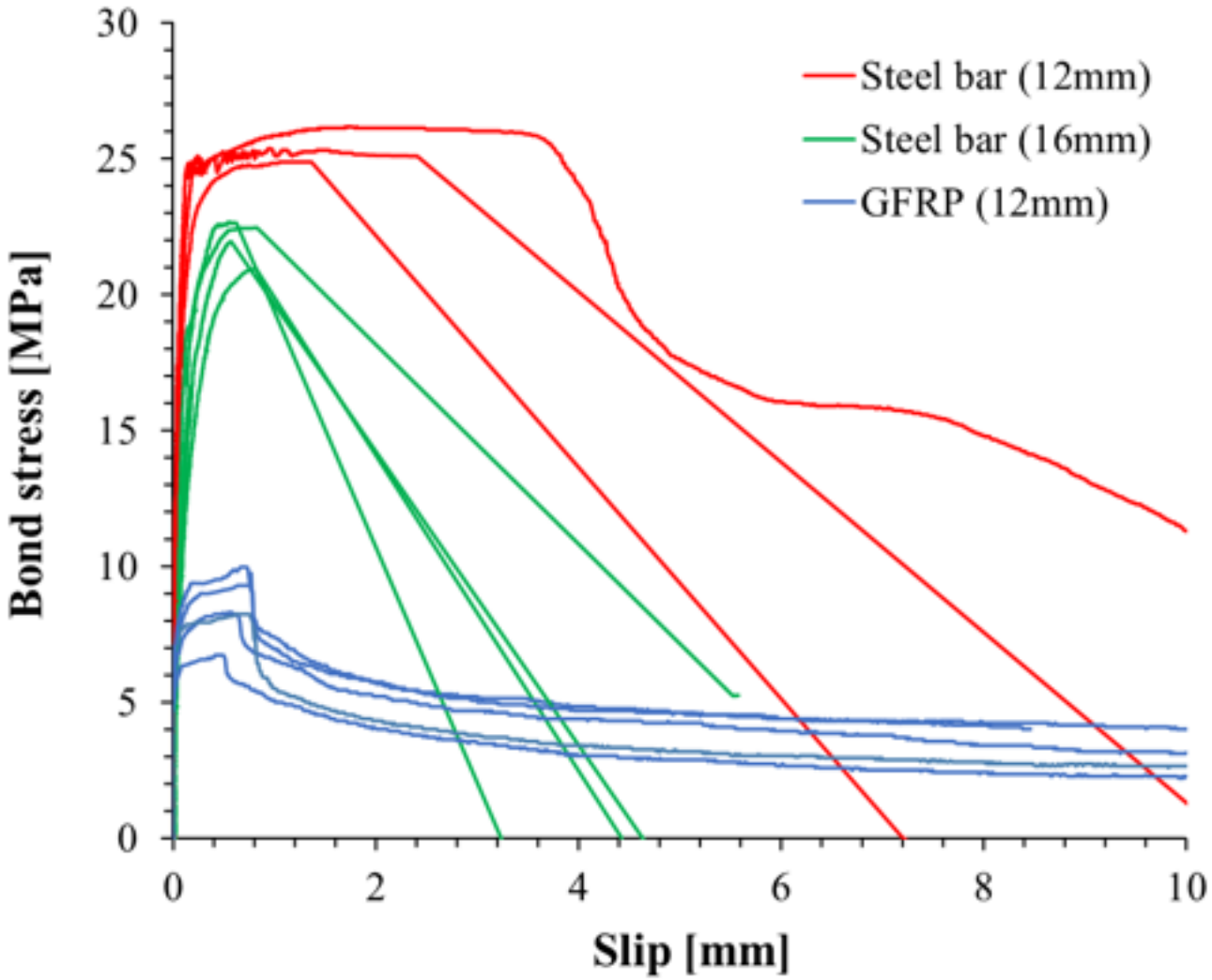
SPLITTING FAILURE

Pull-out test Results

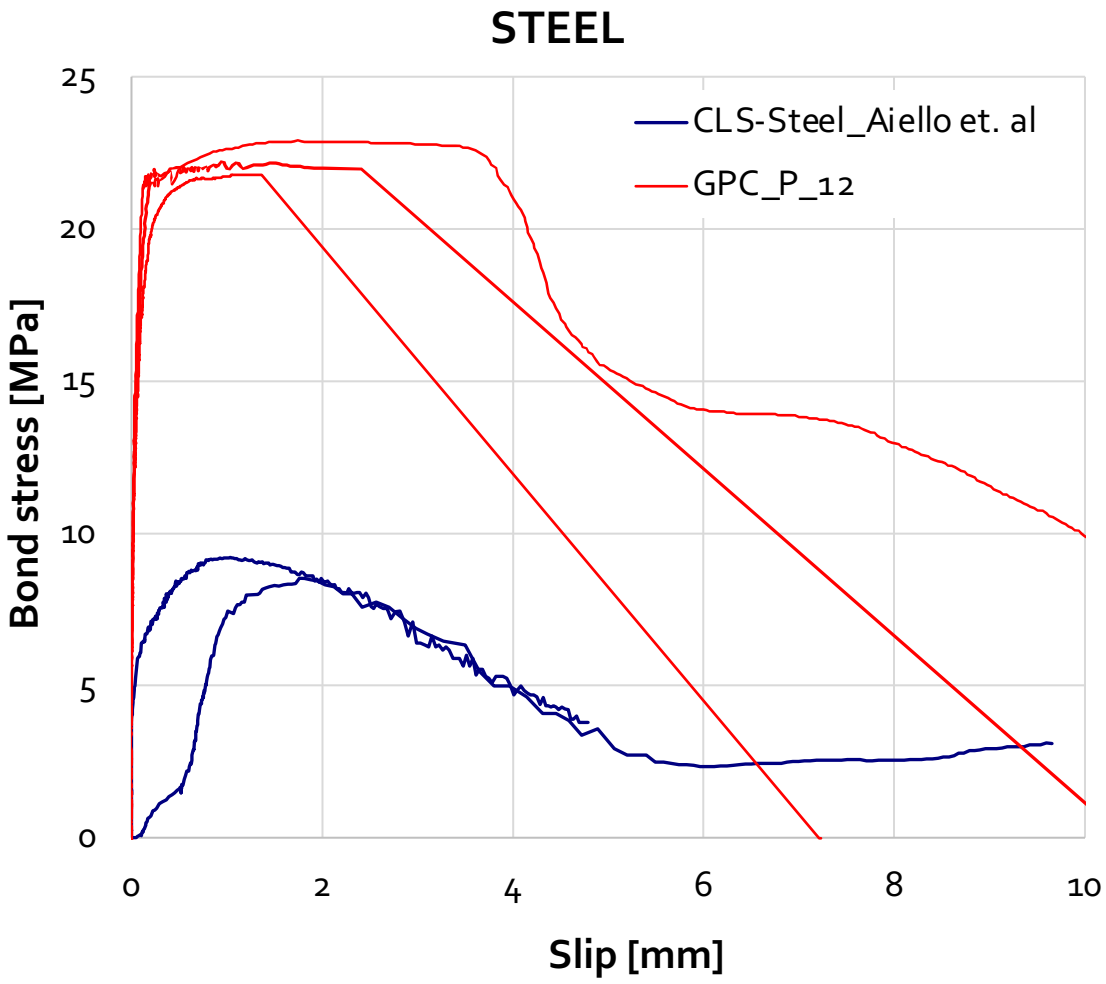
(ϕ16mm steel bar)

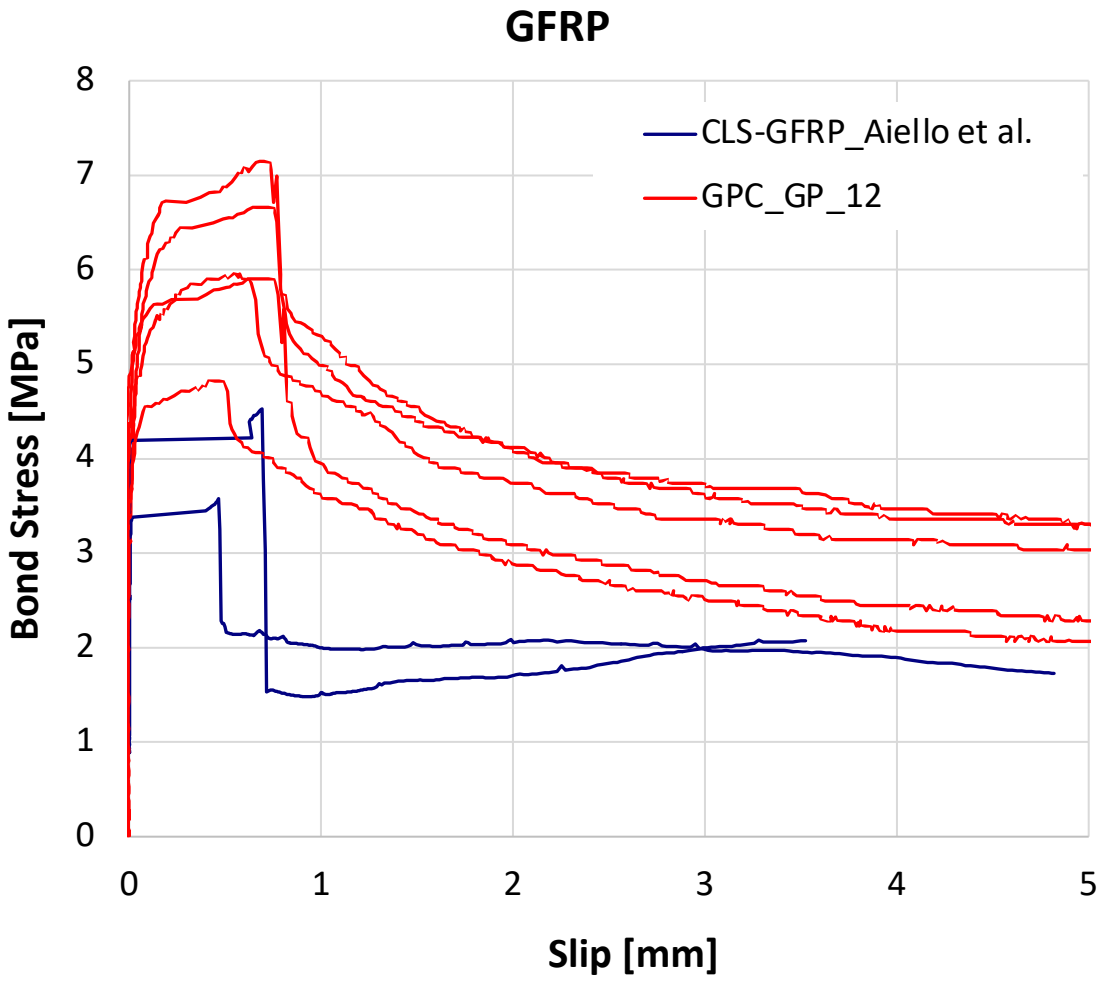


Comparison between steel and GFRP bar



Comparison with OPC – Aiello *et. al* (2010)





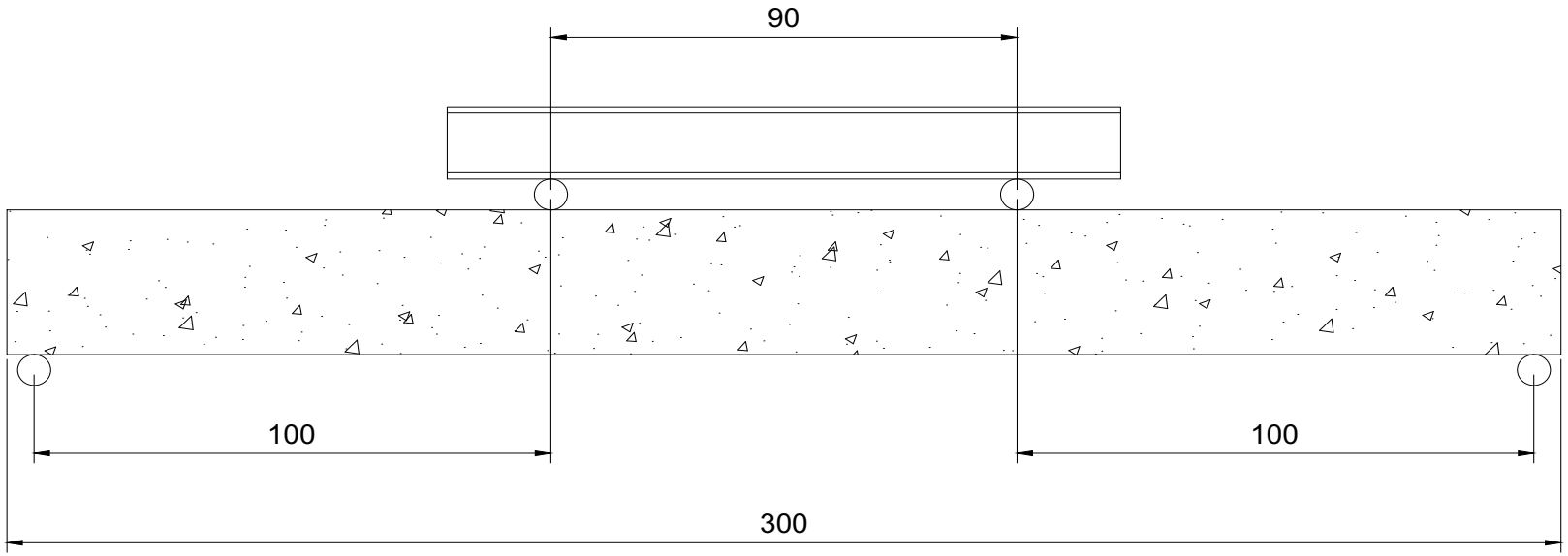
The average bond strength between GPC and deformed steel bar resulted about 48% higher than the corresponding value obtained for OPC

The average $\tau_{max,adj}$ between GPC and GFRP bars resulted about 55% higher than that obtained in case of OPC

Travi in calcestruzzo geopolimerico

Schema statico di prova

- Tipologia prova: Flessione su quattro punti
- Numero travi da testare: 1 OPC
  2 GPC



Travi in calcestruzzo geopolimerico

Work in Progress

Work in Progress

Travi in calcestruzzo geopolimerico

Calcestruzzi solfoalluminati

Campagna sperimentale

GOAL**: comportamento a breve e lungo termine* di ***elementi in calcestruzzo armato e non *realizzati mediante l'impiego di* ***cemento a base di calcio solfoalluminato (CSA) in miscela con Portland (OPC) al variare del rapporto OPC/CSA***

MISCELE DI CALCESTRUZZO					
Materials	**OPC**	**OPC+**	**70/30 OPC/CSA**	**50/50 OPC/CSA**	**100CSA**
	(kg/m^3)				
Sand	900	839	895	894	895
Gravel	963	900	957	955	957
CSA (i.tech ALICEM®)	-	-	102	170	340
CEM 42.5 II-A-LL	340	450	238	170	-
a/c	0.50	0.40	0.50	0.50	0.50

Campagna sperimentale

I. Proprietà allo stato fresco ed indurito delle miscele di calcestruzzo

I. CARATTERIZZAZIONE MISCELE					
1 gg	7 gg	28 gg	56 gg	90 gg	1 anno

II. Test di flessione su travi in calcestruzzo armato

III. Monitoraggio comportamento a lungo termine di travi in c.a. esposte all'azione combinata degli agenti atmosferici e di carico sollecitante di entità costante: 18 mesi, 60 mesi

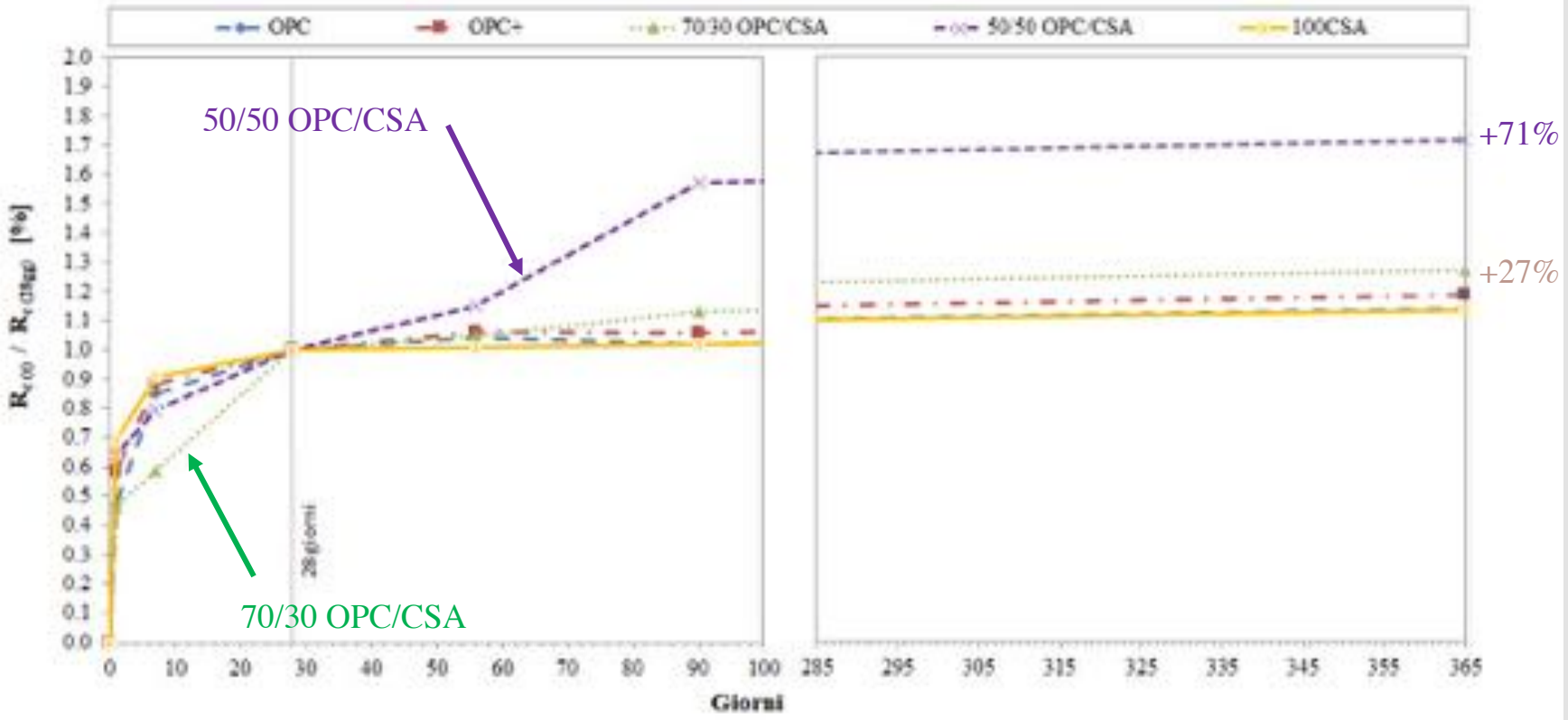
Proprietà allo stato indurito e fresco

- Resistenza a compressione, flessione, trazione indiretta, modulo elastico, slump, % aria

Mix	R_{cm} (MPa)						f_{cf} (MPa)	f_{ct} (MPa)		E_{cm} (MPa)		Slump (mm)	Air Perc. (%)
	Giorni												
	1	7	28	56	90	365	28	28	365	28	365		
OPC	17.8	31.4	36.9	38.5	37.6	42.1	4.0	2.8	2.8	28.7	30.1	220	1.2
OPC+	26.8	40.5	45.9	48.7	48.6	54.4	4.3	3.3	3.1	29.6	31.5	225	1.4
70/30 OPC/CSA	21.8	27.8	47.4	49.5	53.6	60.1	6.5	3.2	3.7	28.8	31.2	230	1.6
50/50 OPC/CSA	25.8	32.2	40.4	46.5	63.4	69.1	4.1	3.0	3.7	29.8	32.7	235	1.7
100CSA	44.0	57.6	63.5	64.1	64.7	72.1	8.8	3.4	3.2	31.6	35.8	235	1.8

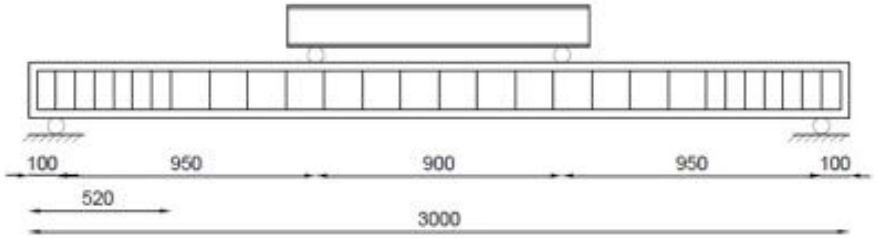
Proprietà allo stato indurito e fresco

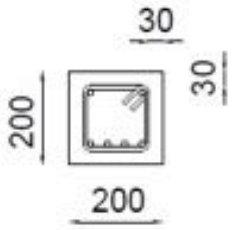
Sviluppo percentuale della resistenza a compressione rispetto al relativo valore valutato a 28 giorni di maturazione del getto

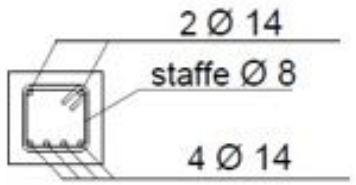


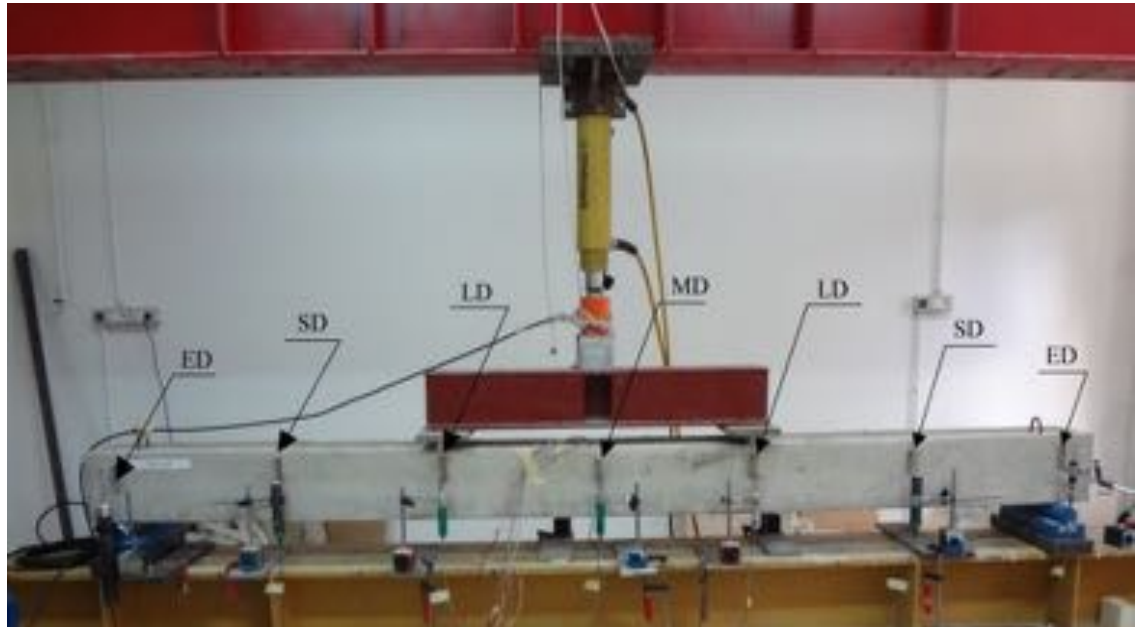
Test di flessione su travi in C.A.

- Test di flessione in configurazione quattro punti di carico









Test di flessione su travi in C.A.

Contemporaneo schiacciamento del corrente compresso e snervamento barre di armatura tese

Test flessione a 4 punti: step di carico (10kN, 20kN, 40kN, 50kN, rottura)

Trave	F_{max}	s_{max}	F_y	ε_s	ε_c
	kN	mm	kN	mm/mm	mm/mm
OPC	86.3	43.2	64.5	2.1%	3.7‰
OPC+	98.5	48.3	77.4	1.4%	3.0‰
70/30 OPC/CSA	98.4	64.7	67.8	2.2%	4.9‰
50/50 OPC/CSA	90.4	32.1	68.6	1.6%	3.0‰
100CSA	102.2	49.8	80.3	1.3%	3.4‰

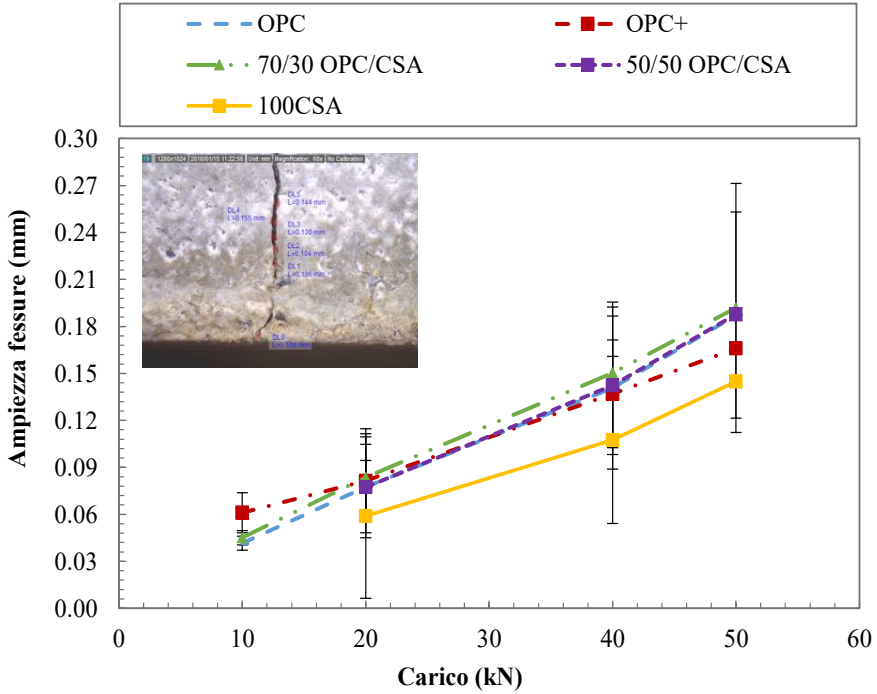
Trave 70/30 OPC/CSA: **elevata freccia in mezzeria** e **deformazione calcestruzzo al lembo compresso**

Trave 50/50 OPC/CSA: **minore freccia in mezzeria** e **deformazione del calcestruzzo al lembo compresso**

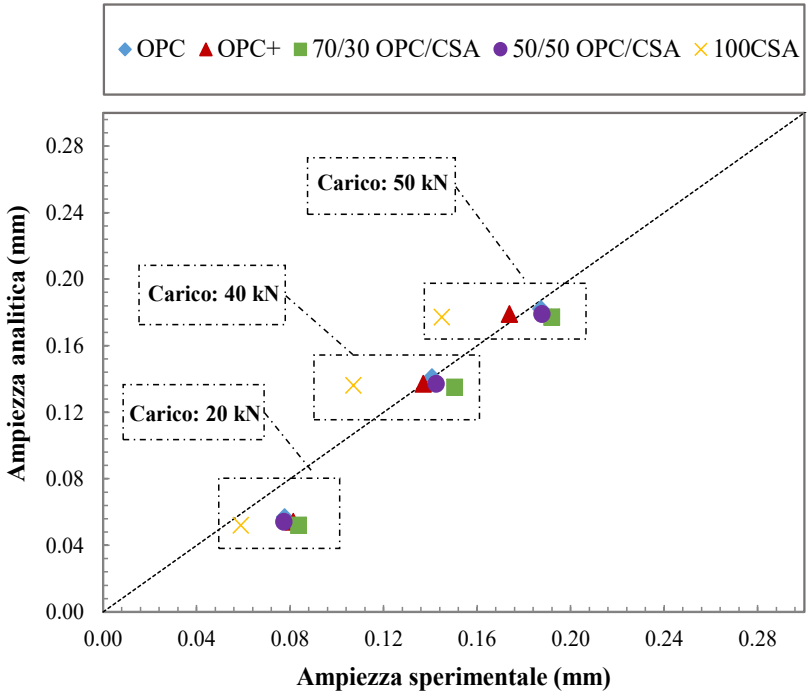
Test di flessione su travi in C.A.

- **Quadro fessurativo (zona M costante):** formulazione analitica (Model Code, 2010)

$$w_k = 2l_{s,max} \cdot (\varepsilon_{sm} - \varepsilon_{cm} - \varepsilon_{cs})$$



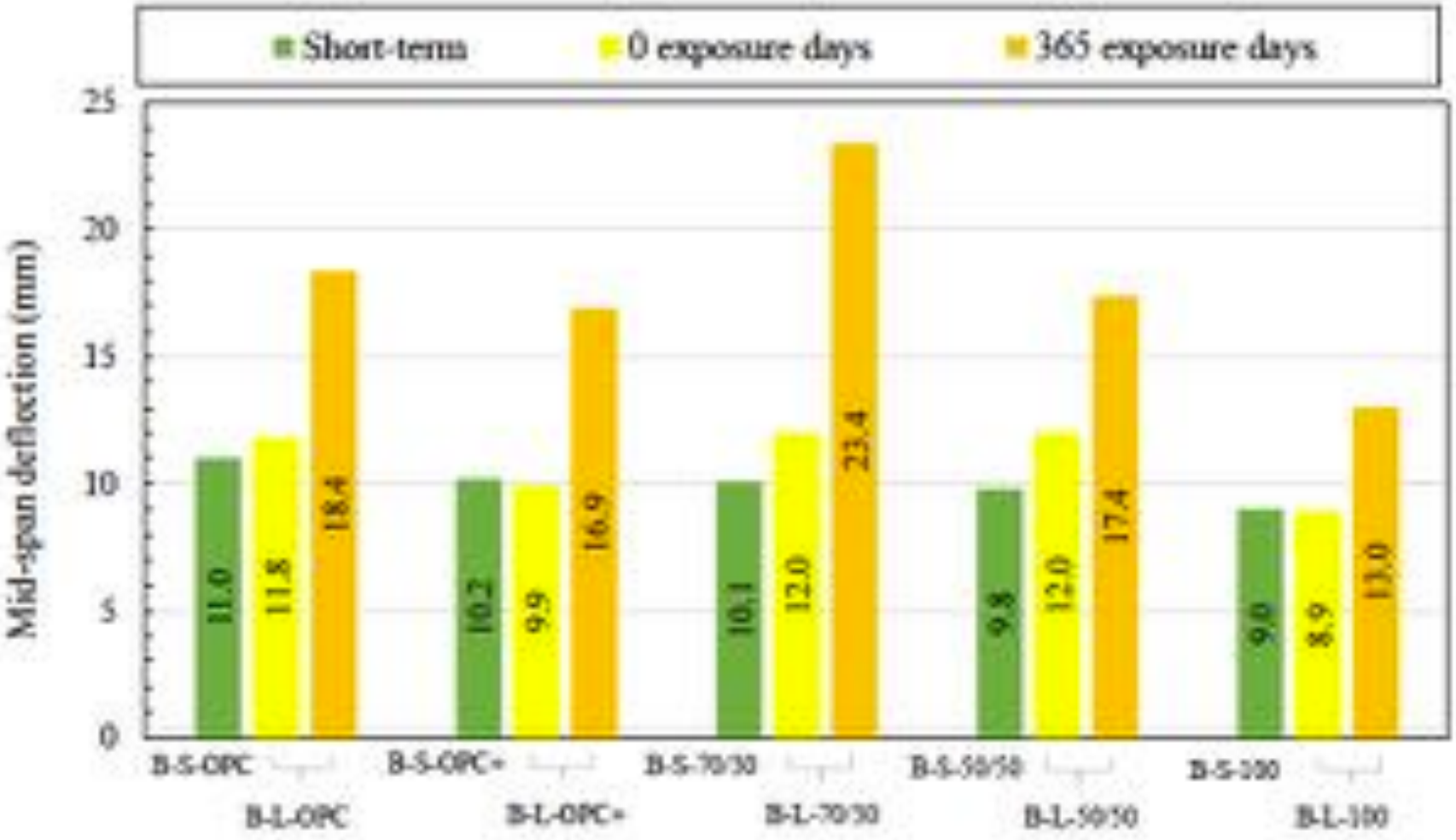
Ampiezza fessure sperimentali – step di carico



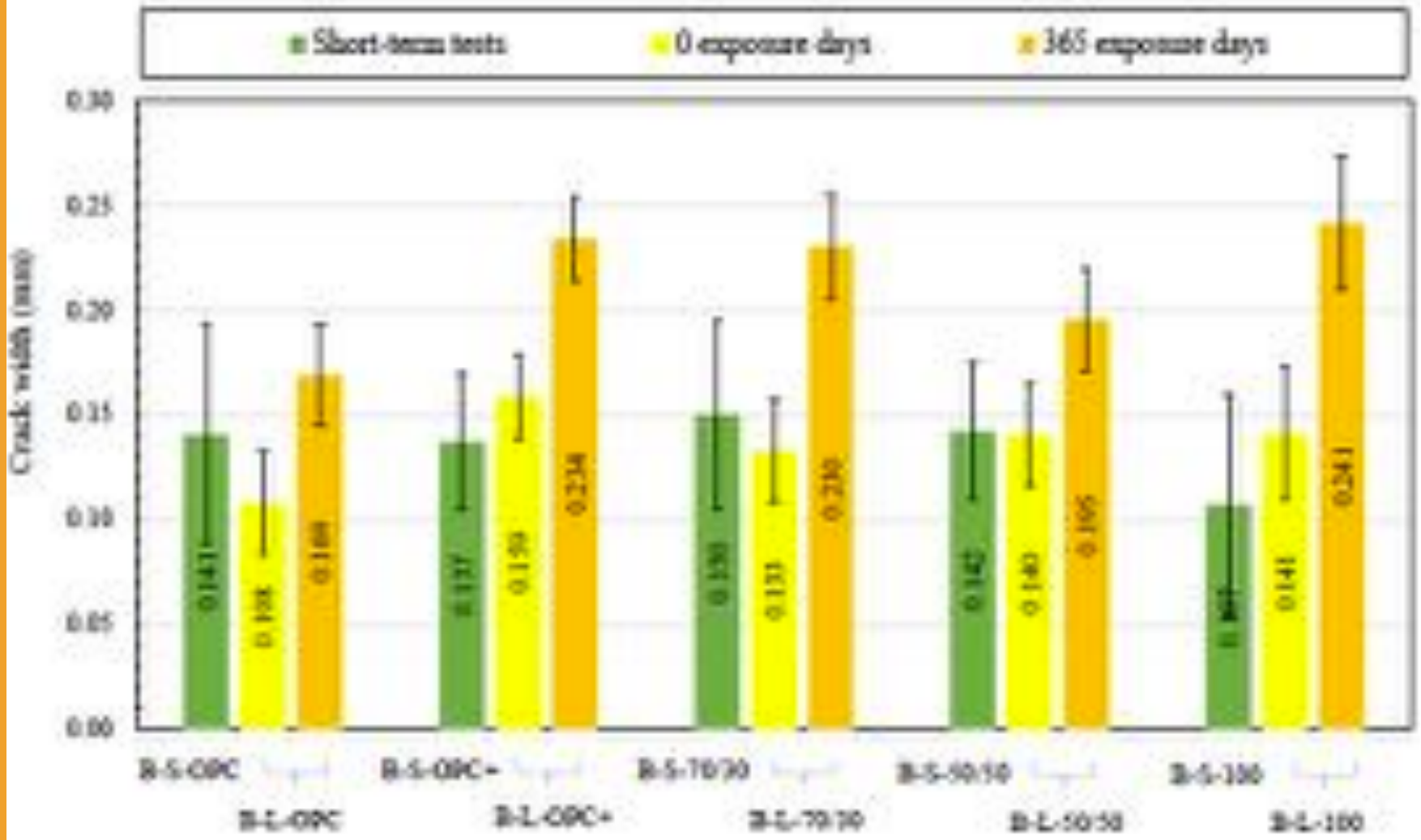
Confronto analitico - sperimentale

Comportamento a lungo termine travi in C.A.

Comportamento a lungo termine travi in C.A.

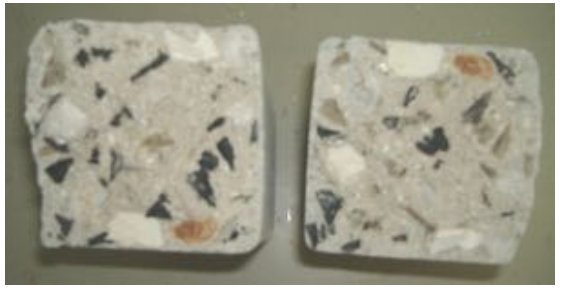


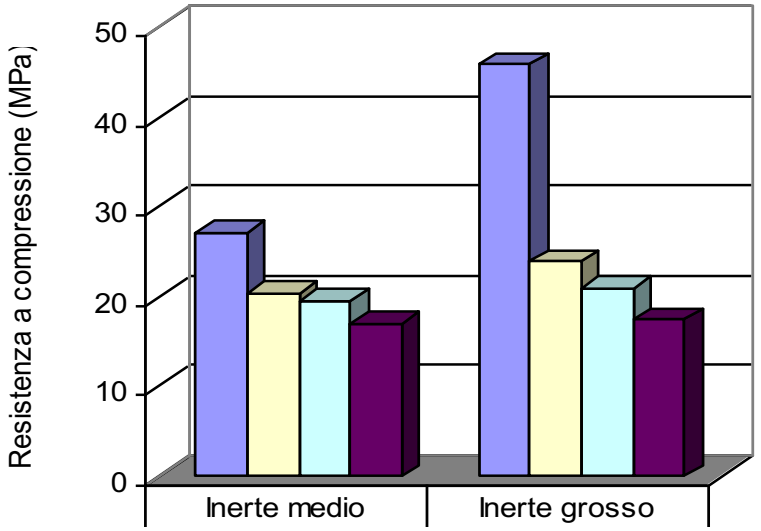
Comportamento a lungo termine travi in C.A.



Calcestruzzi con gomma derivante da PFU

Utilizzo della gomma





Preparazione del calcestruzzo con fibre in acciaio di PFU

MIX DESIGN

Fiber distribution

FRESH CONCRETE

Slump test
Air content
Density

Test sulle proprietà meccaniche

HARDENED CONCRETE

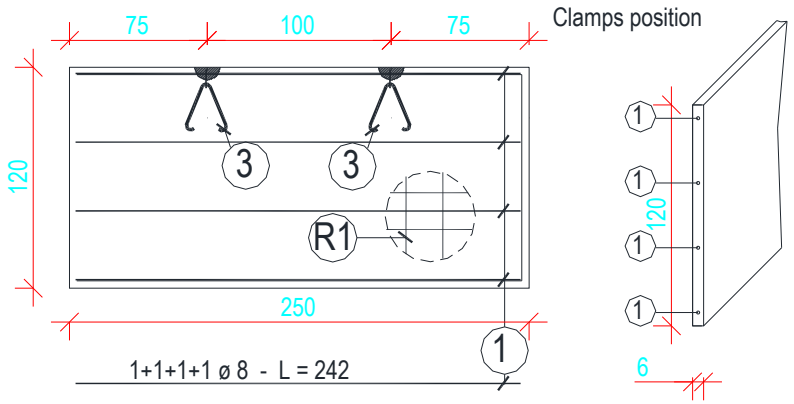
- Compression strength
- Tensile strength
- Flexural behaviour
- $\sigma-\varepsilon$ behavior
- Flexural tests on slabs
- Pull-out test

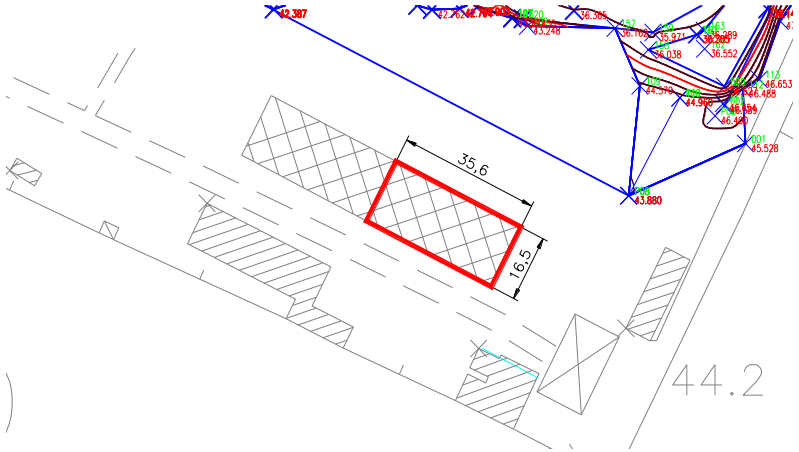
Obiettivo del progetto

PRECAST PANELS

CONCRETE PAVEMENT

Applicazioni dei pannelli

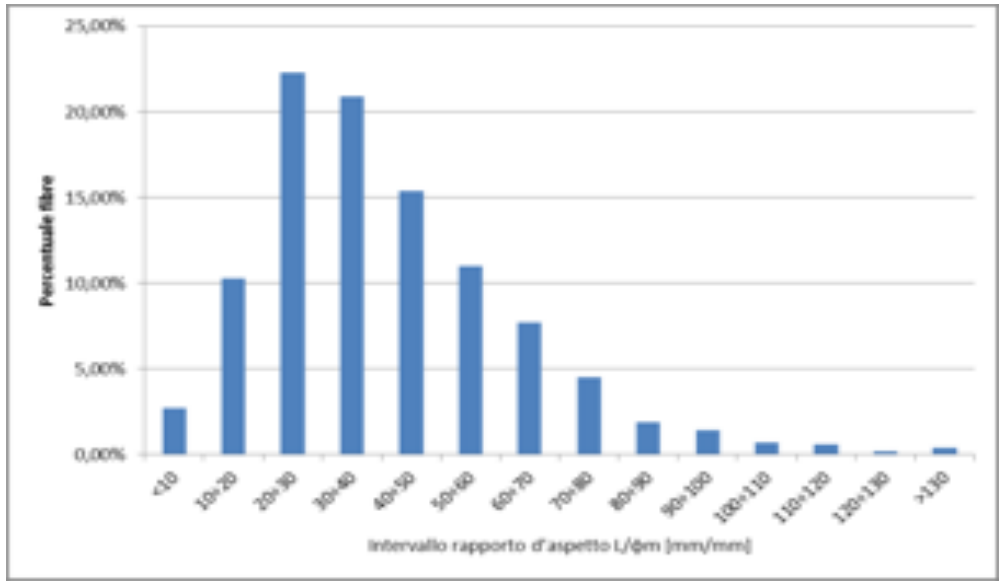


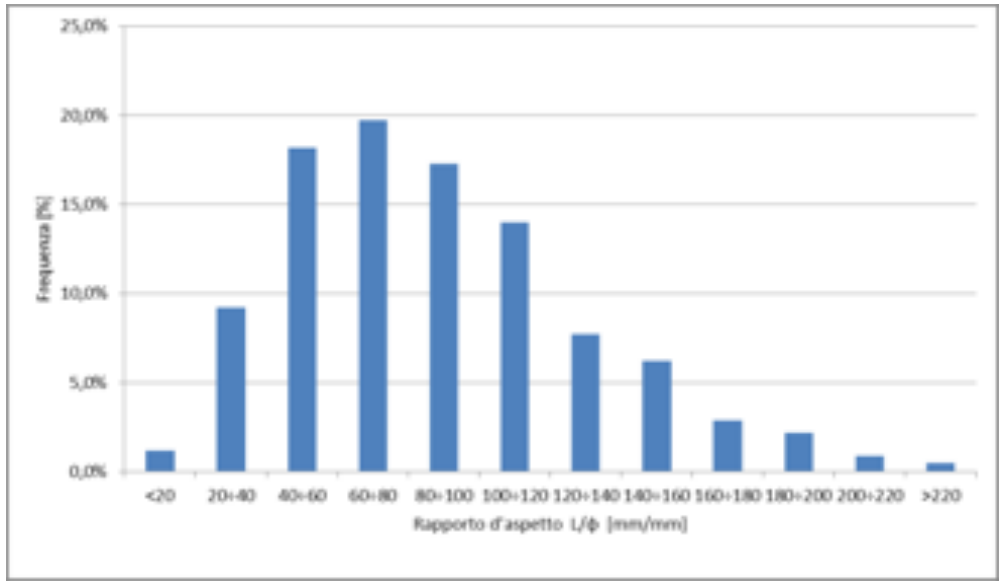


Realizzazione del mix

pavement	S3	pumpability	$R_{cm(28)}$=30 MPa
pannel	S4	$R_{cm(1)}$=35 MPa	$R_{cm(28)}$=55 MPa

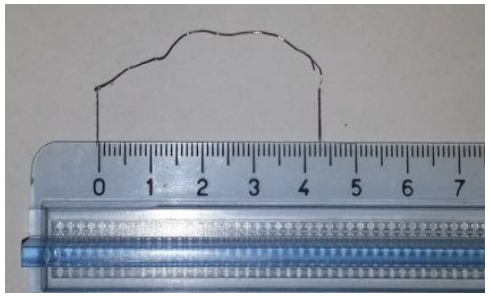
Realizzazione del mix





PAVEMENT

PANNEL



Realizzazione del mix

Components		Panel mix	
		PTQ	PP11
Sand (0-3.15)	[kg/m^3]	971	965
Aggregate I (3.15-8)	[kg/m^3]	342	340
Aggregate II (11.2-20)	[kg/m^3]	552	548
CEM II A-LL 42.5R	[kg/m^3]	380	380
Water	[l/m^3]	170	170
Fibre FC da PFU	[kg/m^3]	---	25
Water reducing admix.	[l/m^3]	3.20	3.25

Components		Pavement mix	
		PPTQ	PP11
Sand (0-4)	[kg/m^3]	1160	1168
Aggregate I (4-8)	[kg/m^3]	219	205
Aggregate II (8-16)	[kg/m^3]	457	482
CEM II A-LL 42.5R	[kg/m^3]	300	300
Water	[l/m^3]	180	180
Fly ash	[kg/m^3]	60	65
Fibre FT da PFU	[kg/m^3]	---	20
Water reducing admix.	[l/m^3]	3.00	3.70

Proprietà allo stato fresco

Properties	Panel mix		Pavement mix	
	PC	RFRC	PPTQ	PP11
Slump [mm]	210	205	190	200
Fluidity grade	S4	S3	S4	S4
Entrapped air [%]	2.2	1.9	3.2	2.7
Fresh density [kg/m^3]	2400	2425	2387	2416

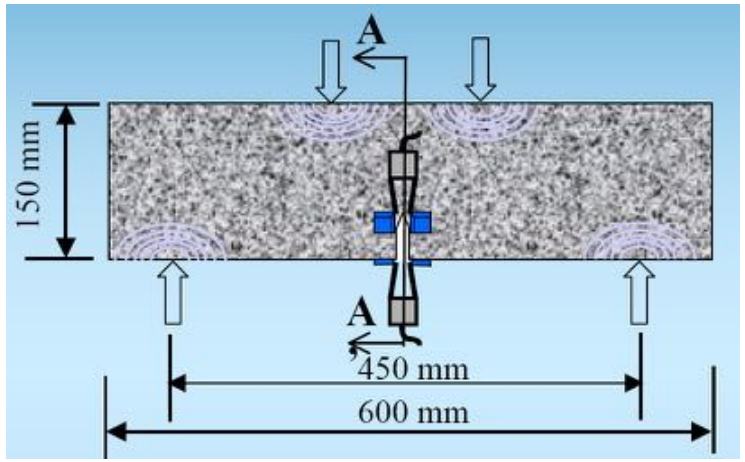
UNI EN 12350

Proprietà allo stato indurito

Compressive strength		Panel mix		Pavement mix	
		PC	RFRC	PC	RFRC
R_c (1 day)	[MPa]	36.8	37.0	---	---
R_c (28 day)	[MPa]	55.7	60.0	43.6	47.8

UNI EN 12390

Proprietà allo stato indurito



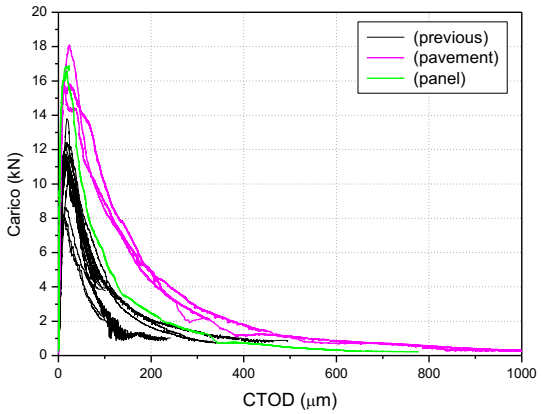
UNI EN 11039

Notched beam: (150 x 150 x 600 mm)

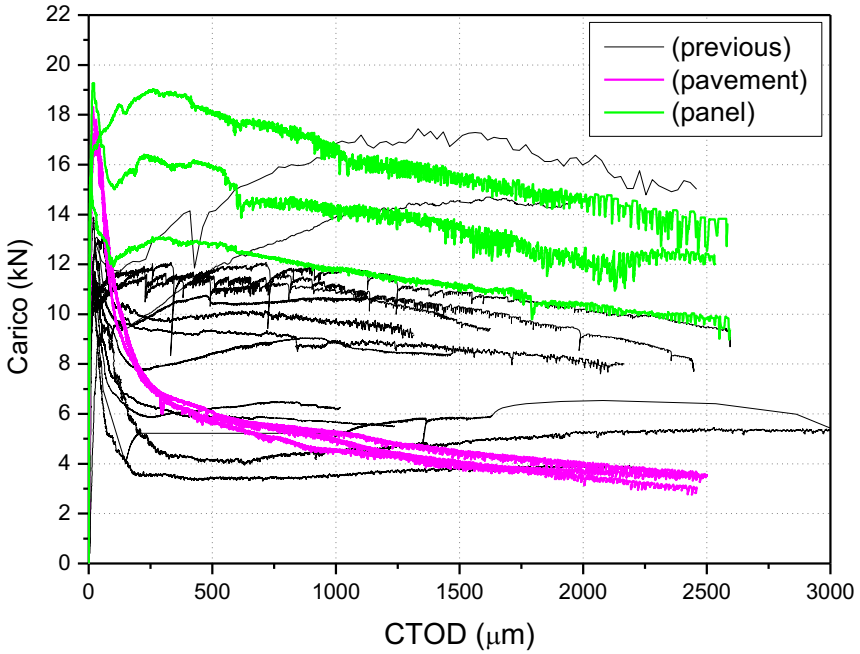
Notched dimension: a_0/b = (0.3±0.01); 3 mm ≤ W_{notch} ≤ 5 mm

Crack mouth opening displacement control **CMOD** (50 μm/min)

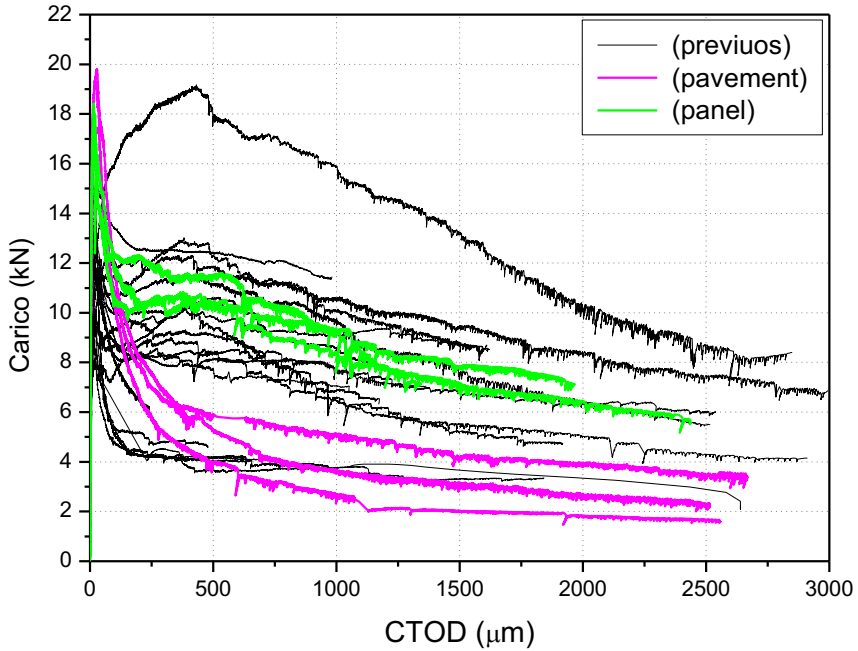
Proprietà allo stato indurito



Plain



Industrial FRC



Recycled FRC

Proprietà allo stato indurito

Applicazione Pavimentazioni

Applicazione Pavimentazioni

Applicazione Pannelli sottili

Applicazione Pannelli sottili

GRAZIE
PER LA VOSTRA ATTENZIONE

Marianovella Leone
Dipartimento di ingegneria dell'Innovazione
Università del Salento

marianovella.leone@unisalento.it