University of Sheffield

STRUCTURES IN FIRE FORUM

Mitigation and Mechanism Study of Fire Spalling of Concrete with Recycled Tyre Fibres

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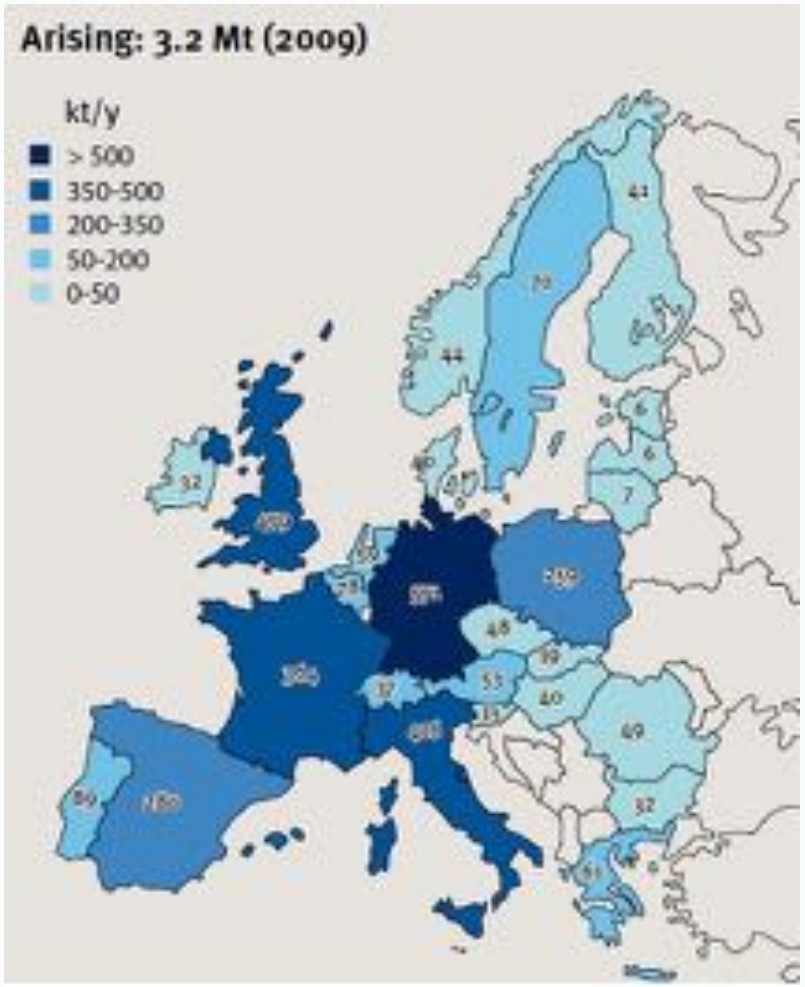
Why recycled tyre fibres?

Waste tyres and recycled fibres

- Every year, **1.5 billion waste tyres** produced globally
- In Europe, **3.5 million tons** of waste tyres
- In each tyre, 15 % steel and 5 % polymer
- Compared with virgin fibre, only ~ **10 % of the embedded carbon** for recycled fibre

Source: https://imgur.com/RY8RFK3



Annual used tyres in Europe

Source: https://www.etrma.org/

Fibre properties

Properties	Density (kg/m^3)	Tensile strength (MPa)	Melting point (°C)	Length (mm)	Diameter (mm)
Virgin Steel Fibre	7800	1225	--	60	0.75
RTSF	7800	2000	--	15 - 35	0.16 - 0.35
Virgin PP Fibre	910	--	160	12	0.032
RTPF	500	--	230 - 250	0.8 - 16	0.008 – 0.06

Virgin steel fibre

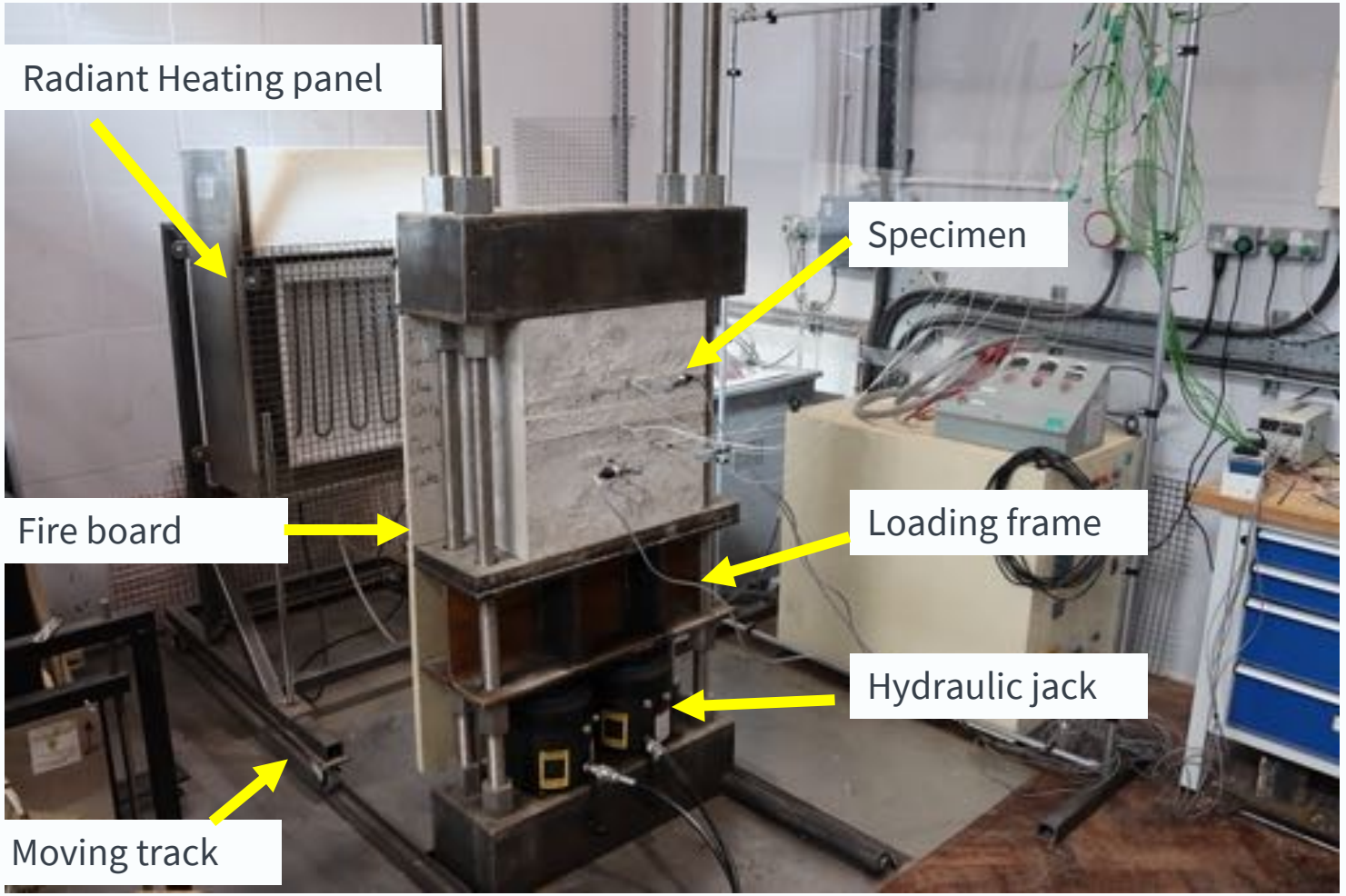
Recycled tyre steel fibre (RTSF)

Virgin PP fibre

Recycled tyre polymer fibre (RTPF)

Are recycled fibres effective in controlling fire spalling?

Fire spalling test setup



Test Conditions	
Load ratio to compressive strength (%)	30 / 10
Load type	Uniaxial compression
Heat curve	ISO 834 Standard curve
Exposure face	One-sided exposure
Exposure time (min)	30
Maximum surface temperature (°C)	830

Specimen list

Specimen type	Name	Fibre dosage of 30kg/m³	Stainless steel grade	Cover depth (mm)	Repeats
Slab	S1	--	1.4401	30	1
	S2	Virgin steel	1.4401	30	3
	S3	RTSF	1.4401	30	3
	S4	--	1.4401	15	1
	S5	RTSF	1.4401	15	3
	S6	--	1.4462	30	1
	S7	RTSF	1.4462	30	1
	S8	--	1.4462	15	1
Column	C1	--	1.4401	30	1
	C2	Virgin	1.4401	30	2
	C3	RTSF	1.4401	30	2
	C4	--	1.4401	15	1
	C6	--	1.4462	30	1
	C7	RTSF	1.4462	30	2
	C8	--	1.4462	15	1

Table 1: Test group for virgin steel fibre vs. RTSF

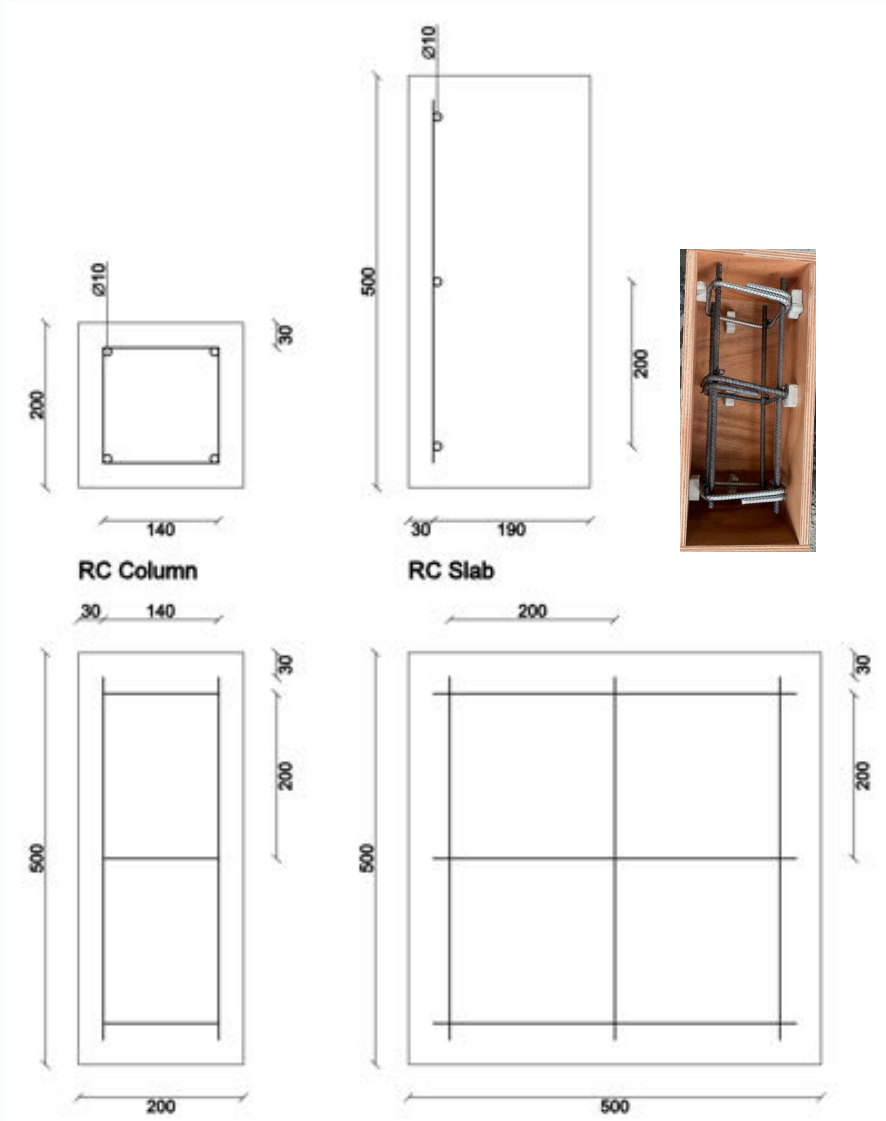
Concrete age	Name	RTPF dosage (kg/m³)	PPF dosage (kg/m³)	Loading ratio (%)	Pressure gauge	Thermo couple Tree	28-day Compressive Strength (MPa)	Test day compressive strength (MPa)
6 years	PC_a	--	--	30	--	yes	48.6	61
	PC_b	--	--	30	--	yes		
	R2_a	2	--	30	--	yes	49.4	59
	R2_b	2	--	30	--	yes		
	PC_c	--	--	30	yes	yes		
	PC_d	--	--	10	yes	--	58.6	64.2
	PC_e	--	--	10	--	--		
4 months	R1_a	1	--	30	yes	--	58.8	62.5
	R1_b	1	--	10	yes	yes		
	R2_c	2	--	10	yes	yes	51.8	55.1
	V1_a	--	1	10	yes	yes	51.3	54.6
	V1_b	--	1	10	yes	--		

Table 2: Test group for virgin PP fibre vs. RTPF

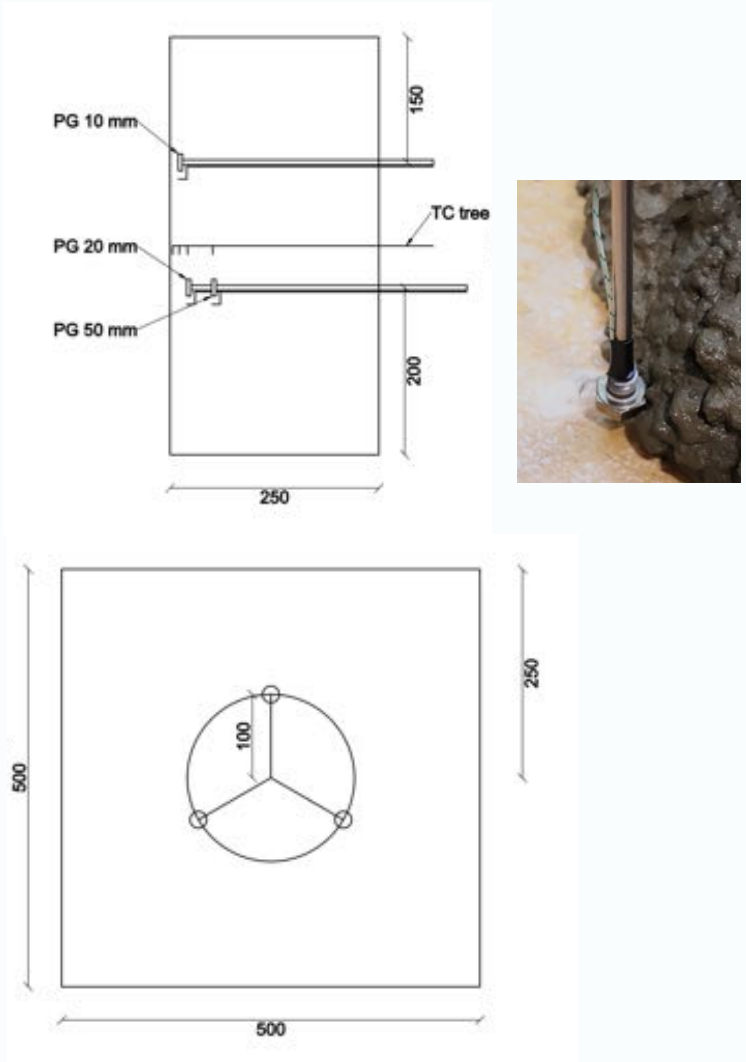
Specimen layout

Slab specimen

Column specimen

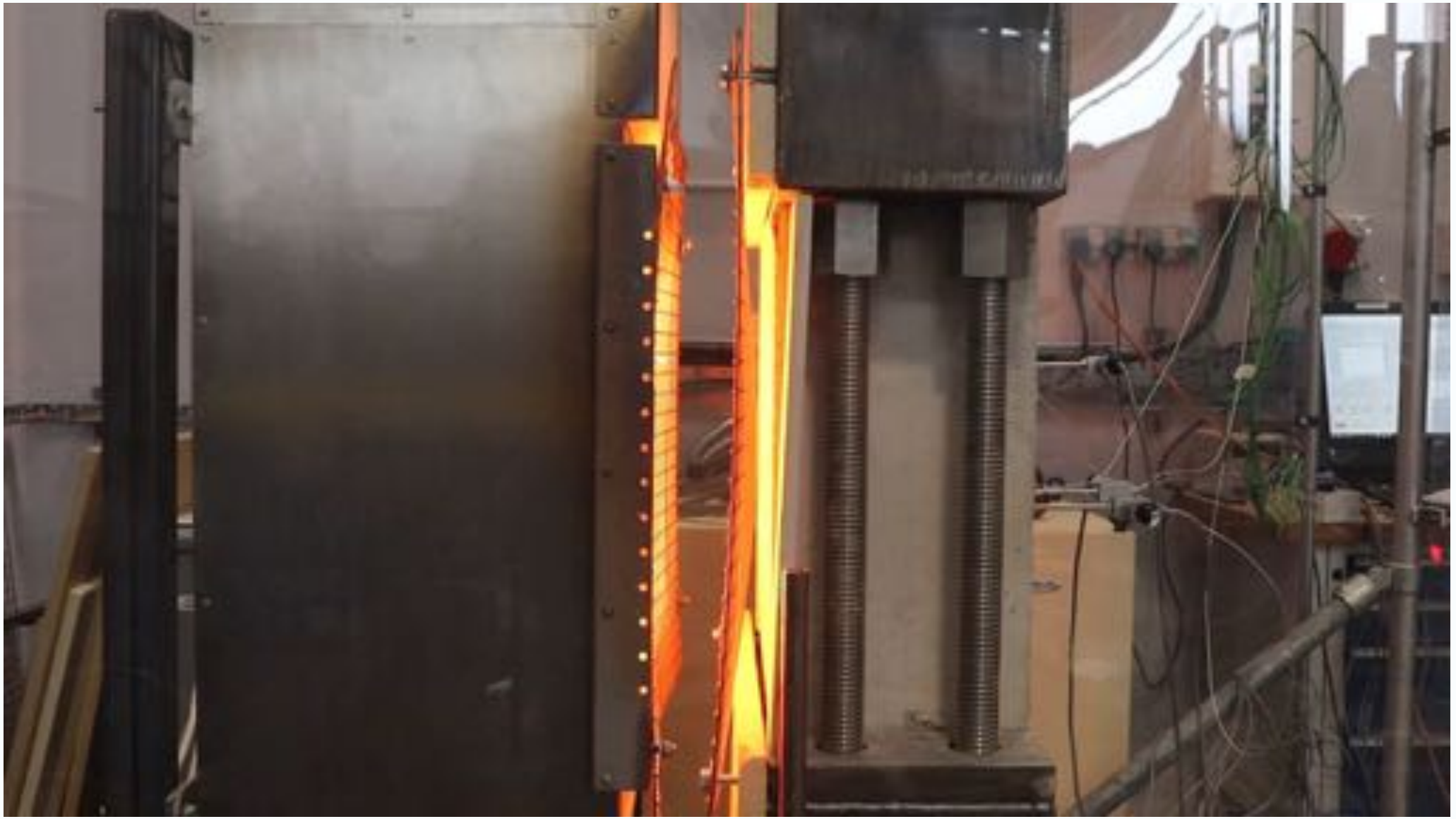


Group 1: virgin steel fibre vs. RTSF



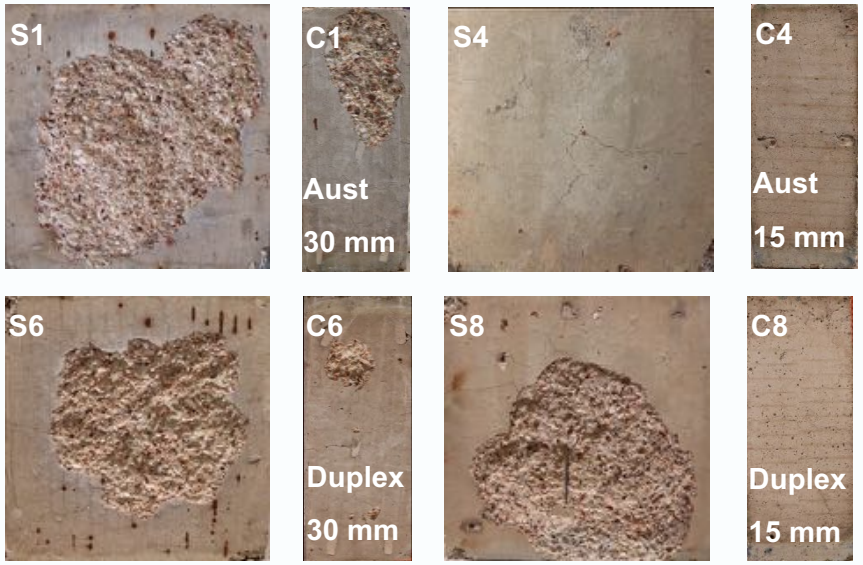
Group 2: virgin PP fibre vs. RTPF

Spalling test in progress

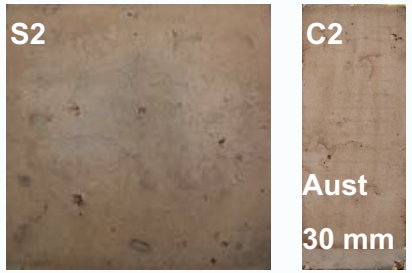


Spalling test result: virgin steel fibre vs RTSF

Plain concrete



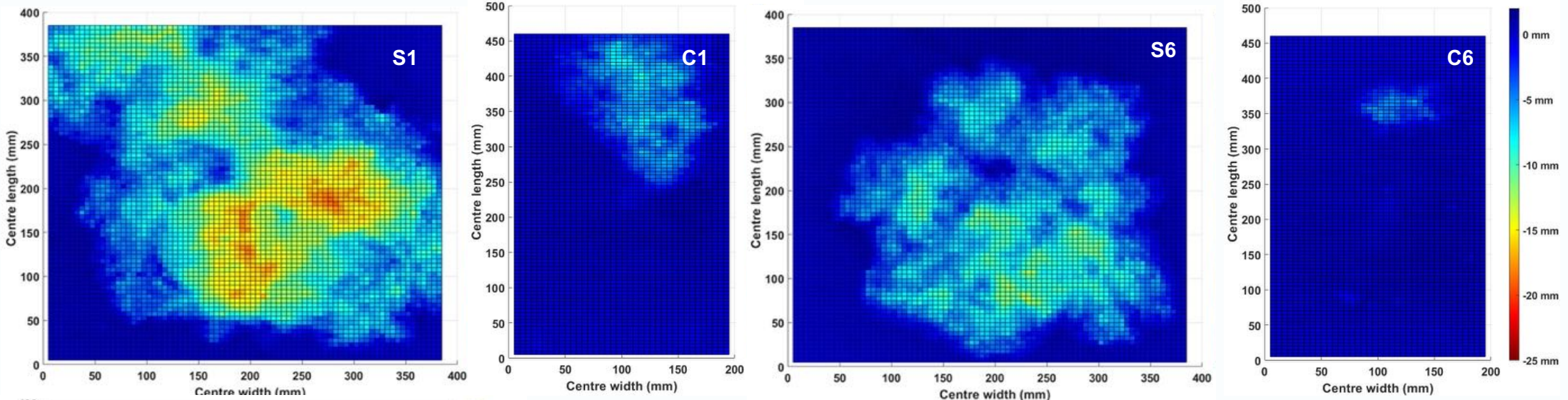
Virgin steel fibre



RTSF

Spalling test result analysis

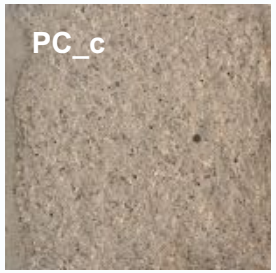
Laser scanned surface profile

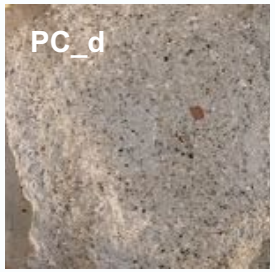


Sample name	Spalling type	First spalling time	Spalling times	Spalling Weight loss (kg)	Maximum spalling depth (mm)	Average spalling depth (mm)	Size of spalled pieces (cm)
S1	Explosive	05:25	9	2.17	19.04	6.08	5
S6	Explosive	07:06	5	1.04	12.86	2.83	3
S8	Explosive	10:24	2	2.25	24.76	5.94	10
C1	Explosive	05:39	2	0.22	8.91	0.88	4
C6	Explosive	07:30	1	0.03	5.86	0.04	3
C2	None	-	-	-	-	-	-
Others	Aggregate	-	-	-	-	-	-

Spalling test result: virgin PP fibre vs RTPF

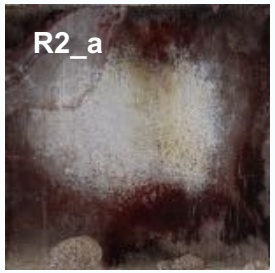
Plain concrete

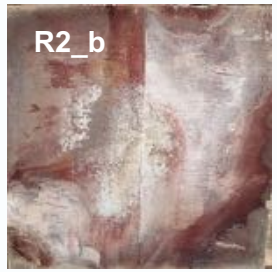


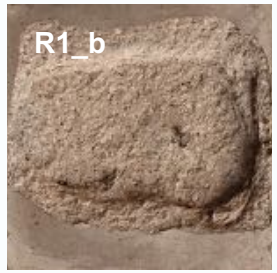


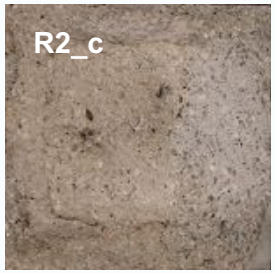
Virgin PP fibre

RTPF



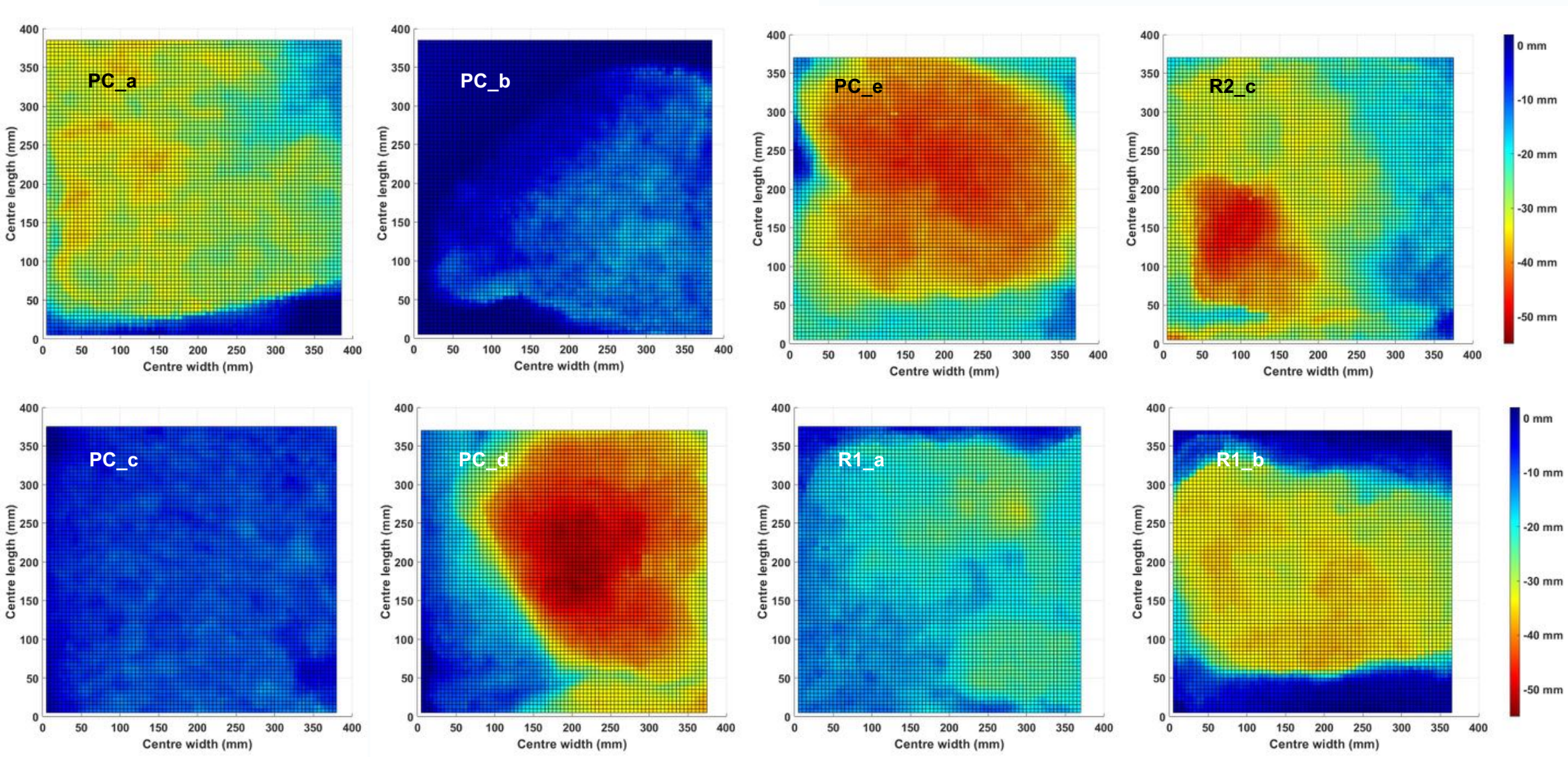






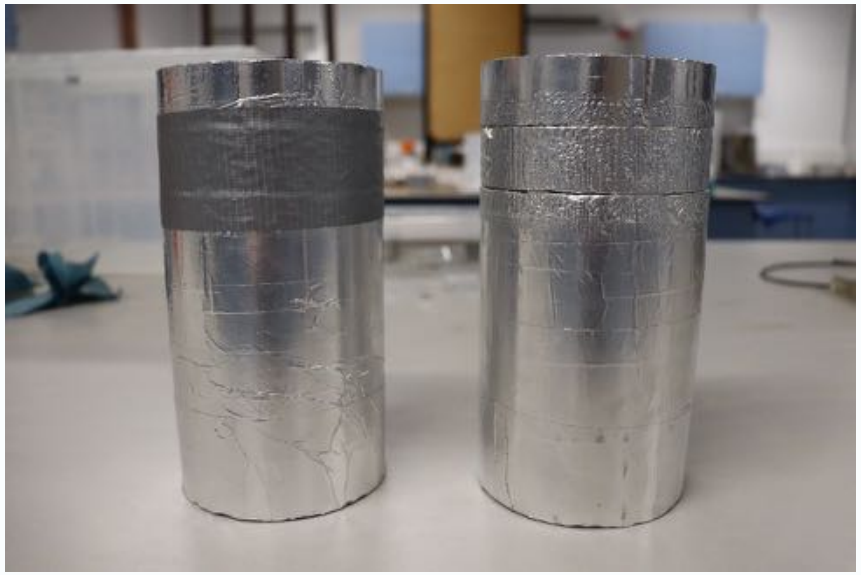
Spalling test result analysis

Laser scanned surface profile



Spalling test result analysis

Sample name	Surface moisture content (%)	Deep Moisture content (%)	Peak pore pressure (kPa)	First spalling time (min)	Number of Spalling	Spalling Weight loss (kg)	Maximum spalling depth (mm)	Average spalling depth (mm)
PC_a	3.7	4.5	--	08:40	5	9.46	37.1	26.6
PC_b			--	06:40	2	2.25	16.9	6.3
R2_a	3.1	4.4	--	--	--	--	--	--
R2_b			--	--	--	--	--	--
PC_c	5.6	7.7	70	13:30	1	3.02	14.9	8.8
PC_d			140	11:10	50	10.6	53	31.9
PC_e			--	14:10	72	11.15	46.5	33.9
R1_a	4.6	8.1	210	13:00	6	6.1	31.7	18.3
R1_b			170	11:20	12	7.6	38.2	23.4
R2_c	4.6	8.6	120	10:30	12	9.27	48	27.8
V1_a	5.4	7.1	410	--	--	--	--	--
V1_b			610	--	--	--	--	--



- Cylindrical specimens for moisture content
- Cut at 25 and 50 mm
- Side surface sealed
- Cast, cured and dried in the same condition

Conclusions

Group 1:

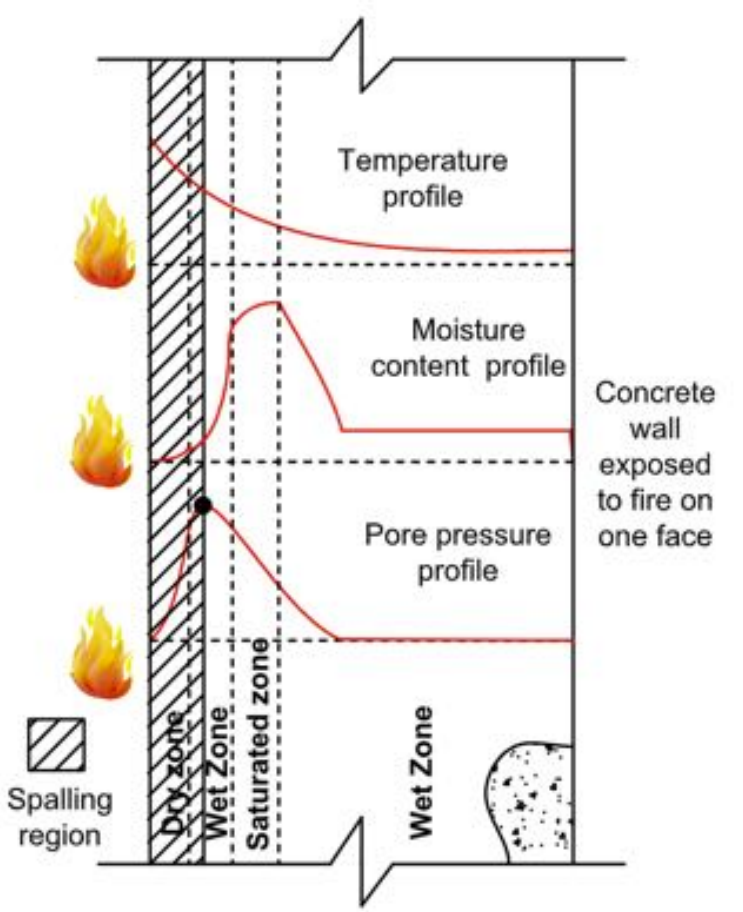
- Both virgin steel fibre and RTSF are effective to mitigate fire spalling at 30 kg/m^3
- Spalling are more severe in large slabs compared to columns
- The use of duplex stainless rebar could delay spalling time

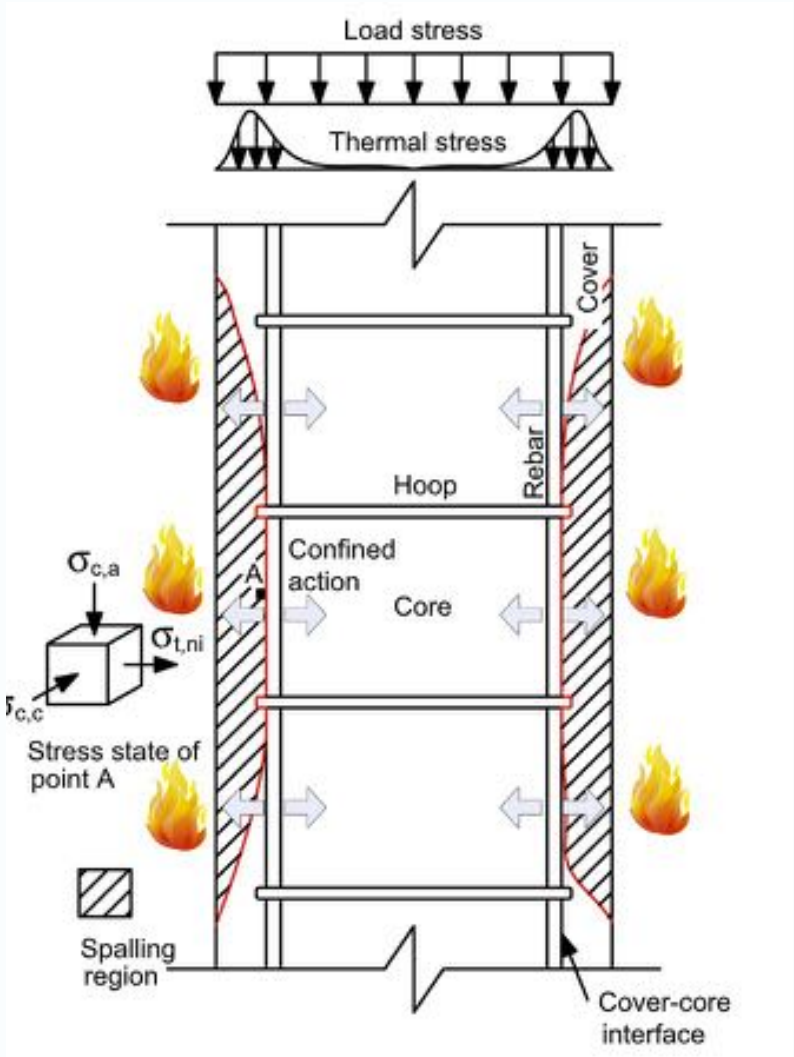
Group 2:

- Virgin PP fibre are the most effective fibre for mitigating fire spalling at low dosage of 1 kg/m^3
- RTPF is less effective but still offers some benefits

What is the mechanism of fire spalling? And the role of polymer fibres?

Mechanism of fire spalling





However, lack of experimental data on:

- Presence of moisture clog
- Moisture distribution
- Porous structure investigation
- Influence of fibres on both mechanisms

Thermo-hydral mechanism

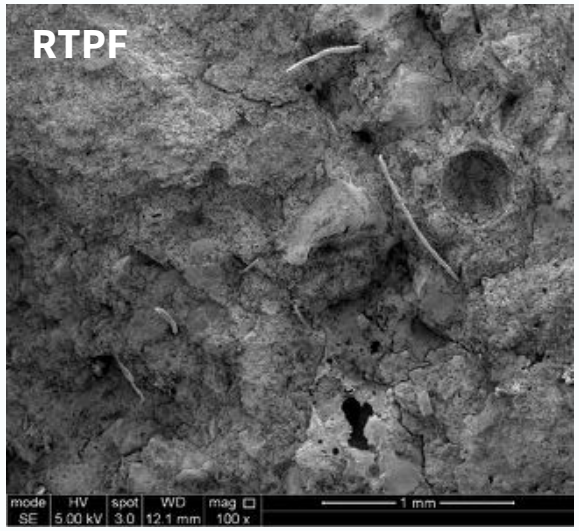
Thermo-mechanical mechanism

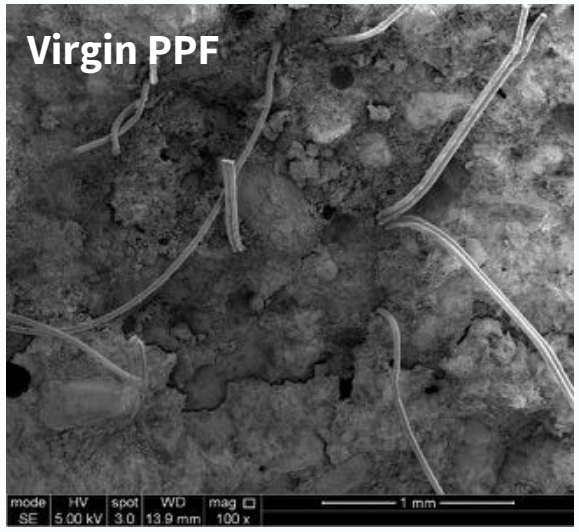
Source: Jin-Cheng Liu, Kang Hai Tana, Yao Yao, 2018 doi.org/10.1016/j.conbuildmat.2018.06.204

Investigation methods of heated concrete with fibres

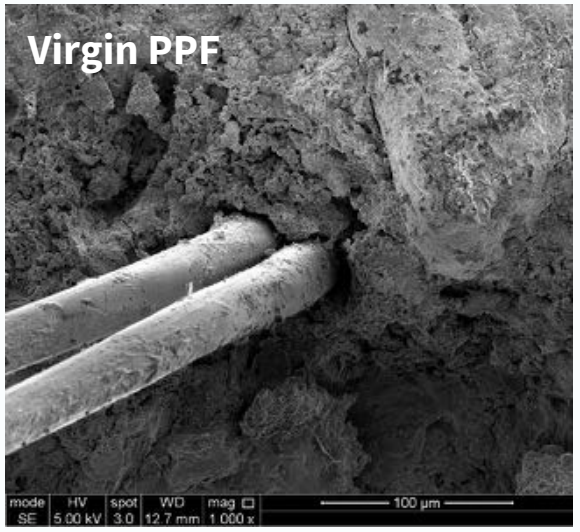
- SEM

Distribution

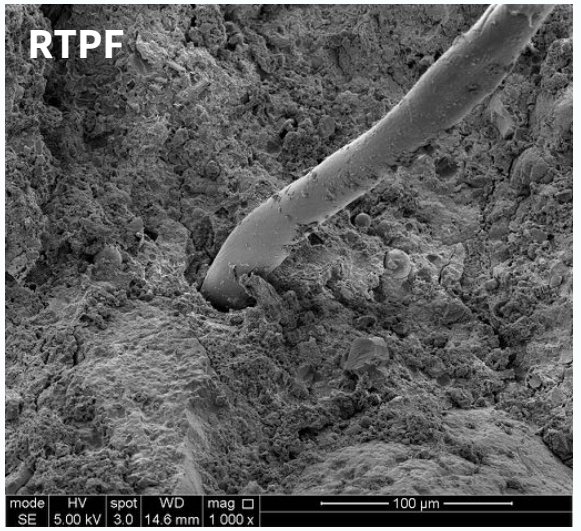


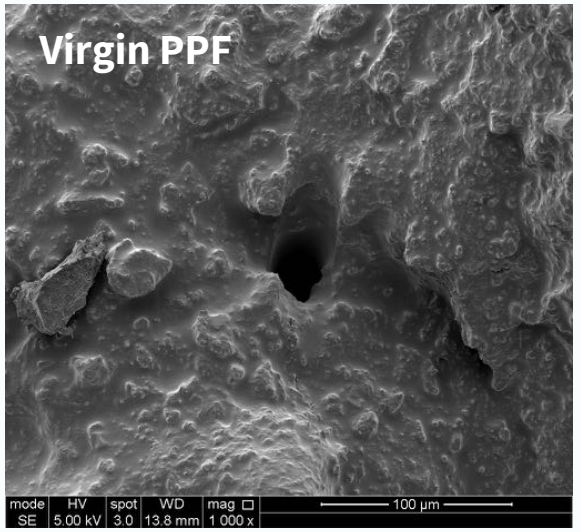


Zoom-in



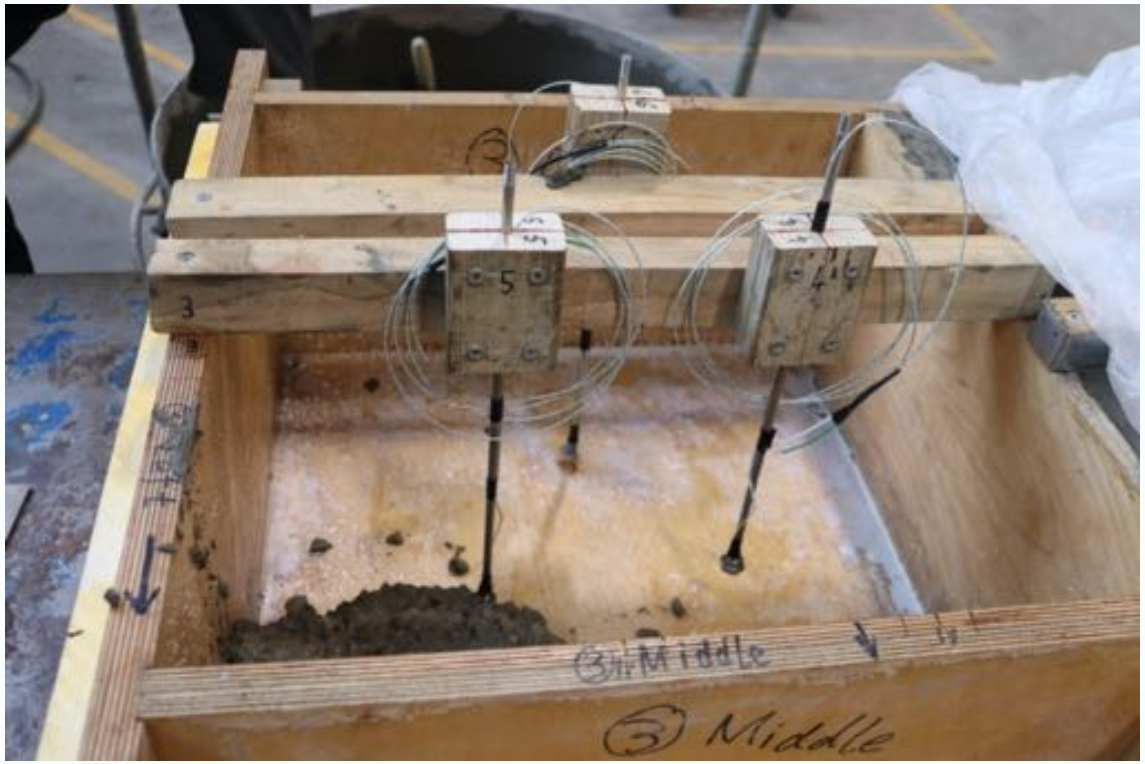
Post heating at 200°C



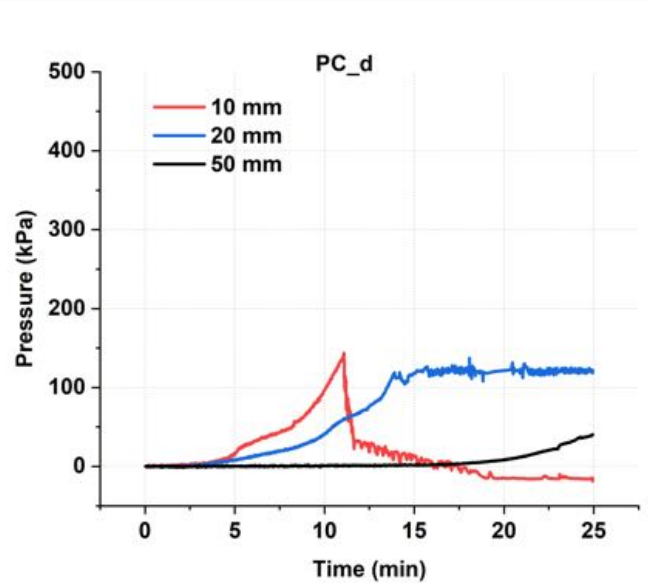


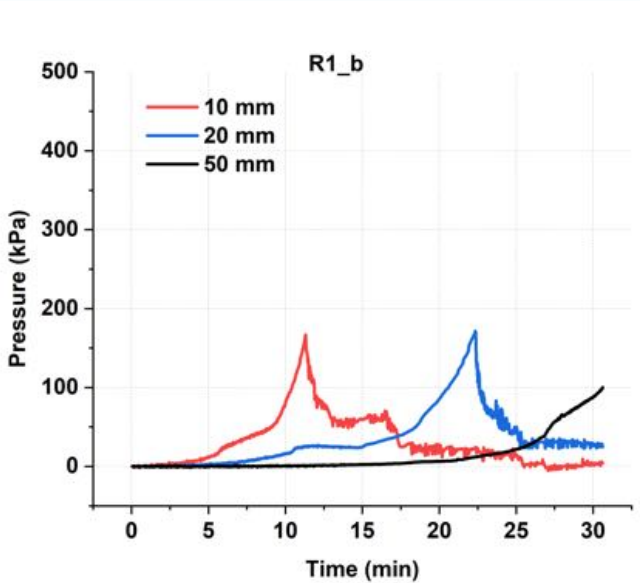
Investigation methods of heated concrete with fibres

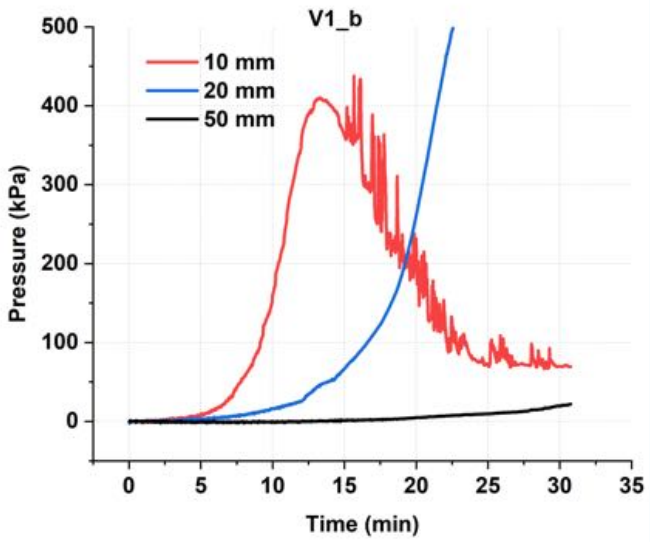
- PTM (pressure, temperature, mass loss)

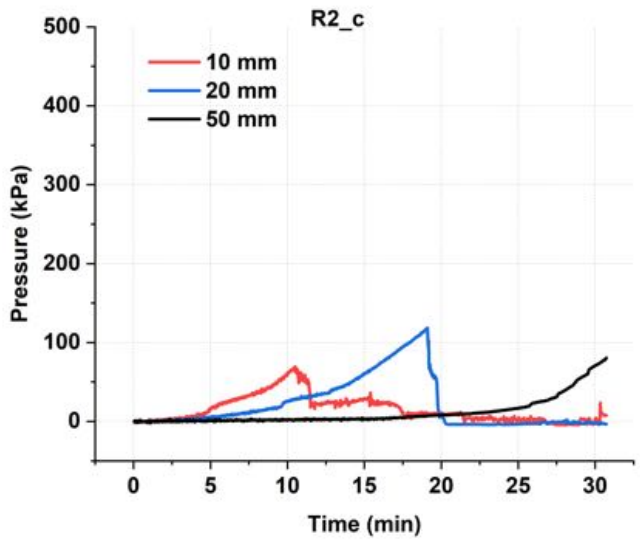


Pore pressure measurement

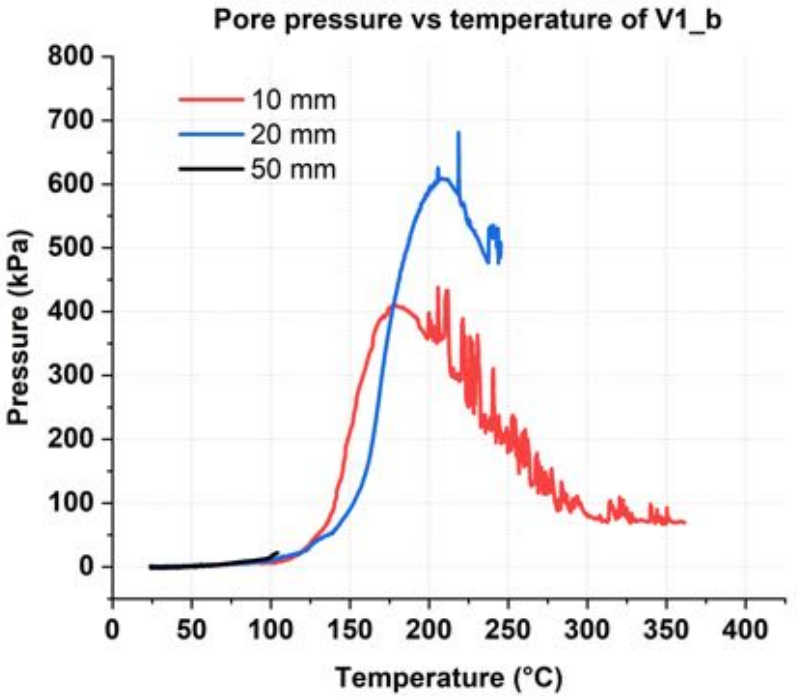








- The peak pressure on other specimens is below 0.2 MPa
- The spalling stops the pressure increase further
- Pressure peaked at melting

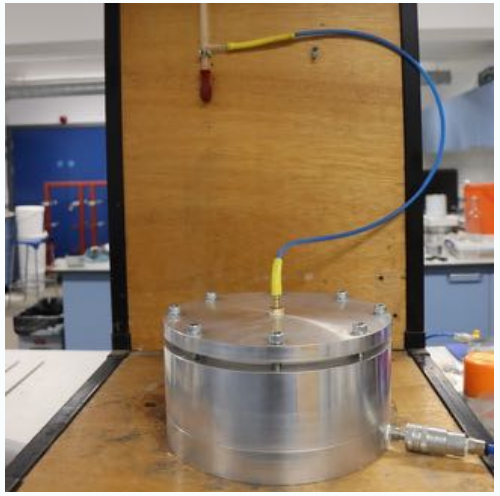


Investigation methods of heated concrete with fibres

- Permeability after 200 ° C heating

Measured using cylindrical specimens with grinded surface to remove the cement layer.

The post heating permeability was measured when concrete cooled naturally.



Air permeability coefficient (m^2)				
Sample name	PC	R2	R1	V1
Before heating	8.26E-17	6.34E-17	6.76E-17	6.80E-17
After heating	2.45E-16	1.66E-16	2.01E-16	5.98E-16

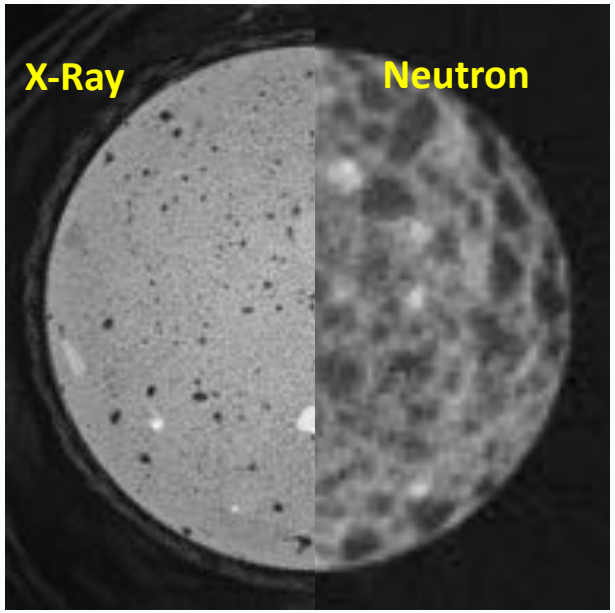
Melting of virgin PP fibre increase the permeability, un-melted RTPF controlled the thermal crack.

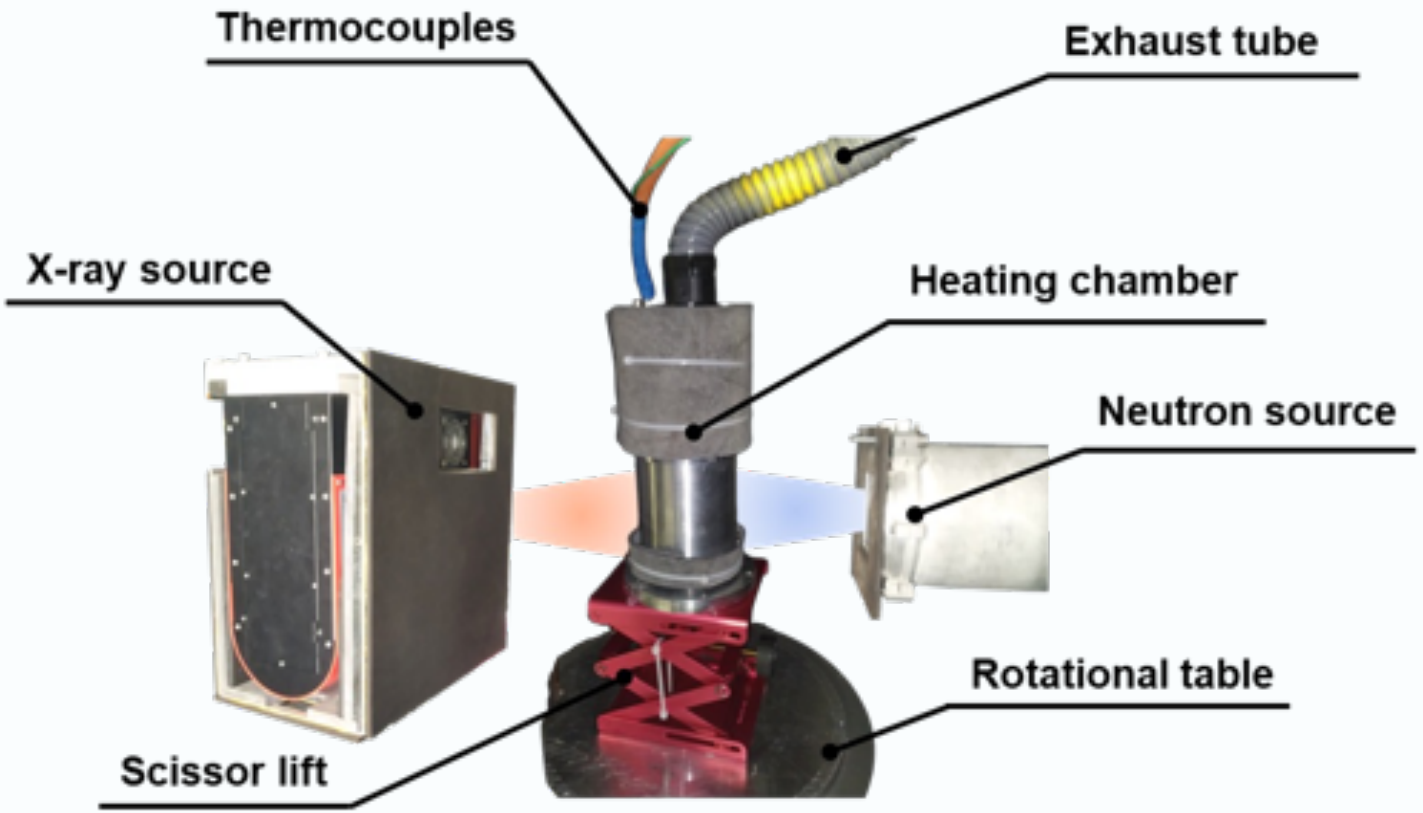
Investigation methods of heated concrete with fibres

- Neutron and X-ray tomographies

Neutron sensitive for moisture

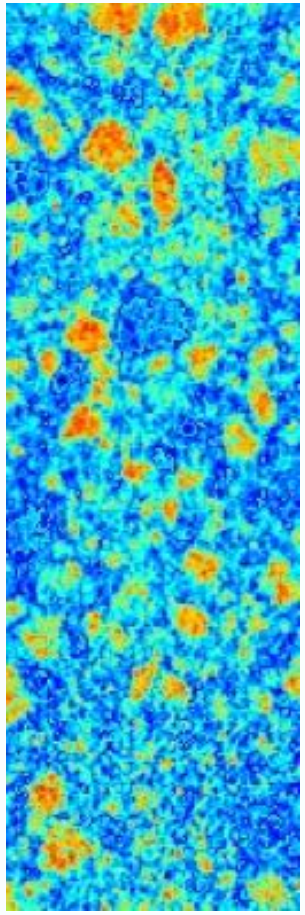
X-ray sensity for pore structure





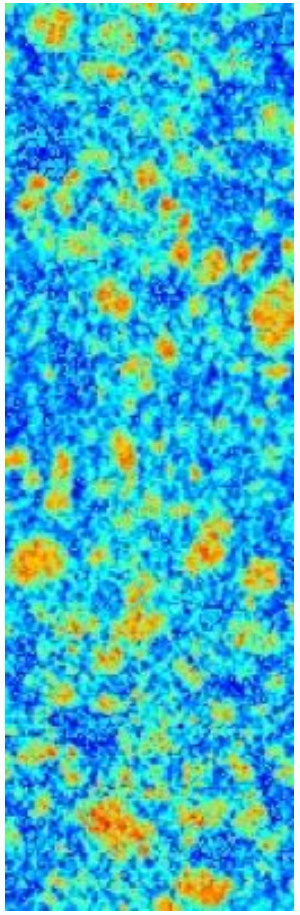
Test setup of neutron and X-ray tomographies

Moisture profile of heated concrete



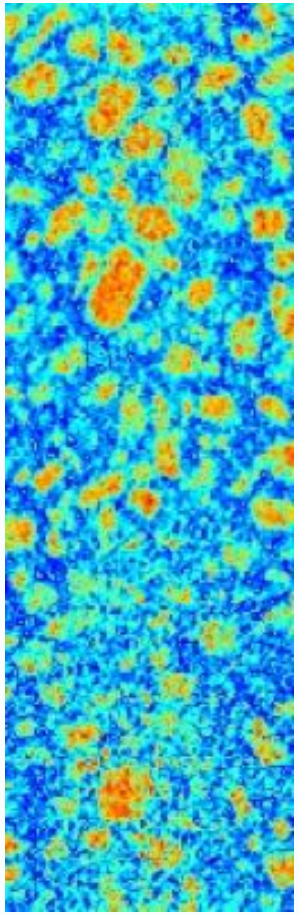
F2

2 kg/m³ of RTPF



F1

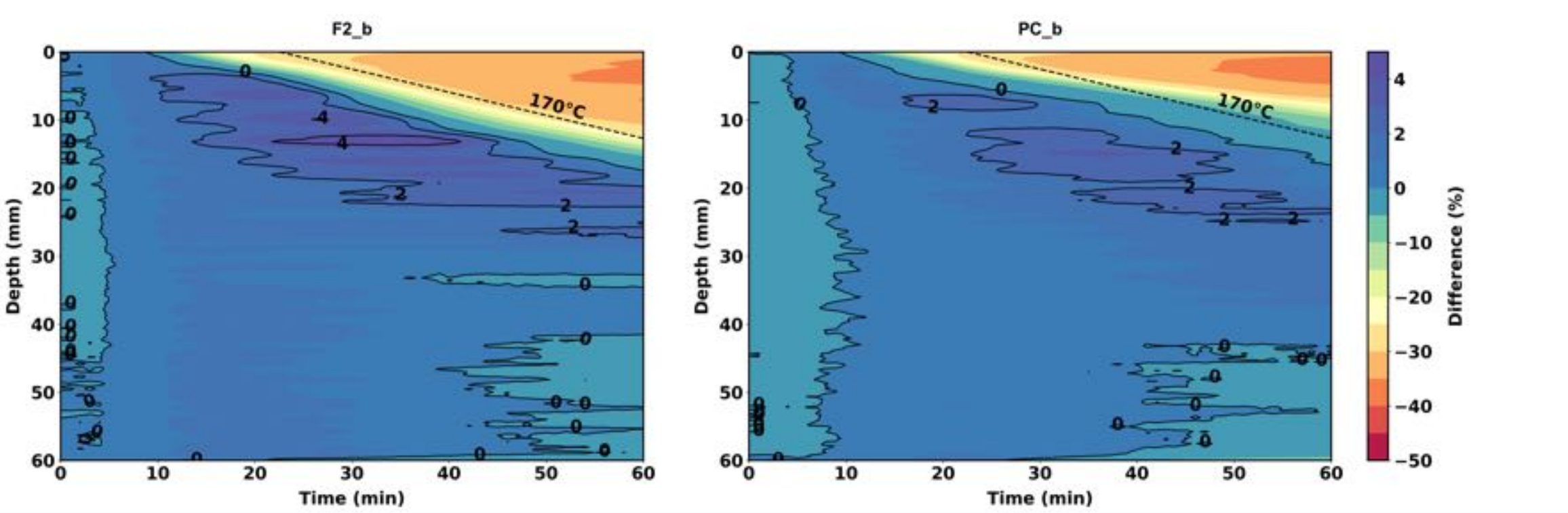
1 kg/m³ of RTPF



PC

Plain concrete

Moisture profile analysis

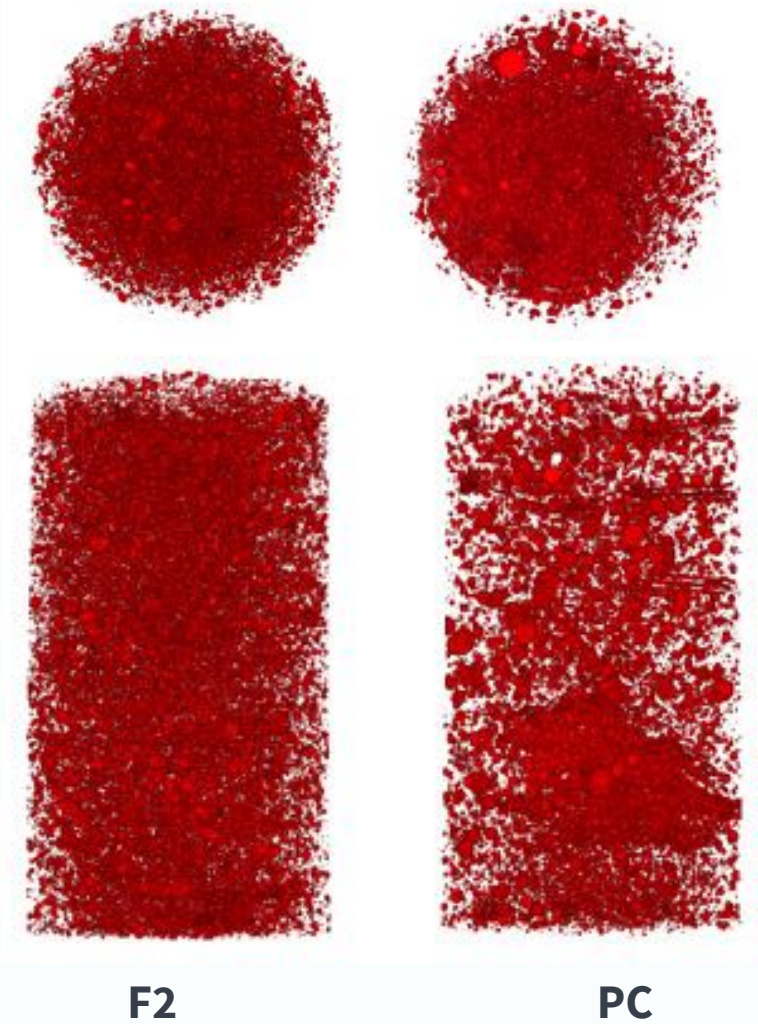


Average grey value map indicating the moisture change in heated concrete.

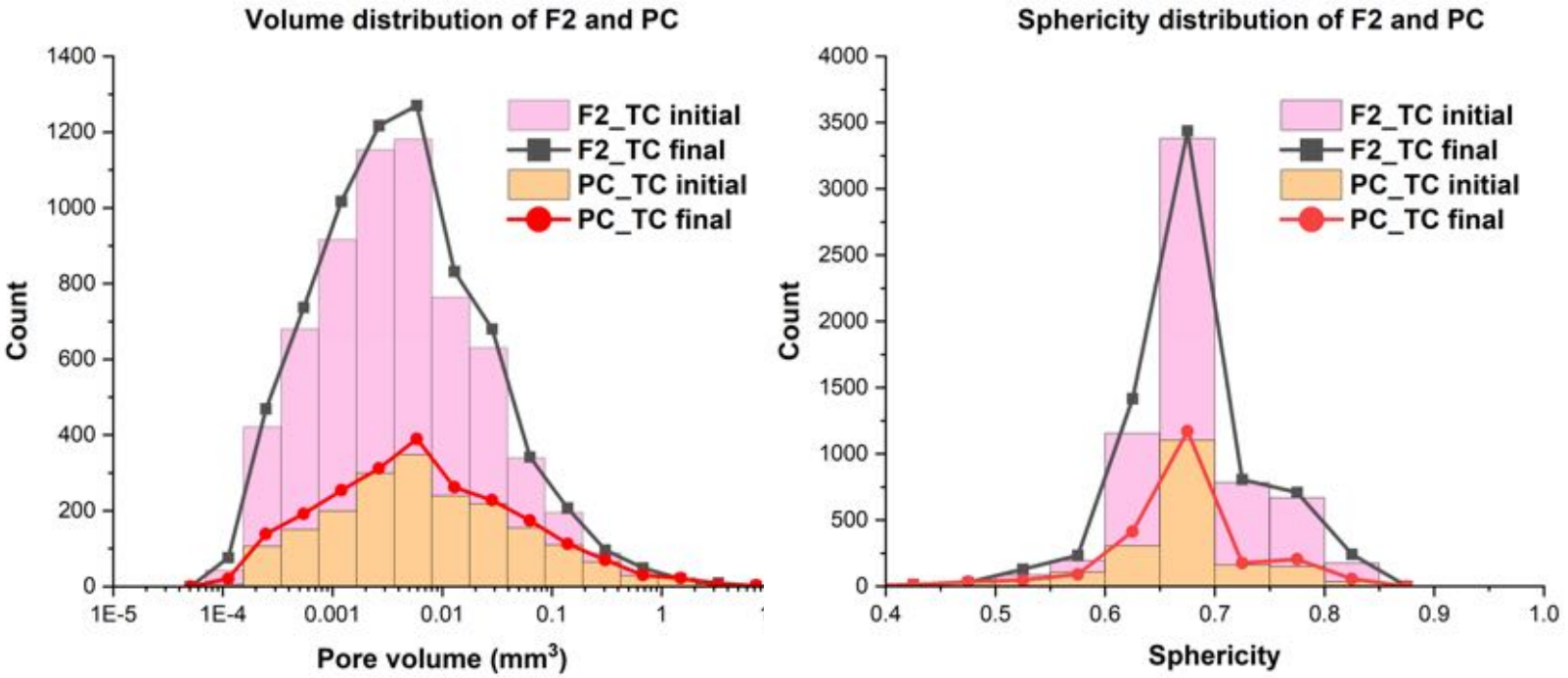
Zero means no difference in moisture compared to the initial state.

Positive value means water accumulation, negative value means water drying

Pore structure of heated concrete



F2 PC



Addition of polymer fibre can increase the intrinsic porosity (Macropores)

The heating process did not significantly increase the macro porosity

No obvious crack opening was observed from the sphericity distribution

Conclusions

- Pore pressure is not the only cause of fire spalling
- The acting mechanism for PP fibre and RTPF could be different
- The presence of moisture clog is confirmed
- RTPF can increase the drying speed of heated concrete without melting
- Polymer fibre can increase the porosity of concrete

Future work

- Optimize the fibre dosages and fibre types in concrete for enhanced fire resistance
- With development of technology, higher-resolution X-ray topography is recommended to investigate the influence of fibres on mesopores and micropores of concrete at more intensive heating curve.

Thank you!