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SPECIAL MOBILITY STRAND

PROPERTIES OF CONCRETE UNDER FIRE CONDITIONS

GORDANA BROĆETA

NOVI SAD, April 2019

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THE CONTENT

- *Concrete*
- *Euro Class of concrete, according to EN 13501-1*
- *Damage of concrete under fire*
- *Fire testing of concrete*
- *Effect of elevated temperatures on hardened cement paste*
- *Influence of aggregate type on concrete fire resistance*
- *Effect of elevated temperatures on steel*

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CONCRETE

https://www.bobvila.com/slideshow/solid-as-a-rock-11-unbelievable-concrete-homes-47069#fire-resistant-house

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According to the decision of the European Commission (94/611/EC), which was published in the official journal of the European Community No. L 241/25, according to EN 13501-1,
the ***concrete*** *is classified as*

Euro Class A1**,**

which ***does not require a fire resistance testing****.*

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*It is assumed that such a **concrete consists of**:*

- *natural **aggregates**, conforming to EN 12620 for normal-weight aggregates and heavy-weight aggregates and EN 13055-1 for light-weight aggregates,*
- ***cement**, conforming to EN 197-1,*
- ***water**, conforming to EN 1008,*
- ***admixtures**, conforming to EN 934-2,*
- ***additions**, conforming to EN 12620 for powder aggregates,*
- ***pigments**, conforming to EN 12878,*
- ***fly ash**, conforming to EN 450,*
- ***silica fumes**, conforming to EN 13263 or*
- ***other inorganic component materials**, conforming to EN 206.*

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REACTION TO FIRE

Classification according to EN 13501-1

*The aim of EN 13501-1 is to define procedure for the classification of **reaction to fire** of construction products.*

It applies to three categories, which are treated separately - construction products, floorings and linear pipe thermal insulation products.

Definition	Construction products			Floorings	
non-combustile materials	A1			$A1_{fl}$	
	A2 - s1 d0 A2 - s2 d0 A2 - s3 d0	A2 - s1 d1 A2 - s2 d1 A2 - s3 d1	A2 - s1 d2 A2 - s2 d2 A2 - s3 d2	$A2_{fl}$ - s1	$A2_{fl}$ - s2
combustible materials - very limited contribution to fire	B - s1 d0 B - s2 d0 B - s3 d0	B - s1 d1 B - s2 d1 B - s3 d1	B - s1 d2 B - s2 d2 B - s3 d2	B_{fl} - s1	B_{fl} - s2
combustible materials - limited contribution to fire	C - s1 d0 C - s2 d0 C - s3 d0	C - s1 d1 C - s2 d1 C - s3 d1	C - s1 d2 C - s2 d2 C - s3 d2	C_{fl} - s1	C_{fl} - s1
combustible materials - medium contribution to fire	D - s1 d0 D - s2 d0 D - s3 d0	D - s1 d1 D - s2 d1 D - s3 d1	D - s1 d2 D - s2 d2 D - s3 d2	D_{fl} - s1	D_{fl} - s1
combustible materials - highly contribution to fire	E	E - d2		E_{fl}	
combustible materials - easily flammable	F			F_{fl}	

https://www.peroni.com/lang_UK/_download/EN_Reaction_to_Fire_Classification.pdf

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not be confused with

REACTION TO FIRE ≠ **RESISTANCE TO FIRE**

... is a response of a product in contributing by its own decomposition to a fire to which it is exposed, under specified conditions (means how the material itself reacts in the case of fire).

A1 A2 B C D E F

... is the ability of building components and systems to perform their intended fire separating and/or loadbearing functions under fire exposure.

R E I

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FIRE RESISTANT

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CONCRETE

A1

NOTE

*the stated fire resistance refers to temperatures **up to 100°C***

*... it is known that in the conditions of fire significantly **higher temperatures** can develop*

FIRE RESISTANT

100°C 200°C 250°C 400°C 500°C 800°C 1000°C 1200°C

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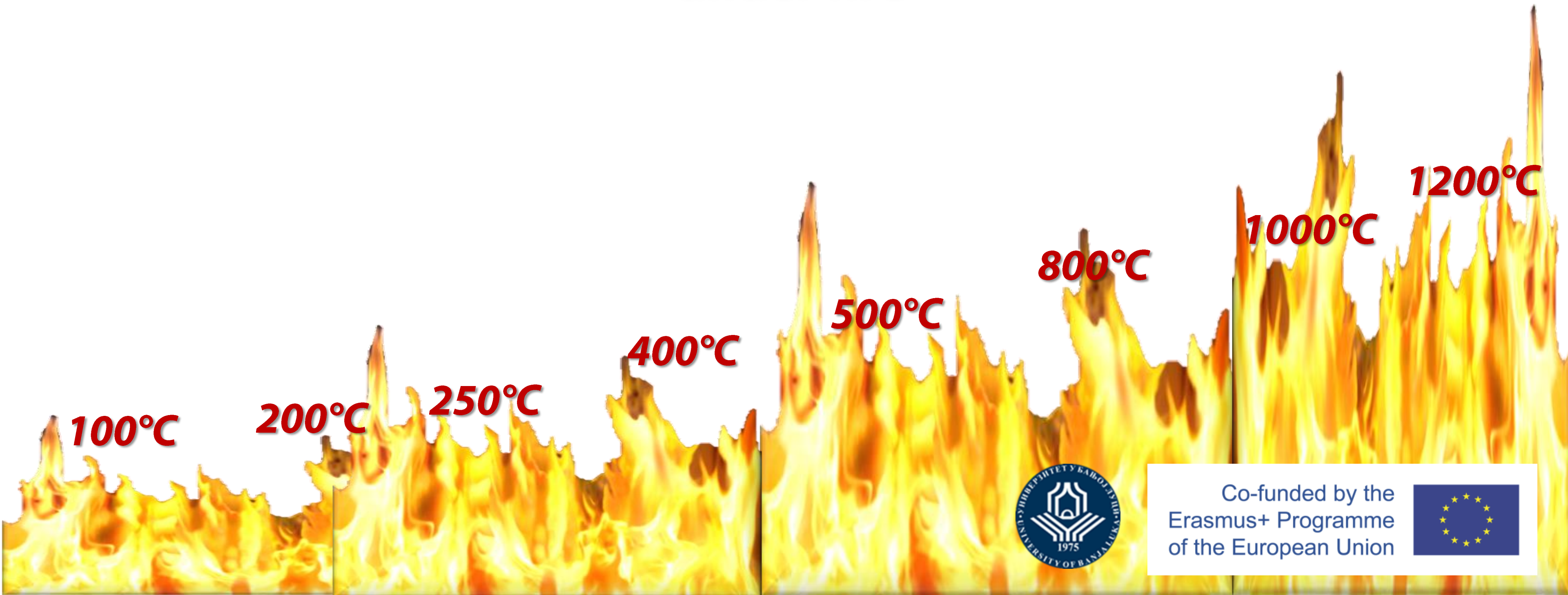
Damage of concrete under fire



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Random hair cracks formed due to fire

https://www.researchgate.net/figure/Cracks-formed-due-to-fire_fig1_257681415

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Damage of concrete under fire

Concrete spalled from a slab soffit revealing pink/red discolouration

https://www.sandberg.co.uk/investigation-inspection/inspection/fire-damaged-concrete.html

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Damage of concrete under fire

Spalling of concrete to beams and a column caused by fire

https://www.sandberg.co.uk/investigation-inspection/inspection/fire-damaged-concrete.html

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Reinforcement on a beam soffit exposed following a fire

https://www.sandberg.co.uk/investigation-inspection/inspection/fire-damaged-concrete.html

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Colapse of floor construction exposed to fire

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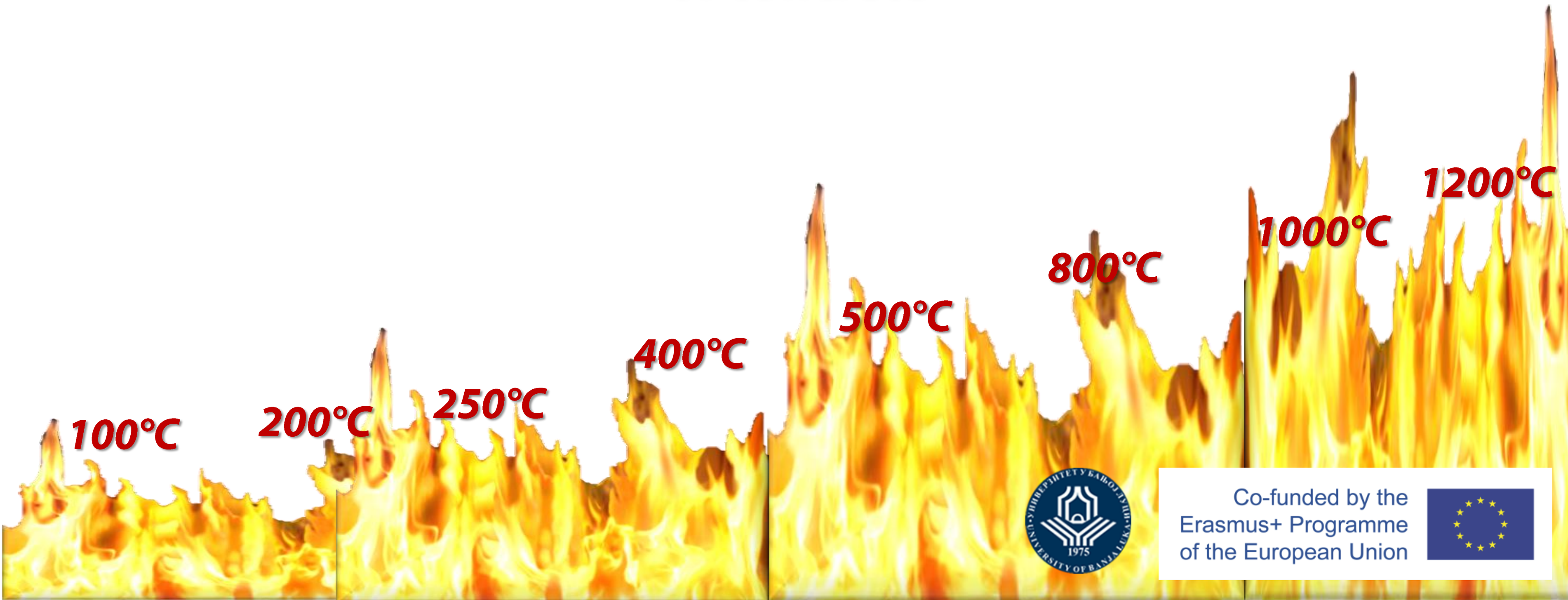
Fire testing

of concrete



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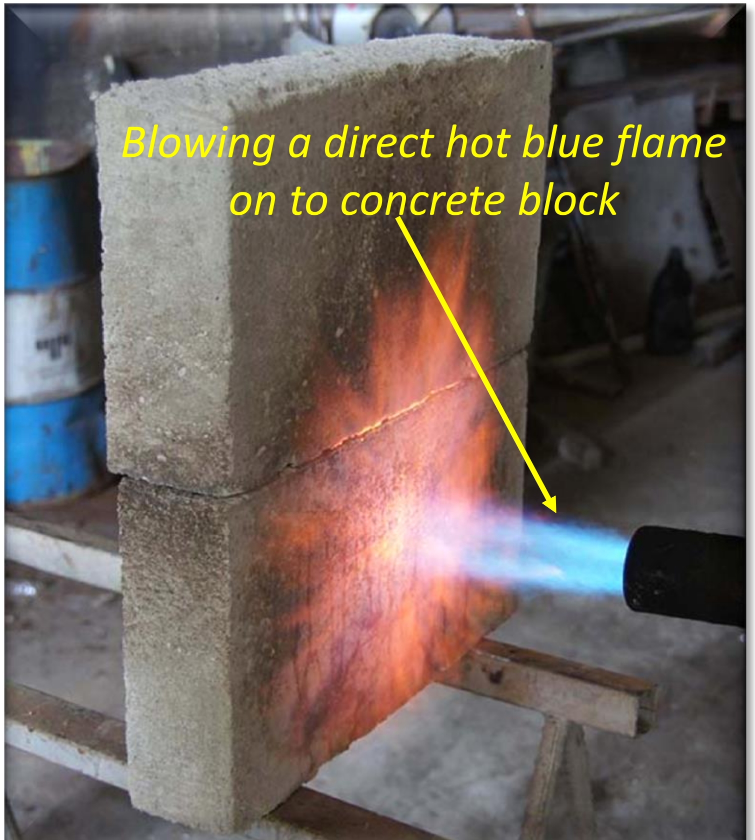
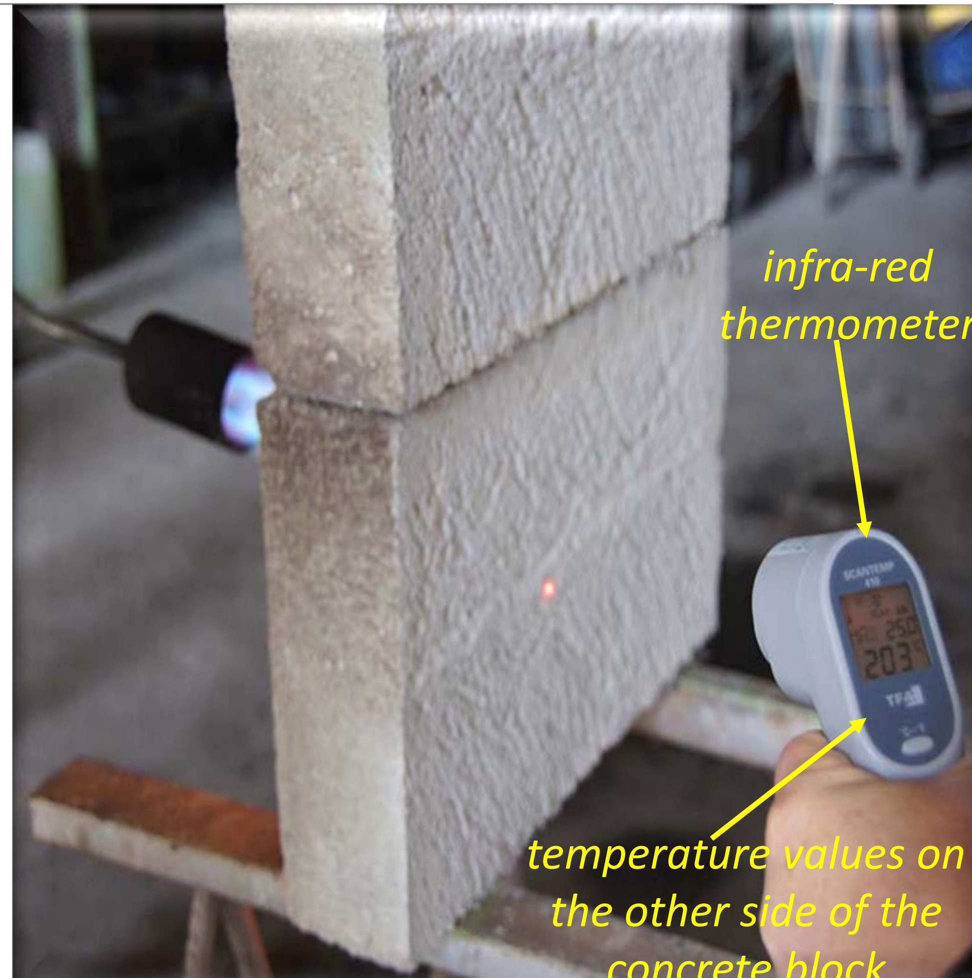
Fire testing of concrete





http://www.acimalta.eu/aciproperties.html

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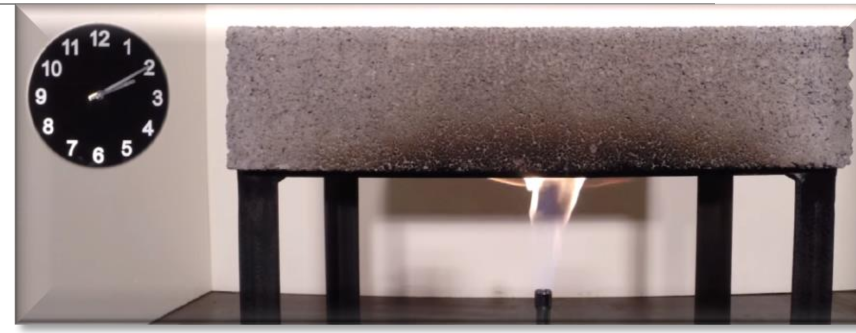
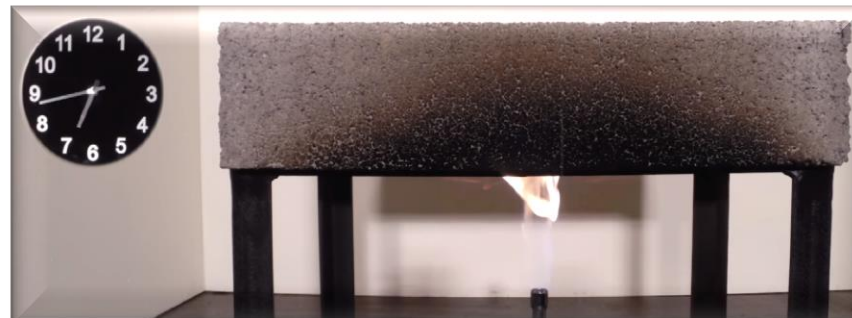
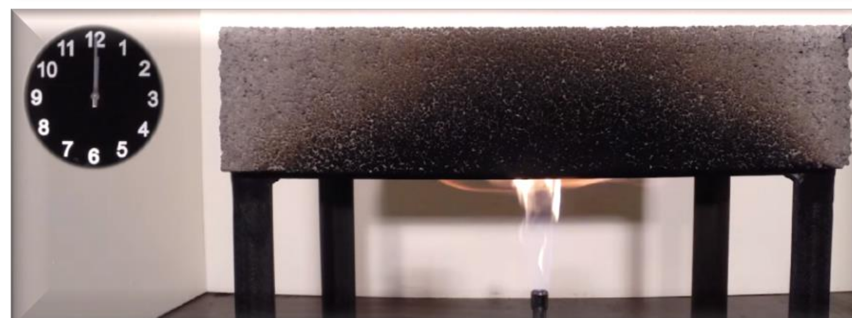
Fire testing of concrete

https://www.youtube.com/watch?v=_ym5x5O6B5A







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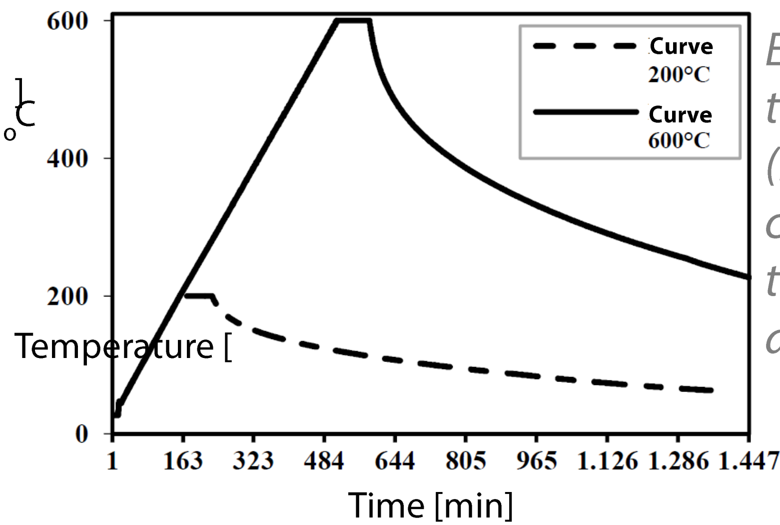
Fire testing of concrete

conforming to Recommendation of RILEM TC 200-HTC



Evolution of temperatures (heating and cooling mode for the oven, 200°C and 600°C)

Electric stove

Samples arranged in the stove

The appearance of the samples after testing

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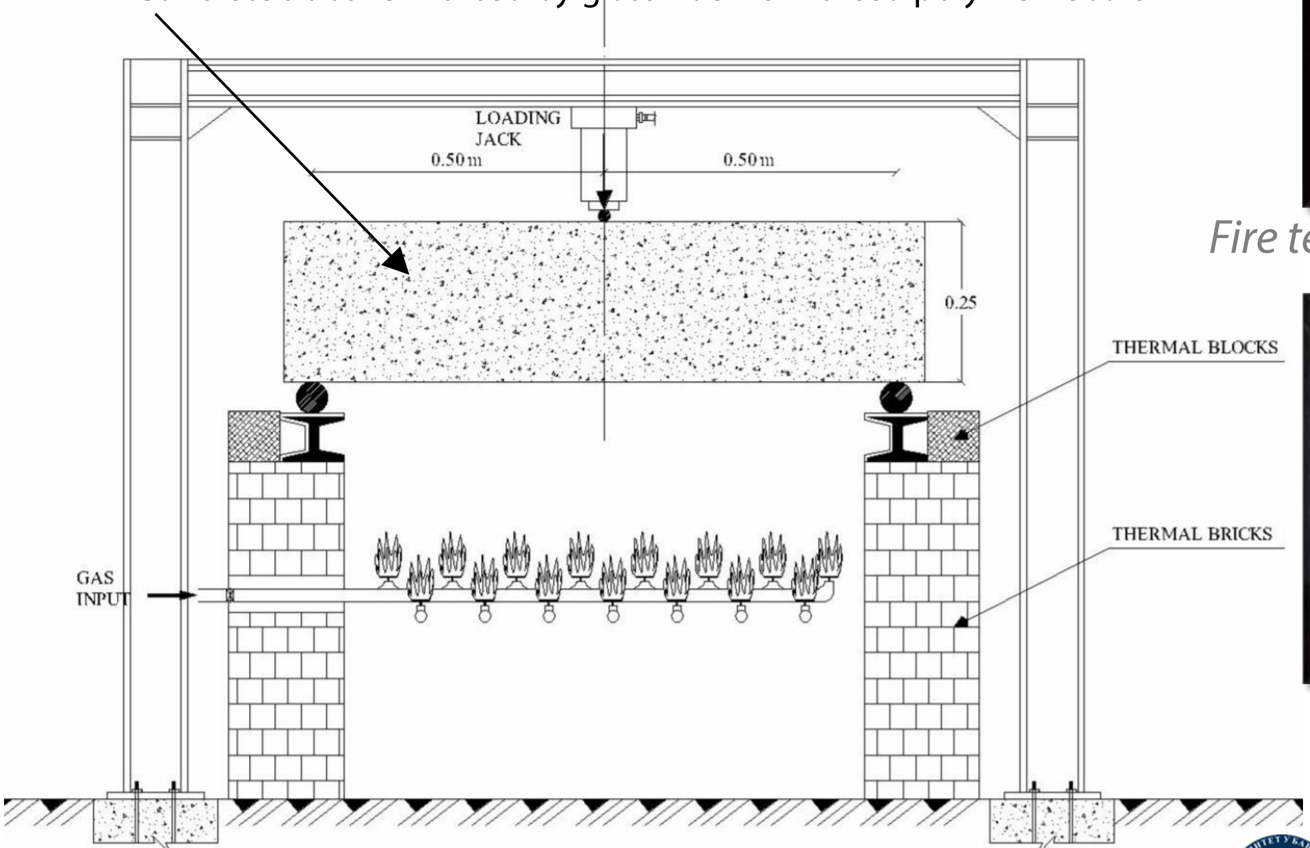
https://dr.nsk.hr/islandora/object/gfos:177/preview

Fire testing of concrete

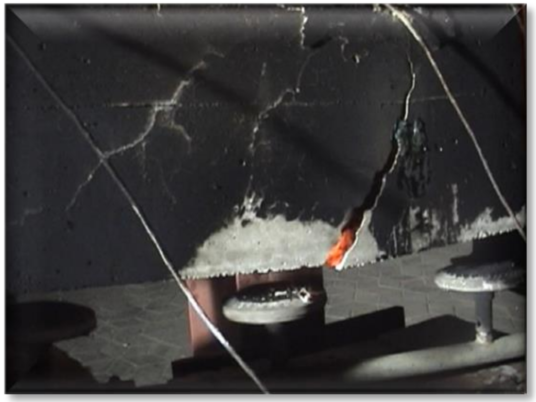
Amr W. Sadek, M. El-Hawary, Amr S. El-Deeb: Fire Resistance Testing of Concrete Slabs Reinforced by GFRP Rebars, European Journal of Scientific Research, Vol.15 No.2 (2006), pp. 190-200
https://www.researchgate.net/publication/250146419_Fire_Resistance_Testing_of_Concrete_Slabs_Reinforced_by_GFRP_Rebars

Concrete slabs reinforced by glass fiber reinforced polymer rebars



Test setup of beams

Fire testing of beam specimen



Fire penetrating cracks in beam specimen

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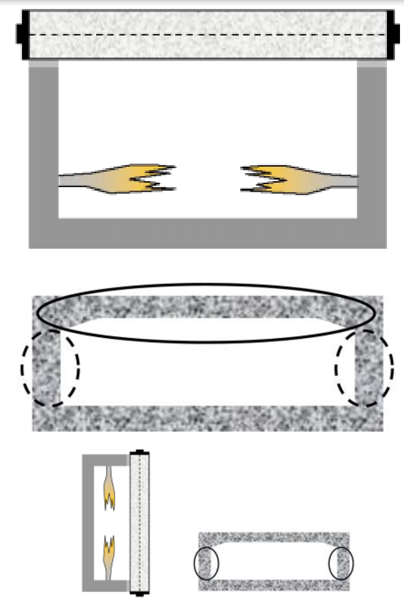
Fire testing of concrete

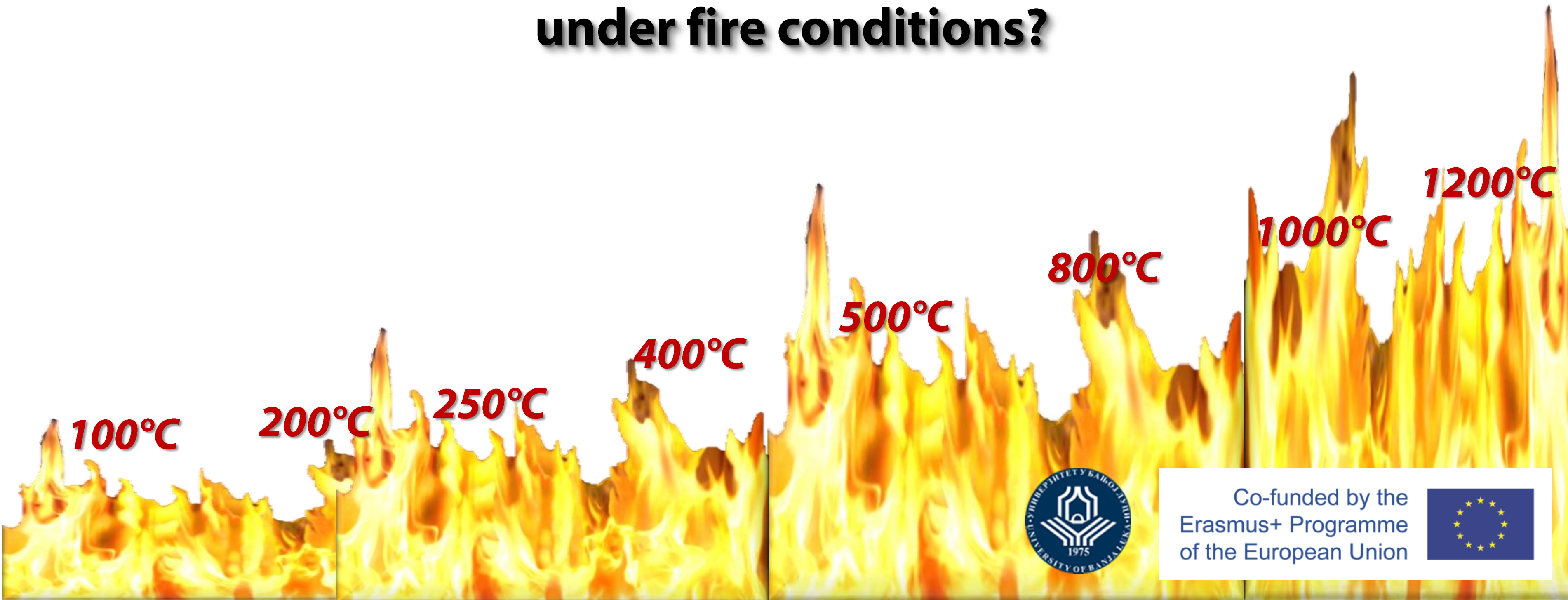
Concrete spalling during a fire test at Efectis Nederland

https://www.youtube.com/watch?v=CixMjo5VtgA

Time [min.]	Temperature [°C]
0	20
3	890
5	1140
10	1200
30	1300
60	1350
90	1300
120	1200
>120	1200



What happens to concrete at elevated temperature under fire conditions?



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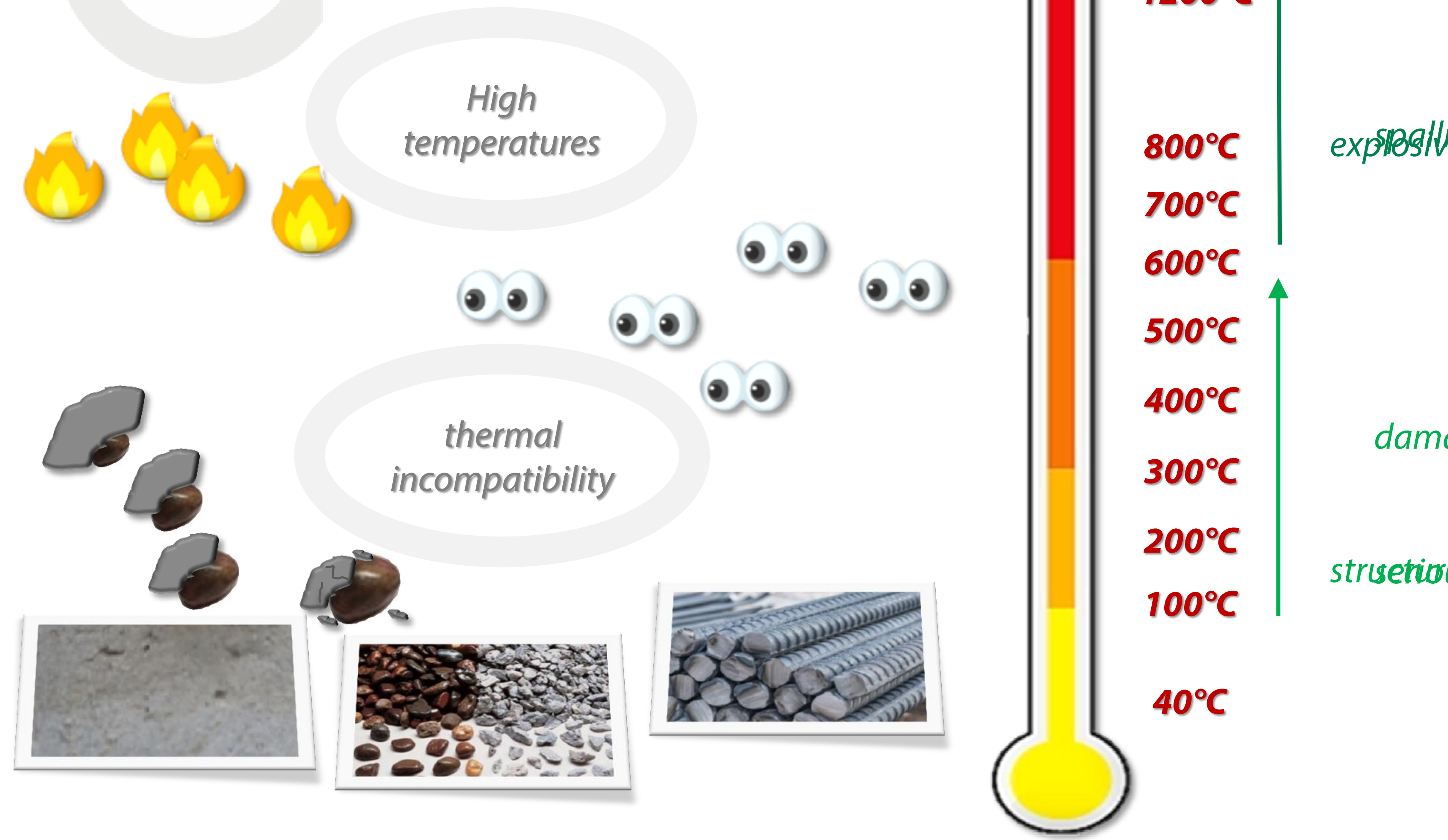

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Physical processes

concrete in the melting phase

melting process starts

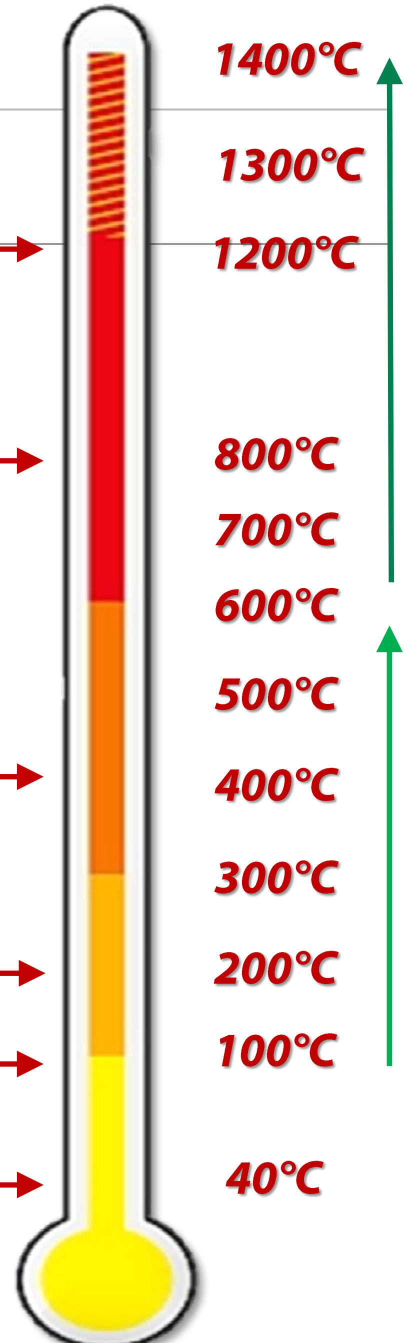
total loss of chemically bound water in cement hydrates

chemically bound water in cement hydrates begins to lose

total loss of physically bound water

total loss of free capillary water

free water from capillary pores begins to lose, and to a much lesser degree, physically bound (gel) water



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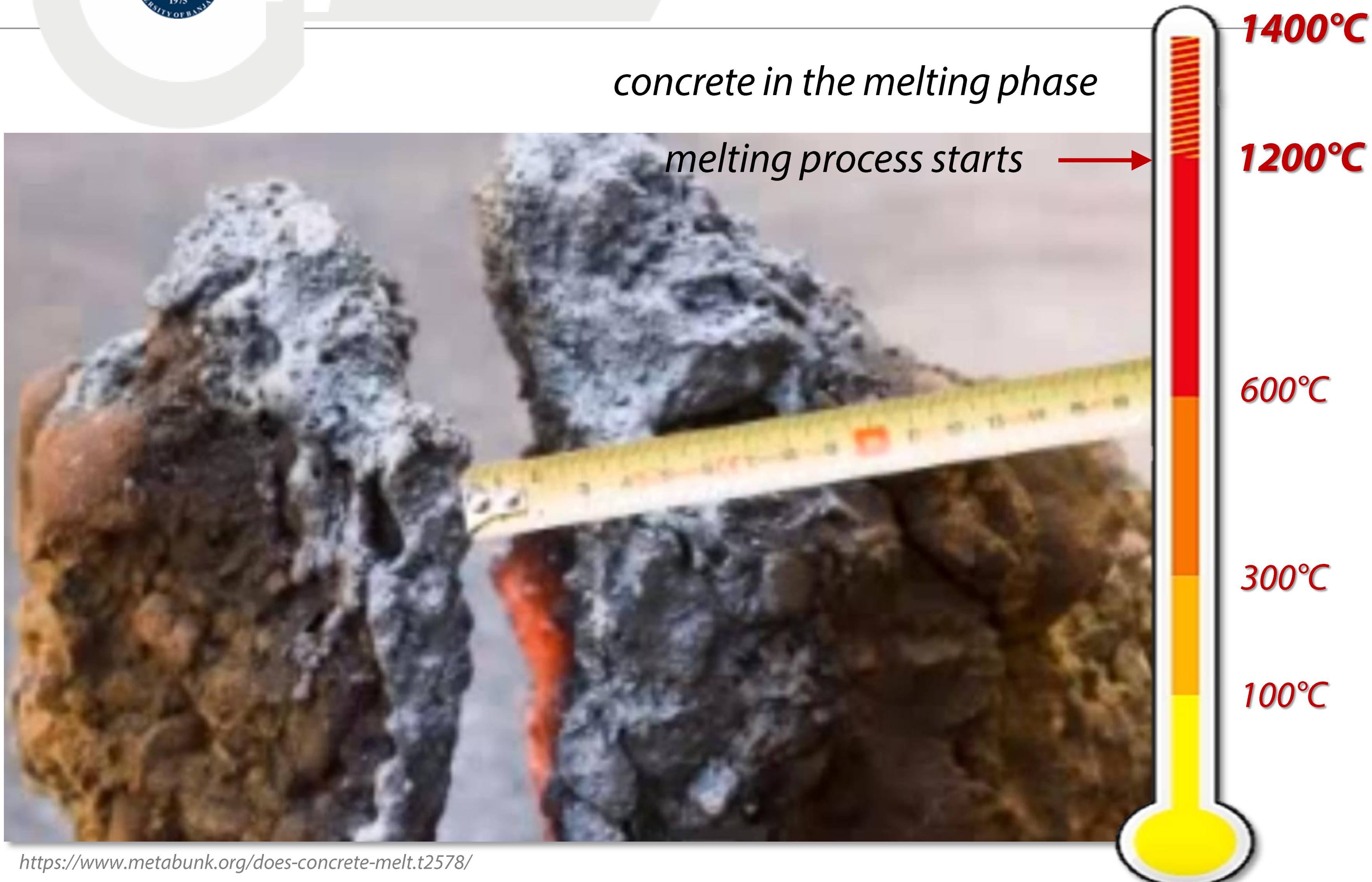
Molten decomposed concrete



https://www.metabunk.org/does-concrete-melt.t2578/

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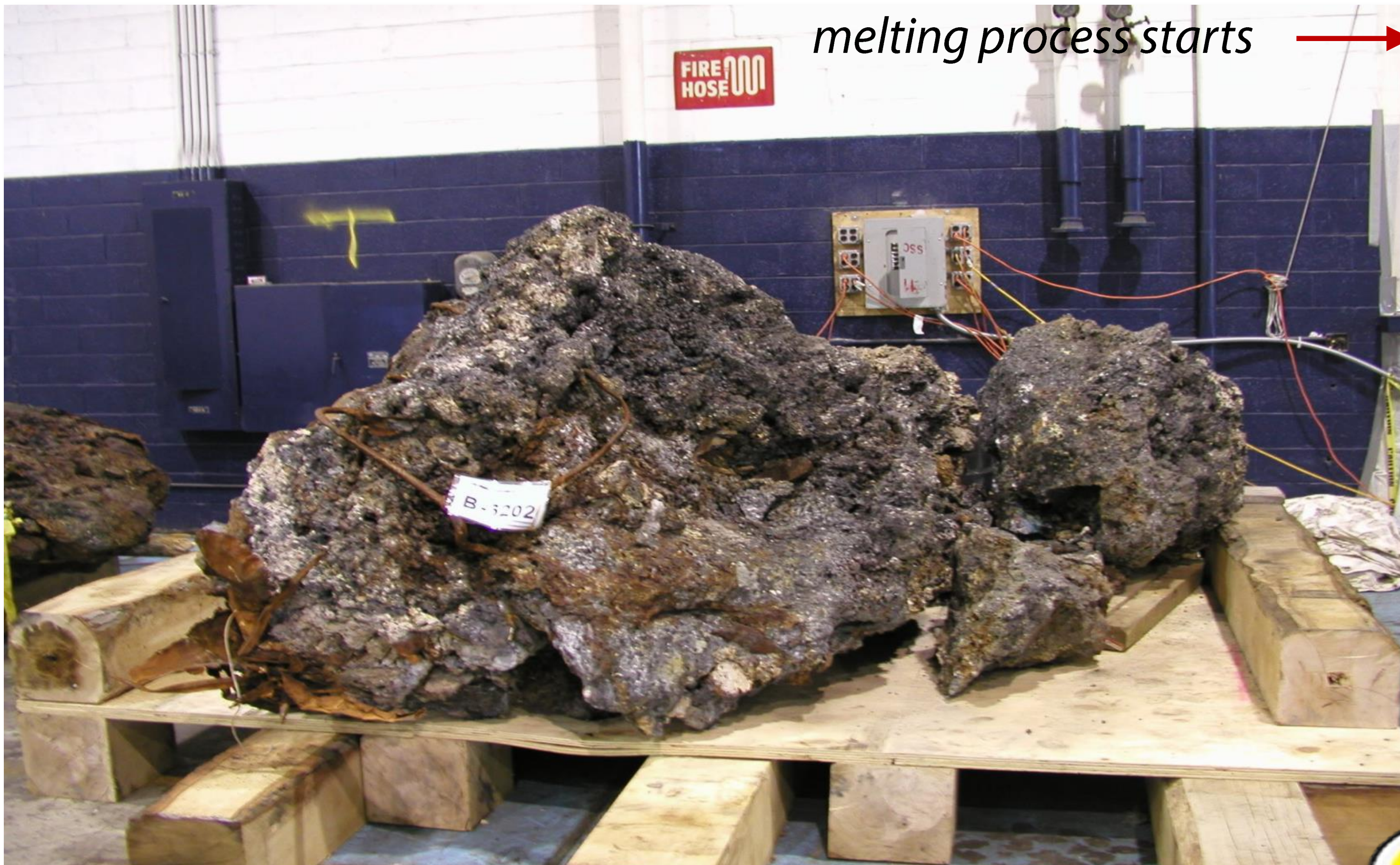
Molten decomposed concrete

concrete in the melting phase

melting process starts



1400℃

1200℃

600℃

300℃

100℃

https://www.metabunk.org/does-concrete-melt.t2578/page-2

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Chemical transformations

concrete in the melting phase

melting process starts

C-S-H gel has completely disappeared

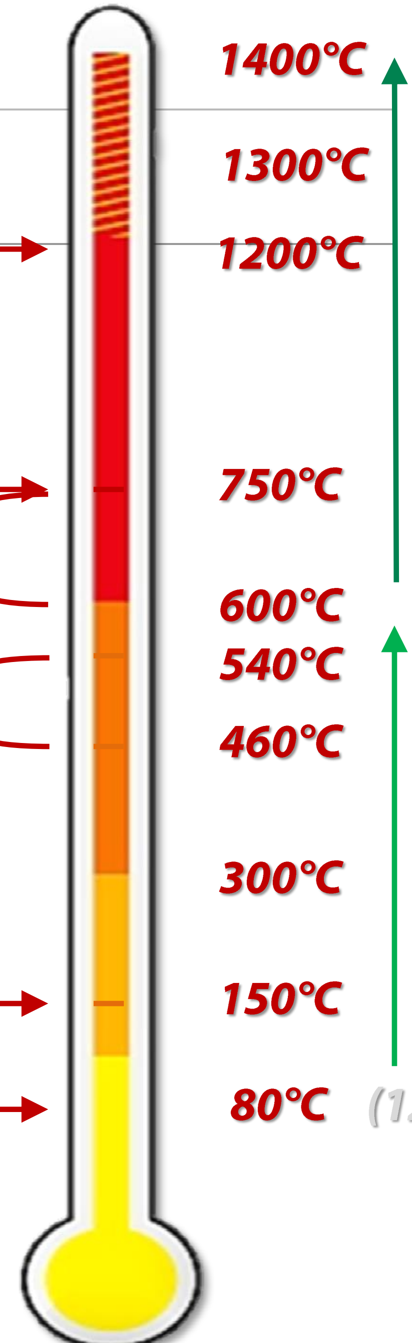
decomposition of the C-S-H (calcium-silicate-hydrate phases) and formation of β-C_2S

decomposition of the portlandite (calcium hydroxide)

$$Ca(OH)_2 \longrightarrow CaO + HO_2$$

stability temperature of Tobermorite gel (C-S-H)
C-S-H gel begins the process of dehydration

ettringite losses its crystalline form



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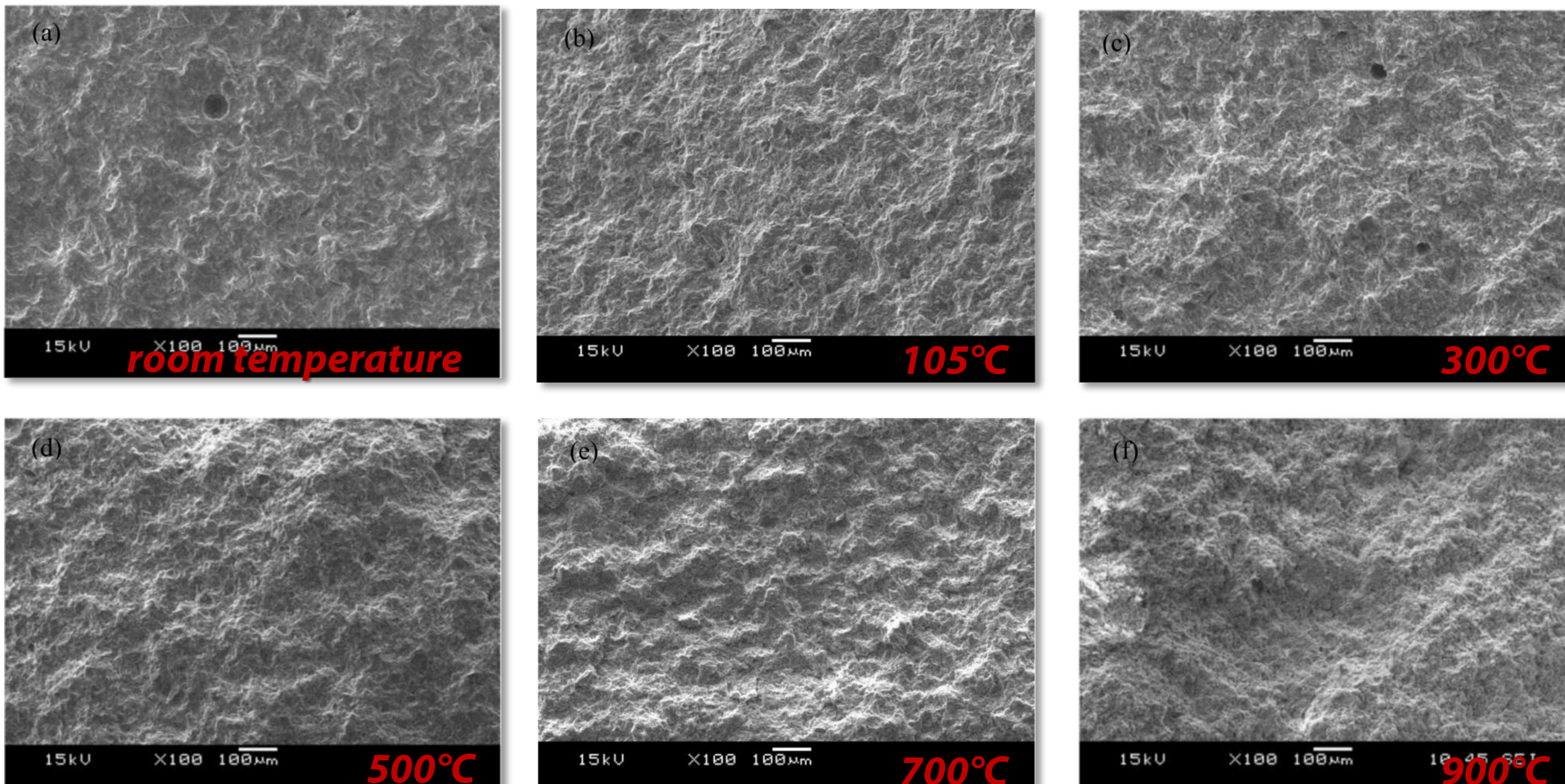
EXAMPLE OF RESEARCH

Seungmin Lim: Effects of elevated temperature exposure on cementbased composite materials, Dissertation, University of Illinois at Urbana-Champaign, 2015

SEM images of fractured surfaces of cement paste with w/c of 0.35 in 100× magnification



https://www.ideals.illinois.edu/bitstream/handle/2142/78451/LIM-DISSERTATION-2015.pdf?sequence=1

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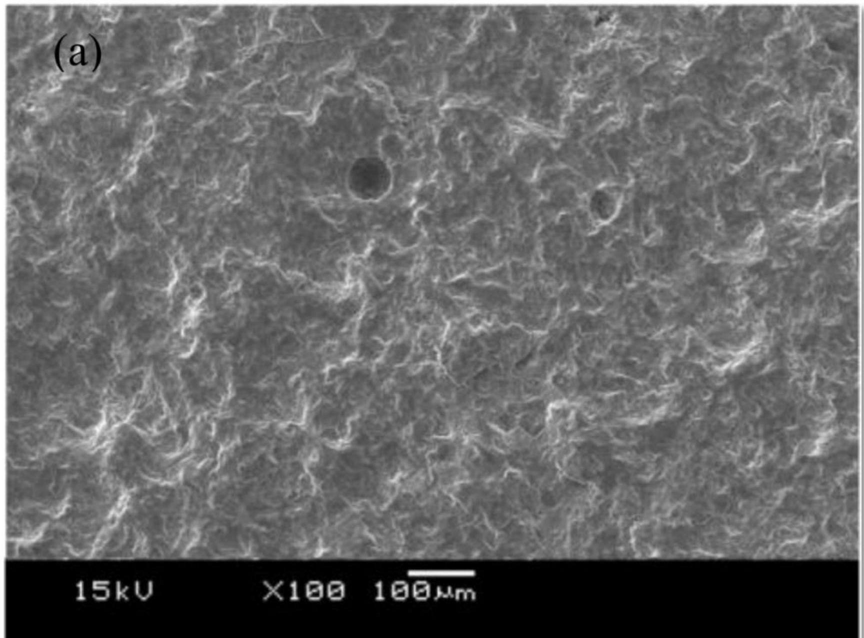
SEM images of fractured surfaces of cement paste with w/c of 0.35 in 100× magnification

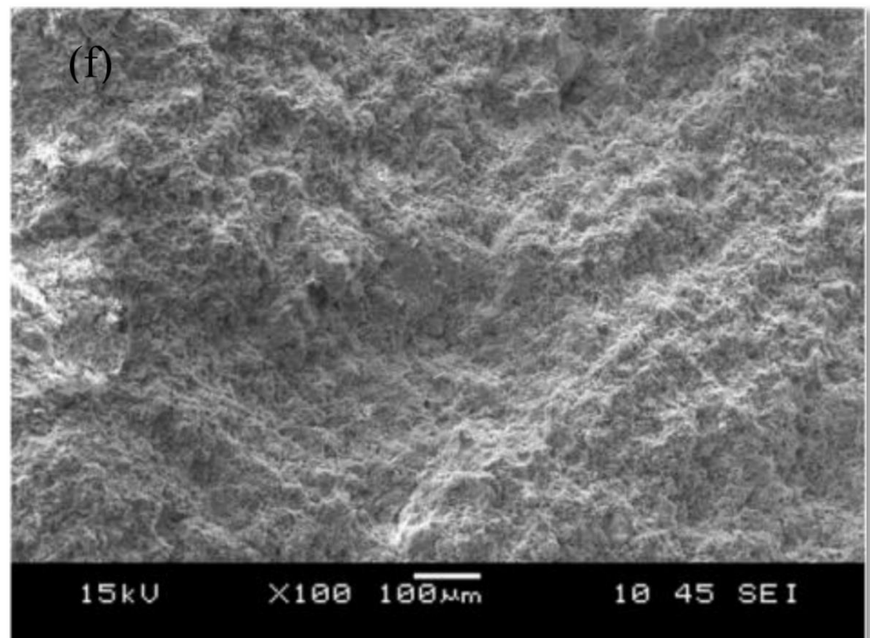
room temperature



surface roughness of a fractured surface increases as temperature increases

morphological changes as a function of exposure temperature

900°C



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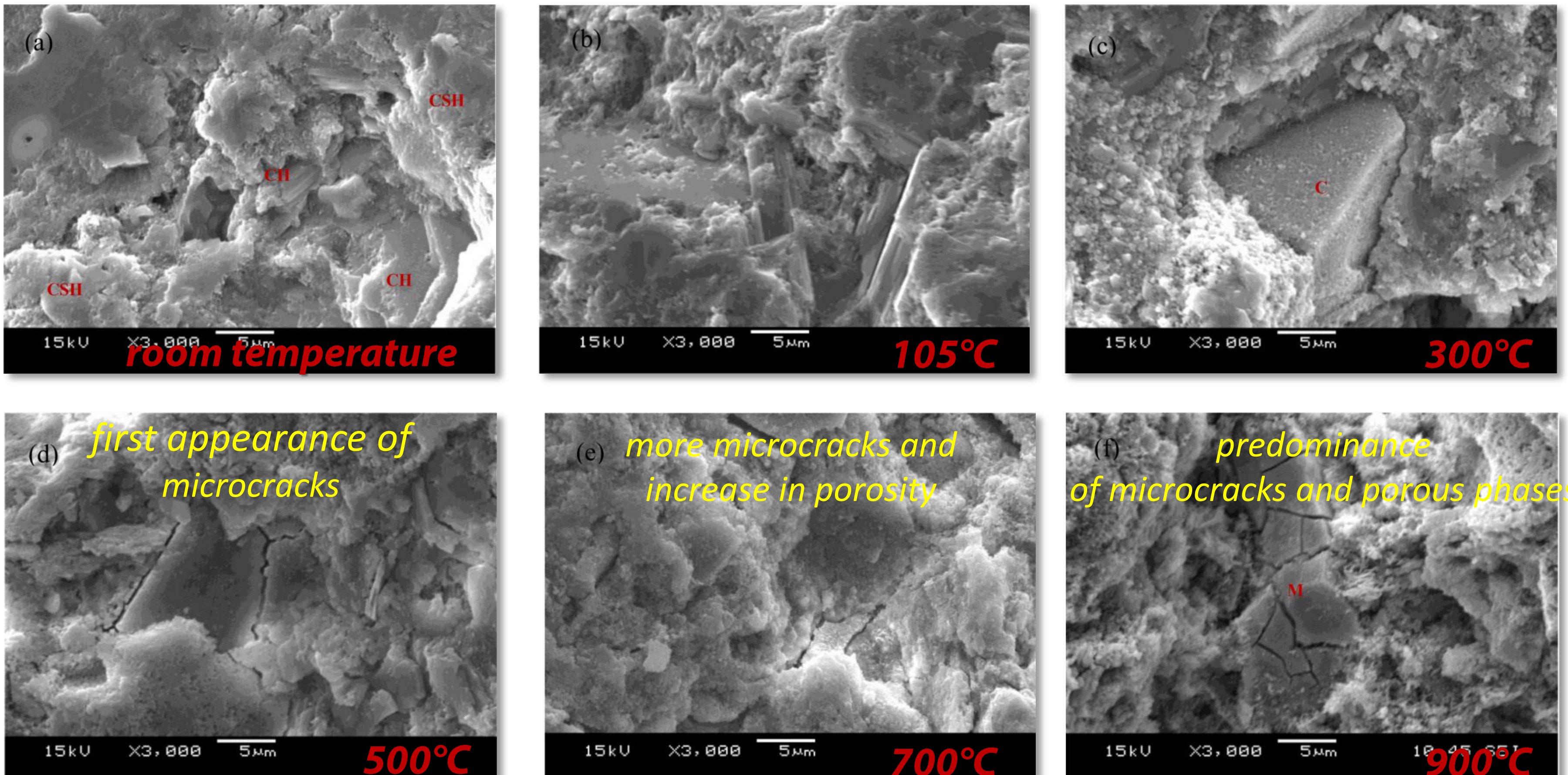
EXAMPLE OF RESEARCH

Seungmin Lim: Effects of elevated temperature exposure on cementbased composite materials, Dissertation, University of Illinois at Urbana-Champaign, 2015

SEM images of fractured surfaces of cement paste with w/c of 0.35 in 3000× magnification



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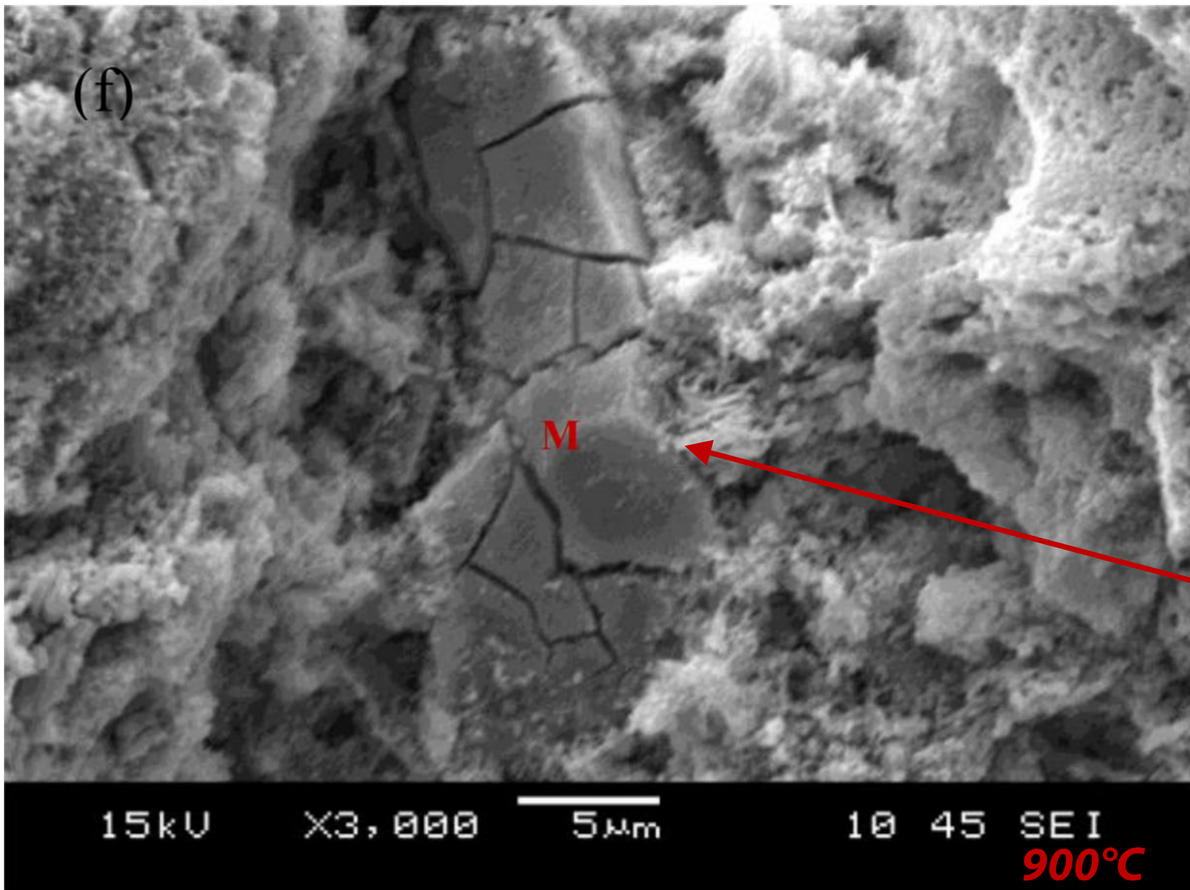

predominance of microcracks and porous phases

*some particles (marked as **M**) are totally cracked*

https://www.ideals.illinois.edu/bitstream/handle/2142/78451/LIM-DISSERTATION-2015.pdf?sequence=1

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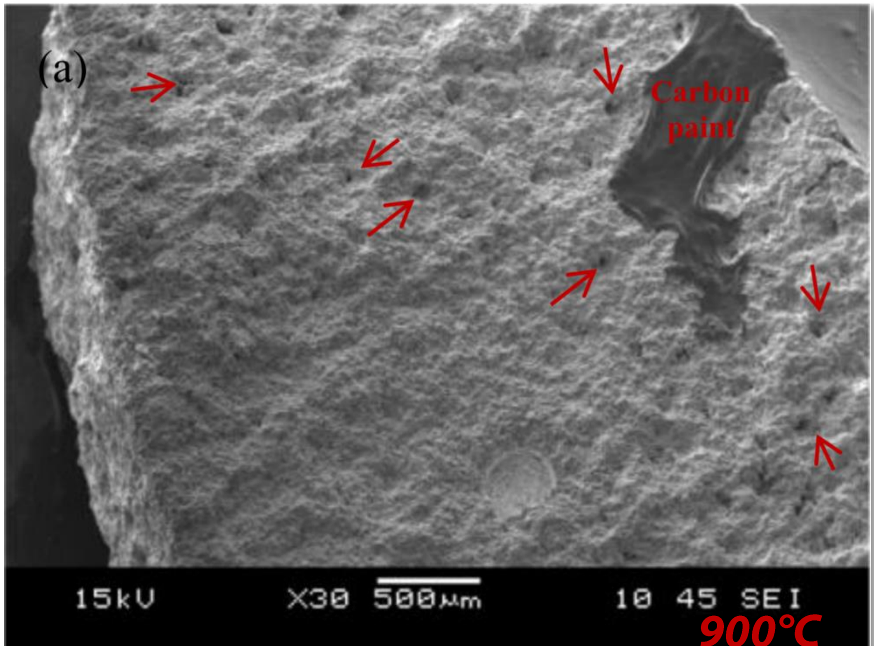
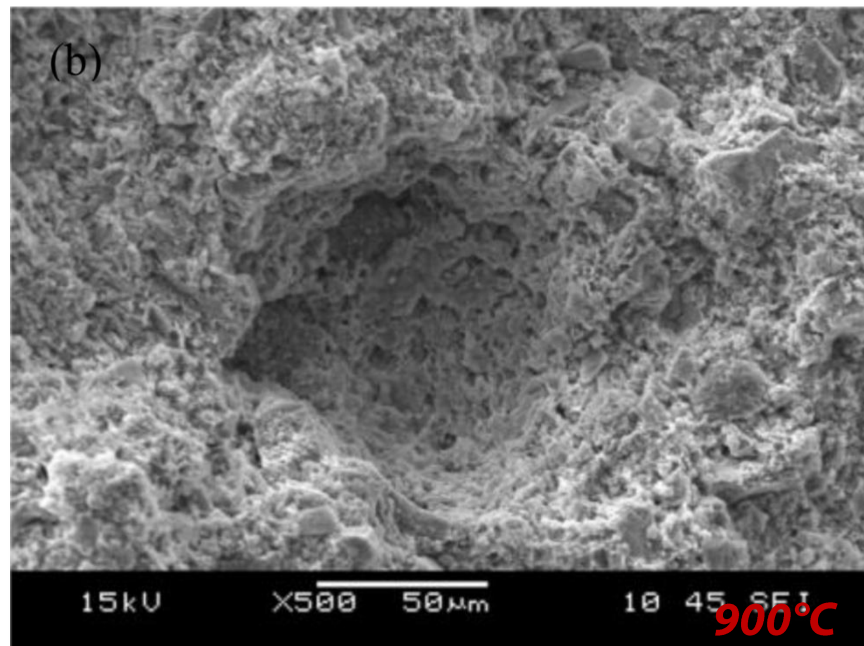
EXAMPLE OF RESEARCH

Seungmin Lim: Effects of elevated temperature exposure on cementbased composite materials, Dissertation, University of Illinois at Urbana-Champaign, 2015

SEM images of fractured surfaces of cement paste with w/c of 0.35 at 900°C in 30× and 500× magnifications



large spherical voids (approx. 50 μm) appear on areas of the fractured surface



particles (possibly in unhydrated phases) "popping out" of the paste

... the exact cause of these voids could not be established

https://www.ideals.illinois.edu/bitstream/handle/2142/78451/LIM-DISSERTATION-2015.pdf?sequence=1

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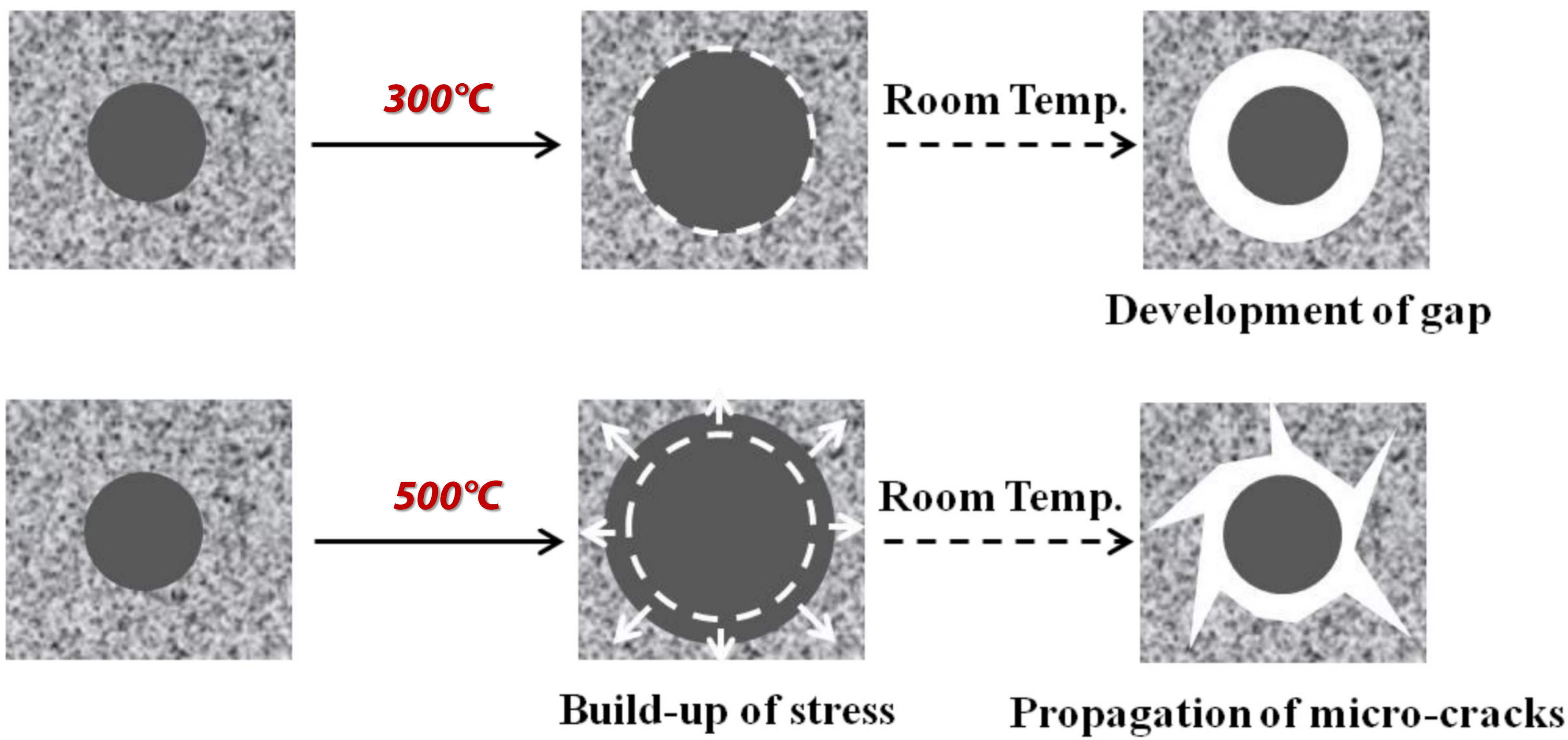
EXAMPLE OF RESEARCH

Seungmin Lim: Effects of elevated temperature exposure on cementbased composite materials, Dissertation, University of Illinois at Urbana-Champaign, 2015

Schematic diagrams of the formation of a gap a and propagation of microcracks at the interface between unhydrated cement particle and paste matrix



https://www.ideals.illinois.edu/bitstream/handle/2142/78451/LIM-DISSERTATION-2015.pdf?sequence=1

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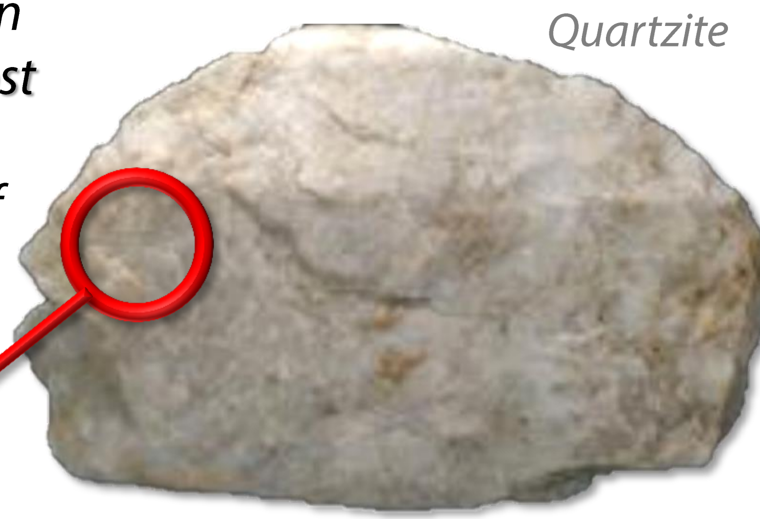
Influence of aggregate type on concrete fire resistance

Aggregates of metamorphic rocks

Due to a significant content of **quartz**, which in conditions of intense heating **is considered most critical mineral of solid rock**, at elevated temperatures (over 500°C) they show signs of degradation - cracking.

Quartzite



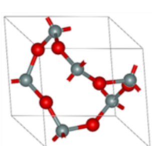
http://www.quartzpage.de/gen_ro
k.html

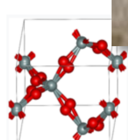
Quartzites are monomineralic rocks, constructed almost entirely of the mineral quartz SiO_2 - over 98%

50°C
increases volume by 0,17%

573°C
the largest expansion

polymorphic transformation





α quartz → high-temperature β quartz

the least favorable aggregates

Influence of aggregate type on concrete fire resistance

Aggregates of igneous rocks (granite, dacite, senitite, diorite, adensite, gabar, basalt, diabase)

*are generally characterized by **good resistance** to the action of elevated temperatures, although they contain mineral quartz.*

Granite

Diorite

Dacite

Adensite

Given the fine-grained structure with well distributed mineral content and proportionally relatively low content of quartz, this cumstance has no significant influence.

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Influence of aggregate type on concrete fire resistance

Aggregates of sedimentary rocks

Limestone

calcite
($CaCO_3$)

Dolomite aggregate for concrete

Limestone aggregate for concrete

Dolomite

dolomite
($CaCO_3 \cdot MgCO_3$)

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Influence of aggregate type on concrete fire resistance

Aggregates of sedimentary rocks

calcite
$CaCO_3$

dolomite
$CaCO_3 \cdot MgCO_3$

Limestone

Dolomite

high temperature

870°C **CaO**

800°C **MgO**

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heating-up at a rate of 1°C/min

EXAMPLE OF RESEARCH

Zhi Xing, Ronan Hébert, Anne-Lise Beaucour, Béatrice Ledésert, Albert Noumowé: Influence of the nature of aggregates on the behaviour of concrete subjected to elevated temperature, Materials and Structures, November 2014, Volume 47, Issue 11, pp 1921–1940

Aggregates of sedimentary rocks (limestone aggregate)

< 600°C *no changes*

600°C *color change for some particles of aggregates, becoming gradually more reddish*

750°C *particles of aggregates are cracked and the particle surface has whitened*

Decarbonation

calcite		lime		carbon dioxide
$CaCO_3$	→	CaO	+	CO_2

Appearance of the aggregate after heating at 750°C

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Zhi Xing, Ronan Hébert, Anne-Lise Beaucour, Béatrice Ledésert, Albert Noumowé: Influence of the nature of aggregates on the behaviour of concrete subjected to elevated temperature, Materials and Structures, November 2014, Volume 47, Issue 11, pp 1921–1940

Aggregates of sedimentary rocks (limestone aggregate)

Appearance of the aggregate

after heating–cooling cycle at 750°C *3 days after heating–cooling cycle at 750°C*

CaO ***$Ca(OH)_2$***

volume expansion of 200%

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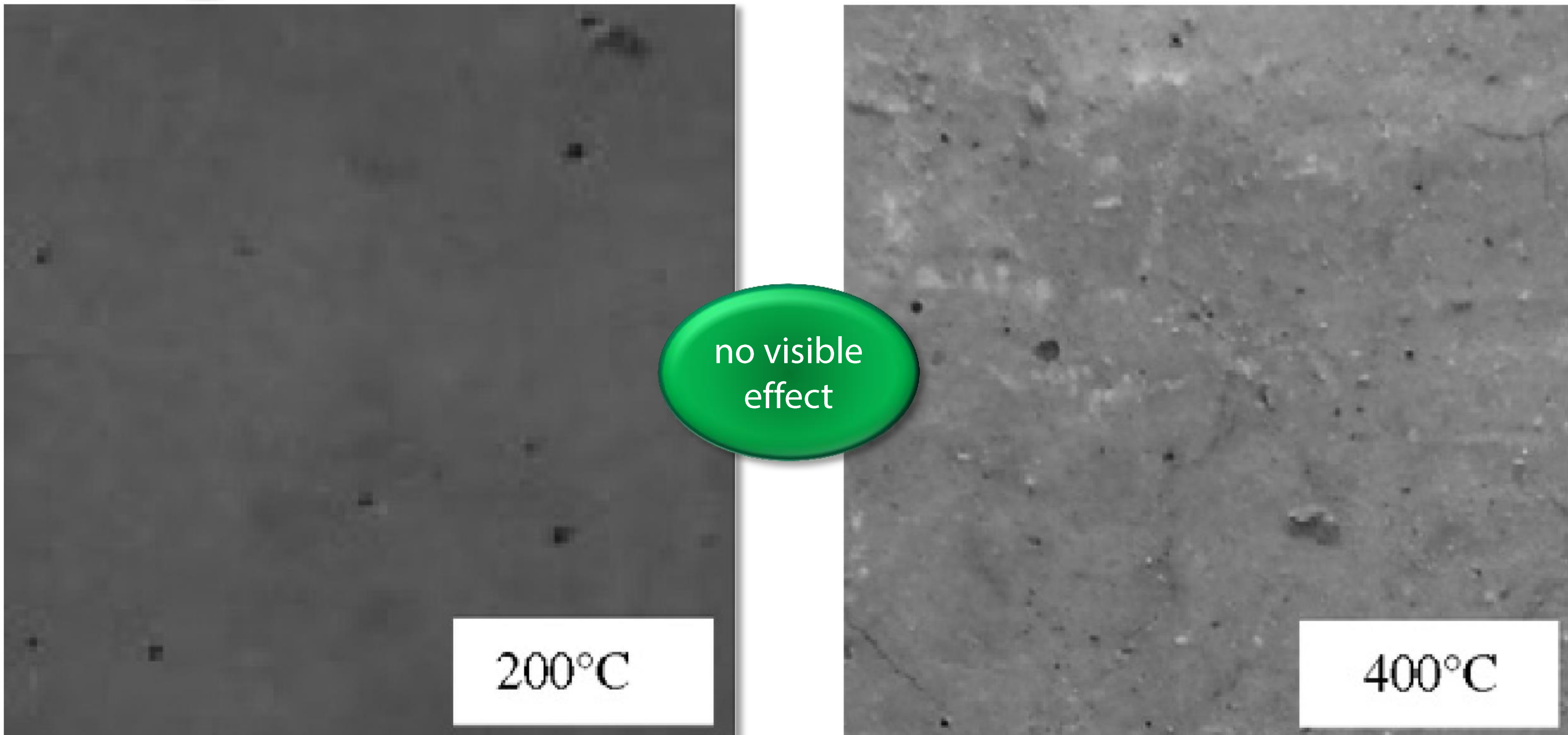
EXAMPLE OF RESEARCH

Omer Arioz: Effects of elevated temperatures on properties of concrete, Fire Safety Journal 42 (2007) pp. 516–522

Aggregates of sedimentary rocks (crushed limestone aggregate)



Surface texture of the concrete exposed to elevated temperatures

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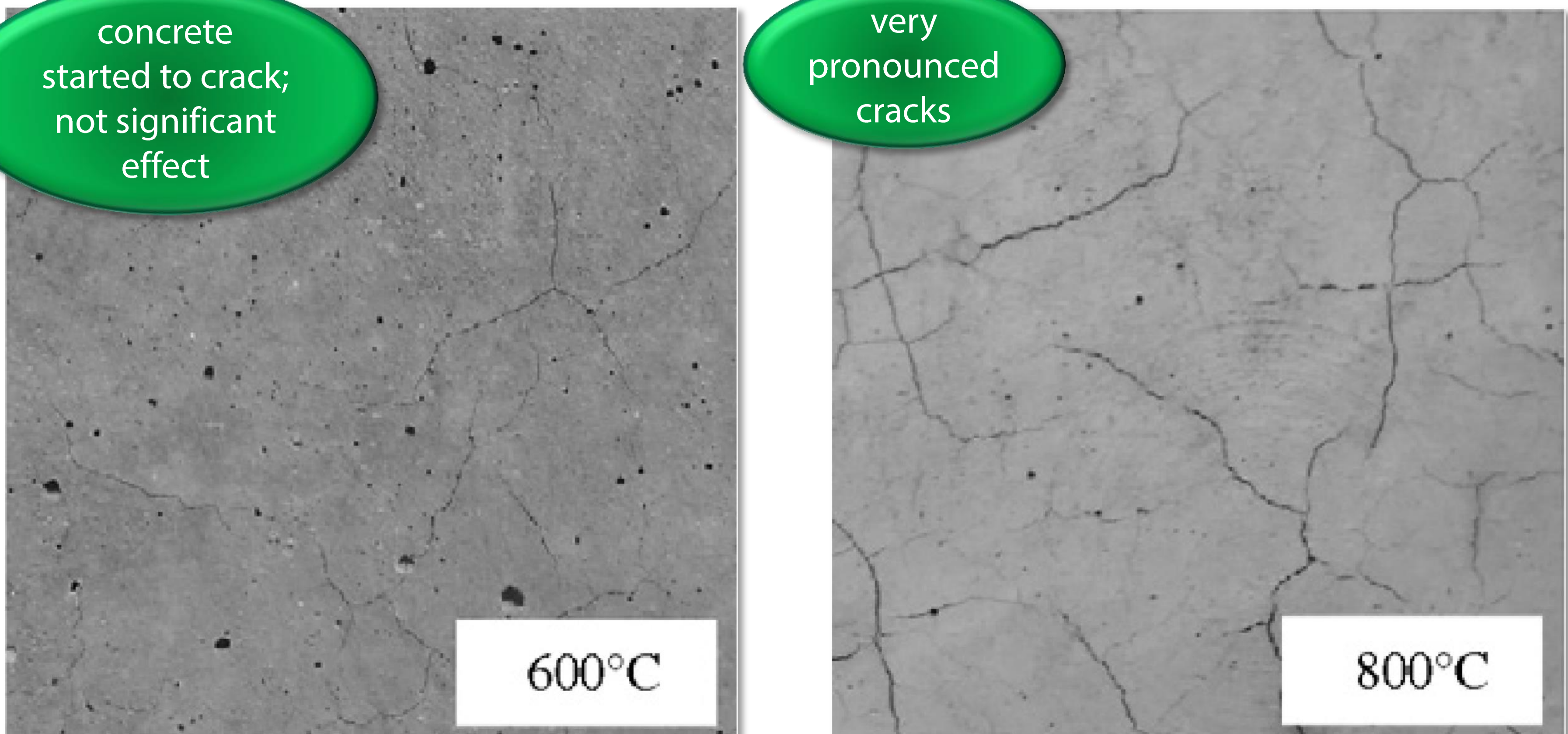
EXAMPLE OF RESEARCH

Omer Arioz: Effects of elevated temperatures on properties of concrete, Fire Safety Journal 42 (2007) pp. 516–522

Aggregates of sedimentary rocks (crushed limestone aggregate)

concrete started to crack; not significant effect

very pronounced cracks



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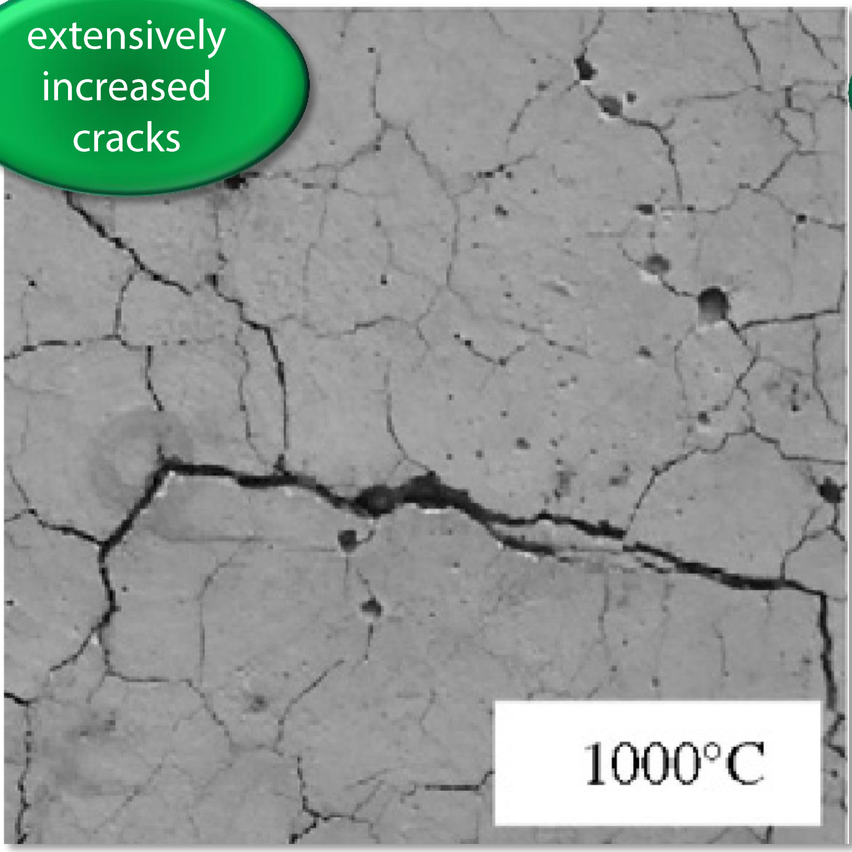

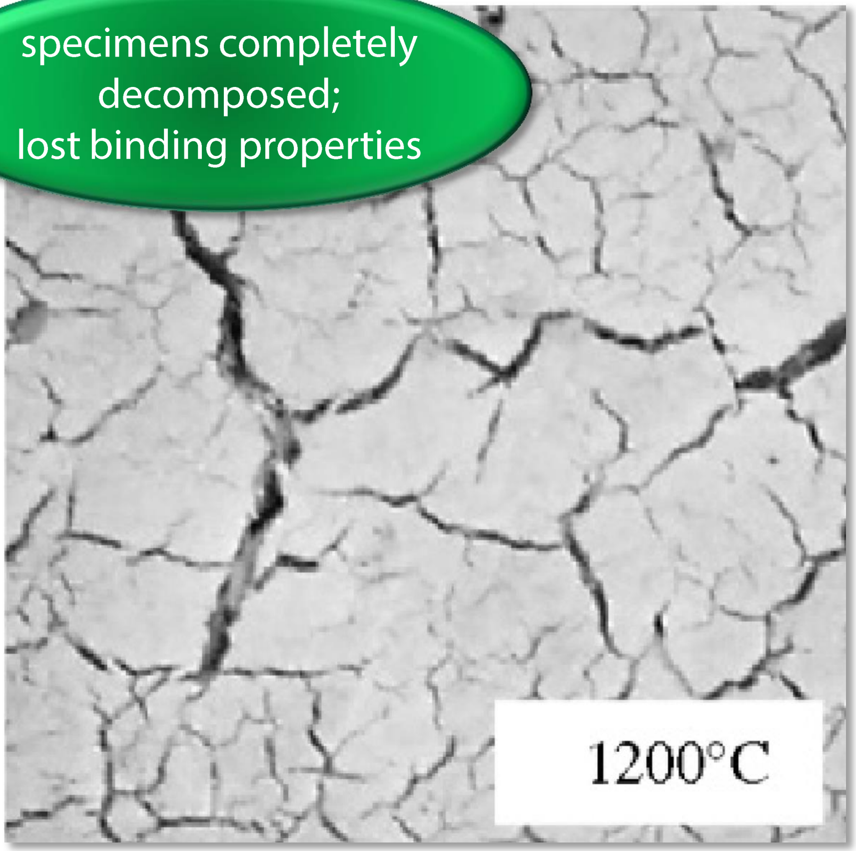

Surface texture of the concrete exposed to elevated temperatures

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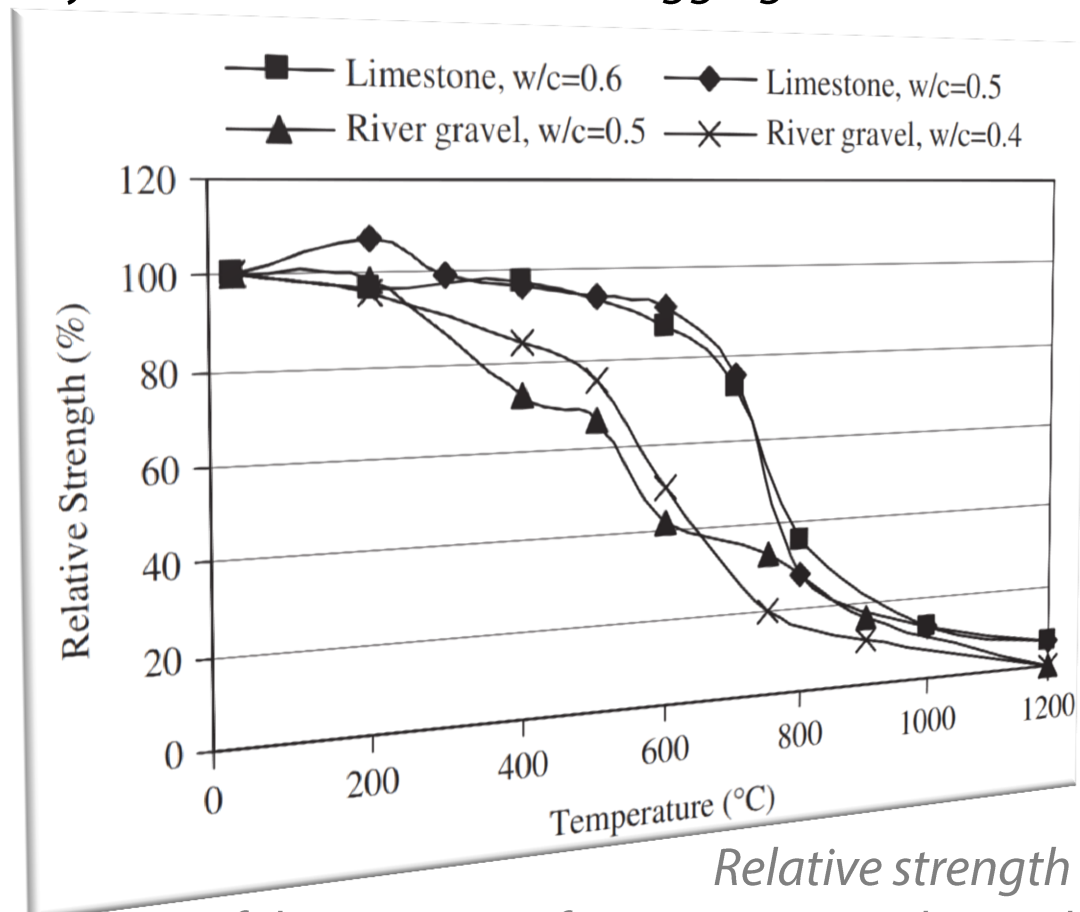
Aggregates of sedimentary rocks (crushed limestone aggregate)

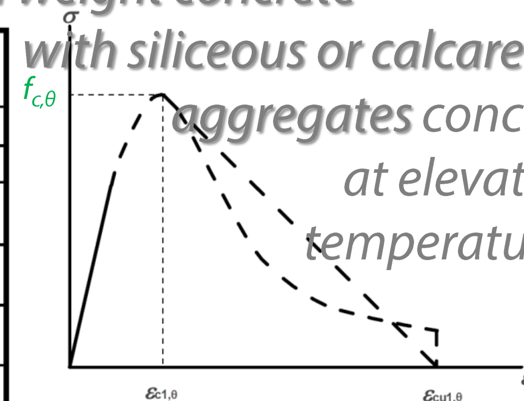
The effect of high temperatures on the relative strength of concrete ***was more pronounced*** *for concrete mixtures produced by* ***river gravel*** *aggregate. This can be attributed to the* ***siliceous composition*** *of the river gravels.*



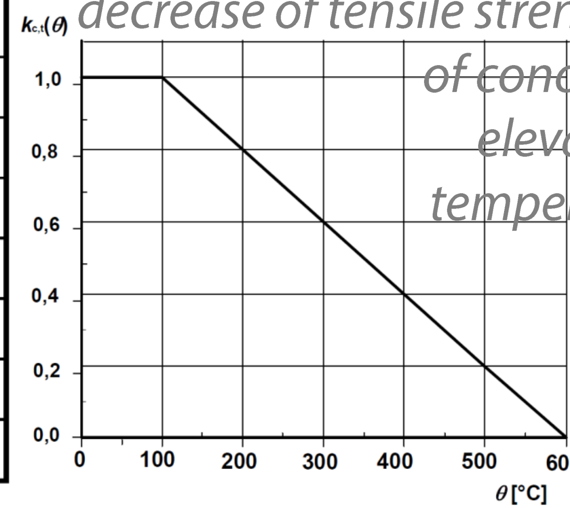
Relative strength of the concrete after exposure to elevated temperatures

Values for the main parameters of the stress-strain relationships of **normal weight concrete with siliceous or calcareous aggregates** concrete at elevated temperatures

Concrete temp. θ	Siliceous aggregates			Calcareous aggregates		
	$f_{c,\theta} / f_{ck}$	$\varepsilon_{c1,\theta}$	$\varepsilon_{cu1,\theta}$	$f_{c,\theta} / f_{ck}$	$\varepsilon_{c1,\theta}$	$\varepsilon_{cu1,\theta}$
[°C]	[-]	[-]	[-]	[-]	[-]	[-]
1	2	3	4	5	6	7
20	1,00	0,0025	0,0200	1,00	0,0025	0,0200
100	1,00	0,0040	0,0225	1,00	0,0040	0,0225
200	0,95	0,0055	0,0250	0,97	0,0055	0,0250
300	0,85	0,0070	0,0275	0,91	0,0070	0,0275
400	0,75	0,0100	0,0300	0,85	0,0100	0,0300
500	0,60	0,0150	0,0325	0,74	0,0150	0,0325
600	0,45	0,0250	0,0350	0,60	0,0250	0,0350
700	0,30	0,0250	0,0375	0,43	0,0250	0,0375
800	0,15	0,0250	0,0400	0,27	0,0250	0,0400
900	0,08	0,0250	0,0425	0,15	0,0250	0,0425
1000	0,04	0,0250	0,0450	0,06	0,0250	0,0450
1100	0,01	0,0250	0,0475	0,02	0,0250	0,0475
1200	0,00	-	-	0,00	-	-



Coefficient $k_{c,t}(\theta)$ allowing for decrease of tensile strength ($f_{ck,t}$) of concrete at elevated temperatures



f_{ck} Characteristic compressive cylinder strength of concrete at 28 days

f_{ctk} Characteristic axial tensile strength of concrete

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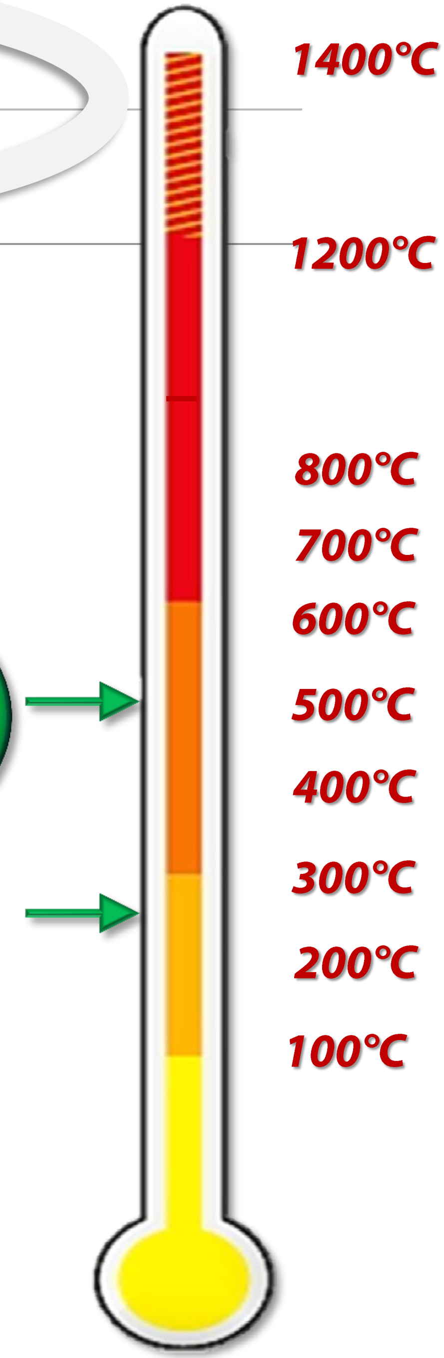
more susceptible to fire damage and elevated temperatures

CONCRETE

REINFORCING STEEL

PRESTRESSING STEEL



When the temperature of reinforced concrete reaches ***250°C****,*
the yield strength of steel bars is reduced,
and at ***500°C*** *it is reduced so much*
that there is a risk of structure collapse.

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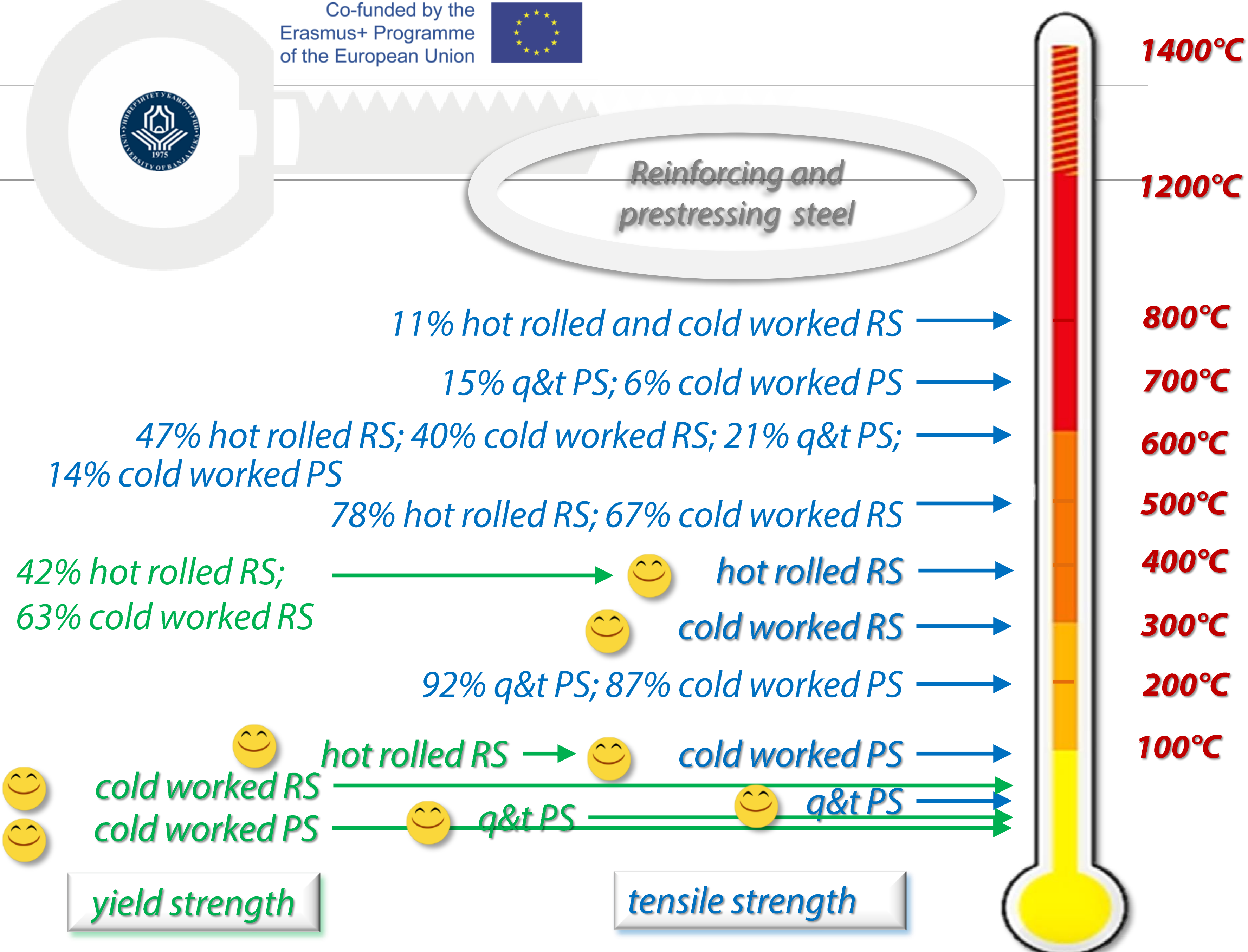
Reinforcing and prestressing steel



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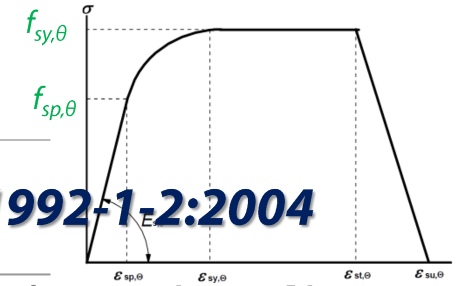
Reinforcing steel

EN 1992-1-2:2004



Values for the parameters of the stress-strain relationship of **hot rolled** and **cold worked RS** at elevated temperatures

Steel Temperature θ [°C]	$f_{sy,\theta} / f_{yk}$		$f_{sp,\theta} / f_{yk}$		$E_{s,\theta} / E_s$	
	hot rolled	cold worked	hot rolled	cold worked	hot rolled	cold worked
1	2	3	4	5	6	7
20	1,00	1,00	1,00	1,00	1,00	1,00
100	1,00	1,00	1,00	0,96	1,00	1,00
200	1,00	1,00	0,81	0,92	0,90	0,87
300	1,00	1,00	0,61	0,81	0,80	0,72
400	1,00	0,94	0,42	0,63	0,70	0,56
500	0,78	0,67	0,36	0,44	0,60	0,40
600	0,47	0,40	0,18	0,26	0,31	0,24
700	0,23	0,12	0,07	0,08	0,13	0,08
800	0,11	0,11	0,05	0,06	0,09	0,06
900	0,06	0,08	0,04	0,05	0,07	0,05
1000	0,04	0,05	0,02	0,03	0,04	0,03
1100	0,02	0,03	0,01	0,02	0,02	0,02
1200	0,00	0,00	0,00	0,00	0,00	0,00

f_{yk} Characteristic yield strength of reinforcement

$f_{sk}(\theta)$ Characteristic strength of reinforcing steel at temperature θ for a specified strain

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EN 1992-1-2:2004

*Values for the parameters of the stress-strain relationship of **cold worked (cw) (wires and strands)** and **quenched and tempered (q&t) (bars) prestressing steel** at elevated temperatures*

Steel temp. θ [°C]	$f_{py,\theta} / (\beta f_{pk})$			$f_{pp,\theta} / (\beta f_{pk})$		$E_{p,\theta} / E_p$		$\varepsilon_{pt,\theta}$ [-]	$\varepsilon_{pu,\theta}$ [-]
	cw		q & t	cw	q & t	cw	q & t	cw, q&t	cw, q&t
	Class A	Class B							
1	2a	2b	3	4	5	6	7	8	9
20	1,00	1,00	1,00	1,00	1,00	1,00	1,00	0,050	0,100
100	1,00	0,99	0,98	0,68	0,77	0,98	0,76	0,050	0,100
200	0,87	0,87	0,92	0,51	0,62	0,95	0,61	0,050	0,100
300	0,70	0,72	0,86	0,32	0,58	0,88	0,52	0,055	0,105
400	0,50	0,46	0,69	0,13	0,52	0,81	0,41	0,060	0,110
500	0,30	0,22	0,26	0,07	0,14	0,54	0,20	0,065	0,115
600	0,14	0,10	0,21	0,05	0,11	0,41	0,15	0,070	0,120
700	0,06	0,08	0,15	0,03	0,09	0,10	0,10	0,075	0,125
800	0,04	0,05	0,09	0,02	0,06	0,07	0,06	0,080	0,130
900	0,02	0,03	0,04	0,01	0,03	0,03	0,03	0,085	0,135
1000	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,090	0,140
1100	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,095	0,145
1200	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,100	0,150

Note: For intermediate values of temperature, linear interpolation may be used.

f_{pk} Characteristic tensile strength of prestressing steel
$f_{pk}(\theta)$ Characteristic strength of prestressing steel at temperature θ for a specified strain

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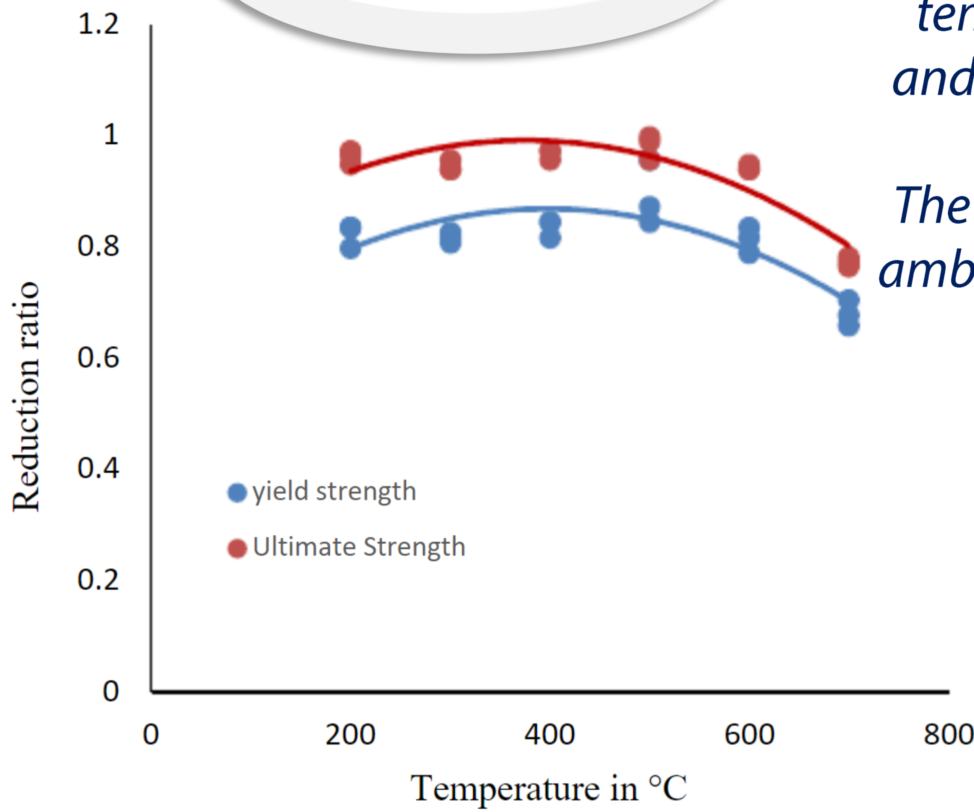
EXAMPLE OF RESEARCH

Mohammad Suhaib Ahmad: Effect of Sustained Elevated temperature on Mechanical Behavior of Reinforcing Bar, Procedia Engineering 173, 2017, pp. 905 – 909

Reinforcing steel



Reduction ratio in yield strength and ultimate strength with increase in temperatures

20 mm diameter bars were heated at temperatures 200, 300, 400, 500, 600 and 700°C and were sustained for 0.5,1 and 2 h.
The bars were cooled naturally in air to ambient temperature and were tested in tension.

Reduction in yield strength is significantly higher in comparison to ultimate strength

https://www.researchgate.net/publication/314250409_Effect_of_Sustained_Elevated_Temperature_on_Mechanical_Behavior_of_Reinforcing_Bar

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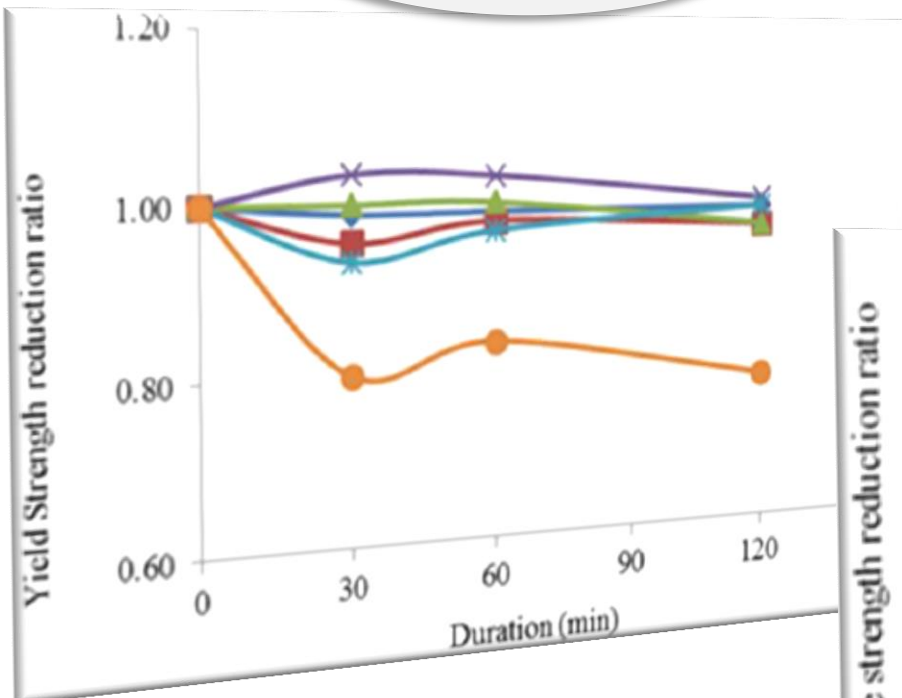
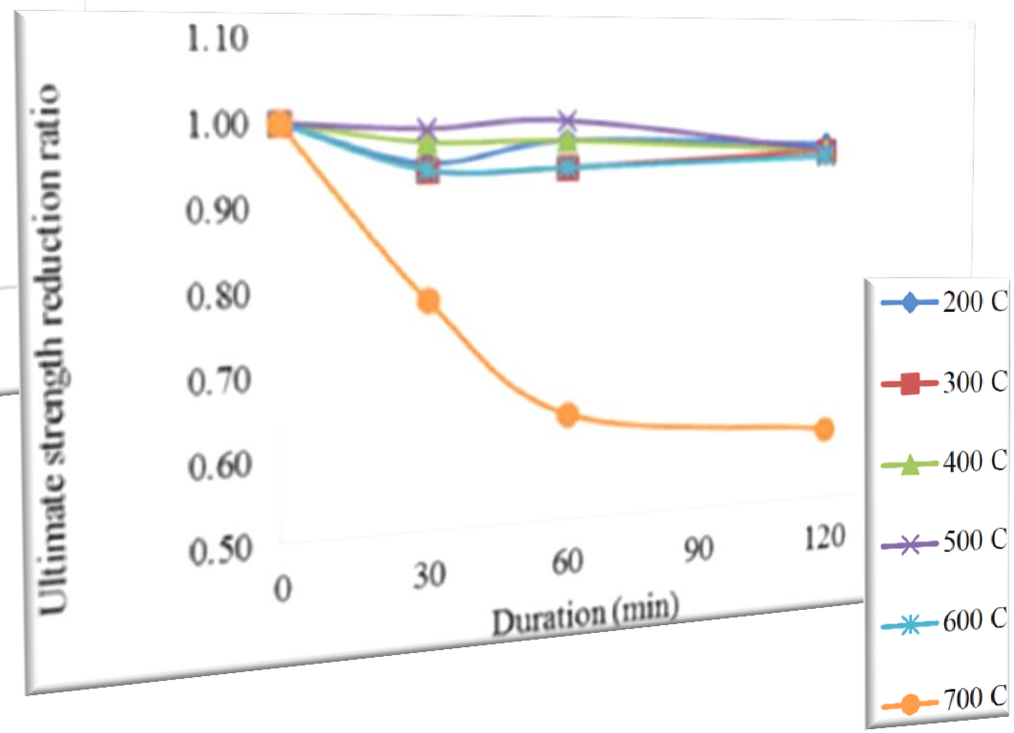


The change in yield strength reduction ratio with duration for all the temperature

The change in ultimate reduction ratio with duration for all the temperatures



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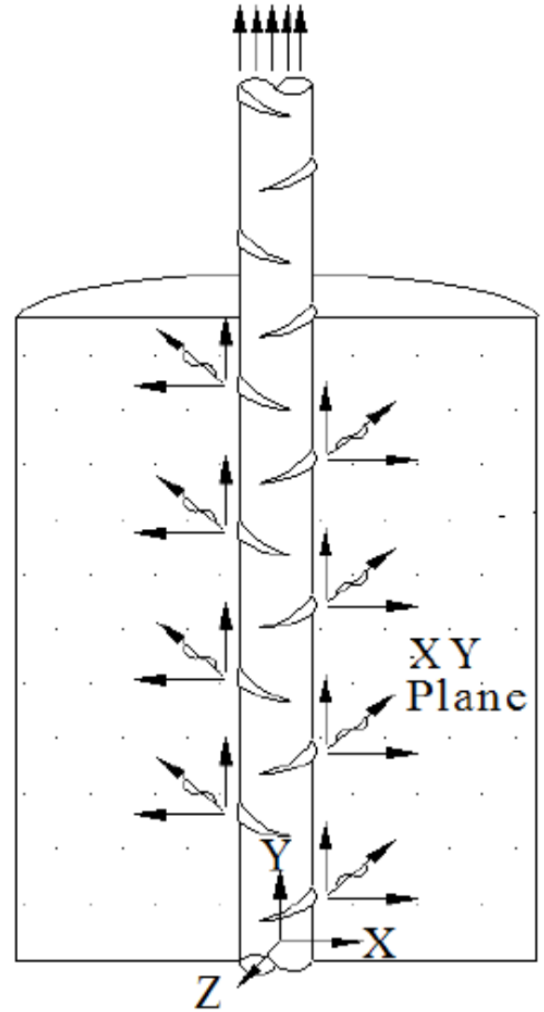
Bond between concrete and steel

The bond between concrete and steel
can be adversely affected
at temperatures
higher than 300°C
*because of the greater **thermal conductivity of steel***
compared to the cover concrete and
differences in thermal expansion properties.



https://www.researchgate.net/publication/266143966_Bond_stress_behavior_between_concrete_and_steel_rebar_Critical_investigation_of_pull-out_test_via_Finite_Element_Modeling

CONCRETE

Conclusion

- *There are differences in the meaning of the terms REACTION TO FIRE and RESISTANCE TO FIRE.*
- *According to EN 13501-1, the concrete is classified as Euro Class A1, which does not require a fire testing.*
- *Type and properties of aggregate play an important role on the properties of concrete exposed to elevated temperatures.*
- *From the aspect of resistance to fire, the least favorable aggregates are obtained from rocks of metamorphic origin, primarily of quartzite rocks.*
- *In this sense, dolomite aggregates, limestone aggregates, recycled aggregate of crushed brick and granulated slag, may be preferred.*

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Conclusion

STEEL

- *Steel is more susceptible to fire damage and elevated temperatures, compared to concrete.*
- *Prestressing steel is more susceptible to fire damage and elevated temperatures, compared to reinforcing steel.*
- *When the temperature of reinforced concrete reaches 250℃, the yield strength of steel bars is reduced and at 500℃ it is reduced so much that there is a risk of structure collapse.*
- *Reduction in yield strength is significantly higher in comparison to ultimate strength.*
- *The bond between steel and concrete can be adversely affected at temperatures higher than 300°C.*

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Thank you for your attention

Ass. prof. Gordana Broćeta
gordana.broceta@aggf.unibl.org

Knowledge **FO**r **R**esilient so**C**i**E**ty