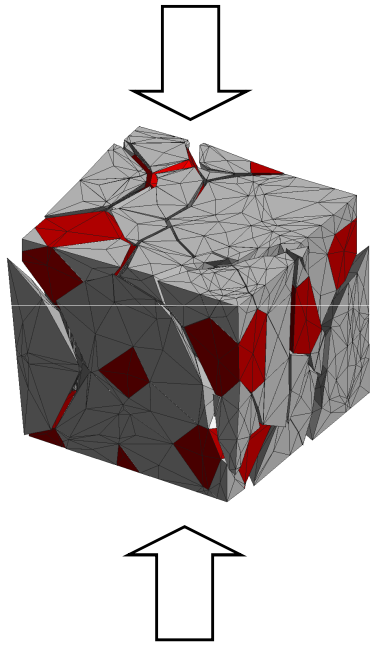
MESO-MECHANICAL STUDY OF HIGH-TEMPERATURE CRACKING IN MORTAR AND CONCRETE SPECIMENS USING FRACTURE-BASED ZERO-THICKNESS INTERFACES



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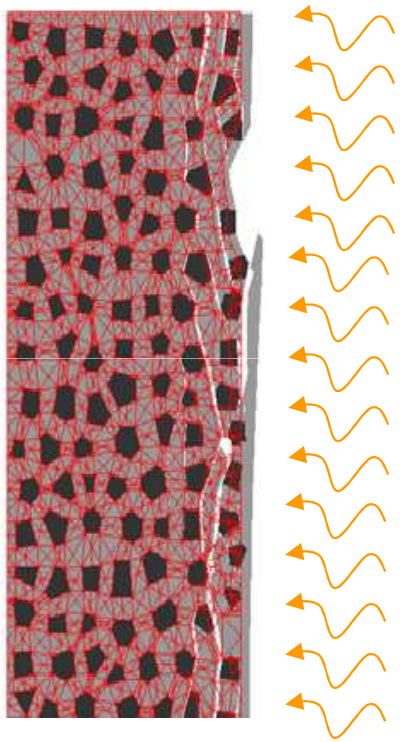
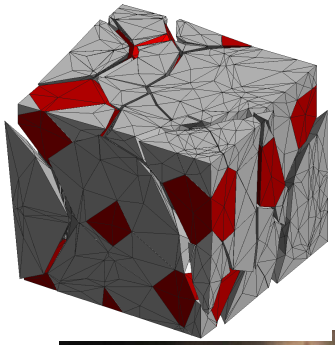
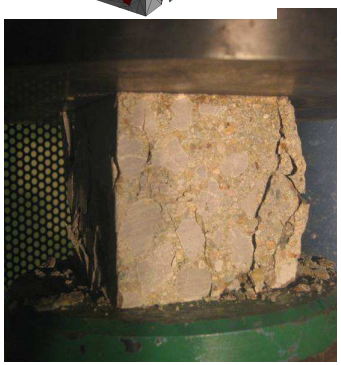


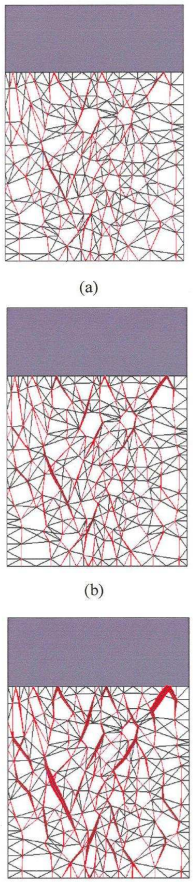
BACKGROUND

-*Mesomechanics of concrete and mortar at cm/mm scale using fracture-based interface elements,*

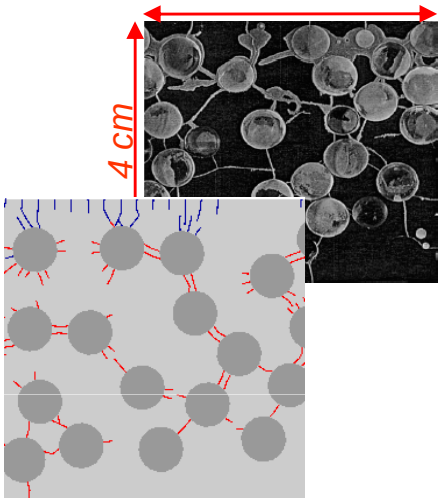
-*Extensive verification for cracking-dominated mechanical and as diffusion-driven behavior (drying shrinkage, sulfate attack.)*

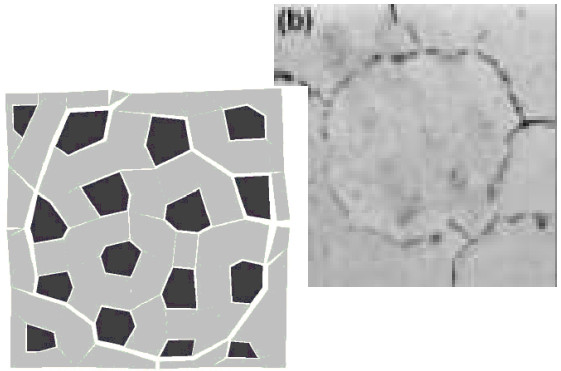


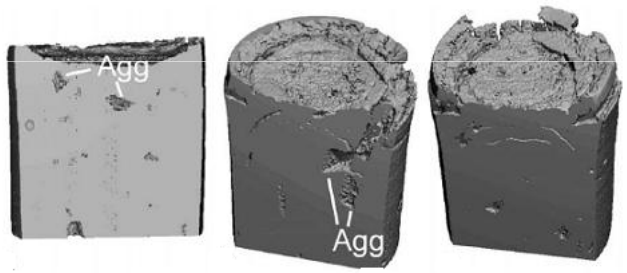




Crack evolution for σ = 31 MPa, at t - t'= a) 0, b) 100 and c) 10000 days (t´ = 28 days).



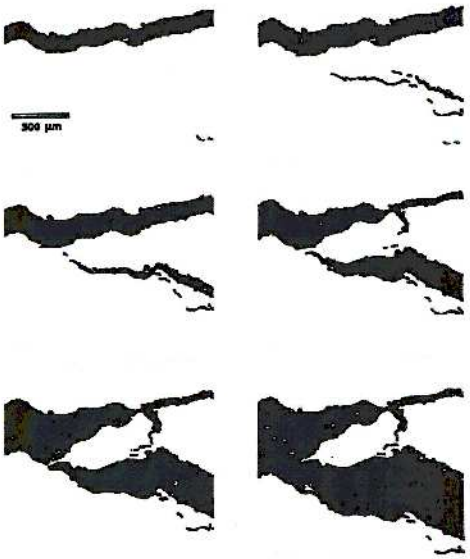




Lopez et al(2000), Lopez and Carol (2001), Roa et al (2001), Caballero et al 2004,2005,2006, 2007), Idiart et al (2010, 2011), Rodriguez et al (2011).

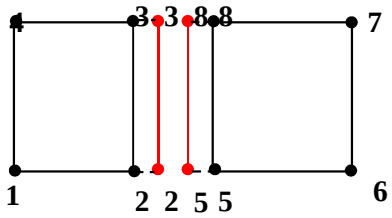
CHARACTERISTIC INGREDIENT: CRACKS via INTERFACE ELEMENTS pre-inserted along FE MESH LINES

Complex physical phenomena: (bridging, branching, etc)

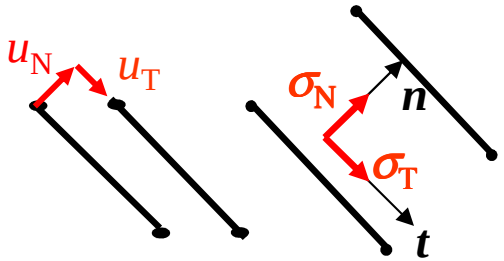


(from *Fracture processes in concrete,* van Mier, 1997)

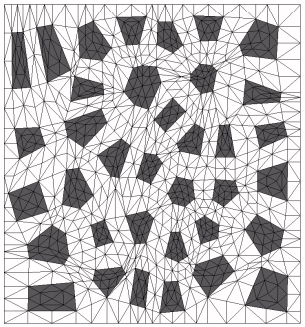
Modeling via zero-thickness interface elements



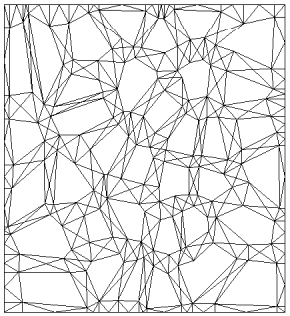
Insertion between standard FE



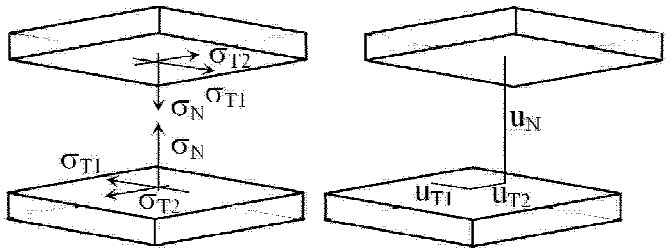
2D
Constitutive variables
3D



Full FE mesh



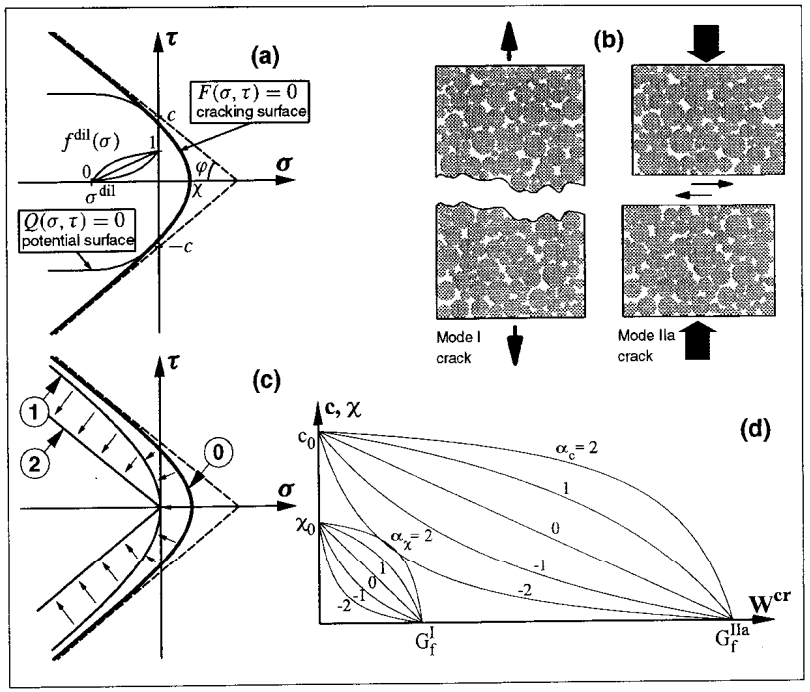
Interface elements



INTERFACE CONSTITUTIVE MODEL

(Carol, Prat, Lopez, JEM 1997… Caballero, Willam, Carol CMAME 2008)

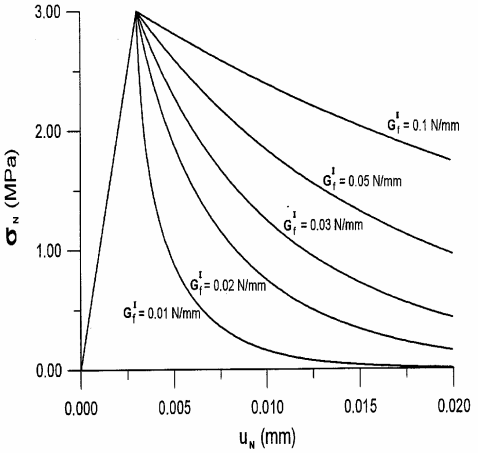
Within Elasto-Plastic framework



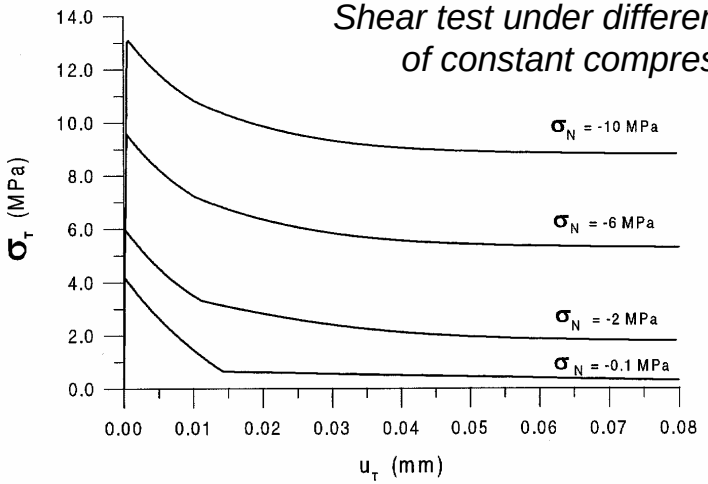
- Static Variables: normal and tangential stresses σ_N, τ
- Kinematic variables: normal and tangential relative displacements
- Hyperbolic fracture surface
- Associated flow in tension, dilatancy reduced in compression
- Work-softening in terms of W^{cr}, with parameters G_f^I and G_f^{IIa}

Resulting interface behavior

Pure tensile behavior



Shear test under different values of constant compression



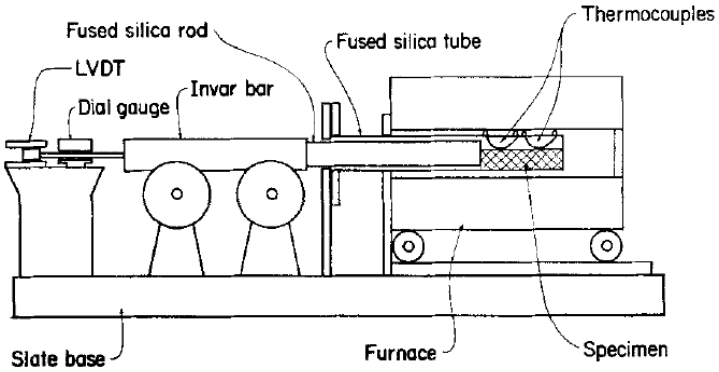
Motivation: EXPERIMENTS BY CRUZ AND GUILLEN (1980)

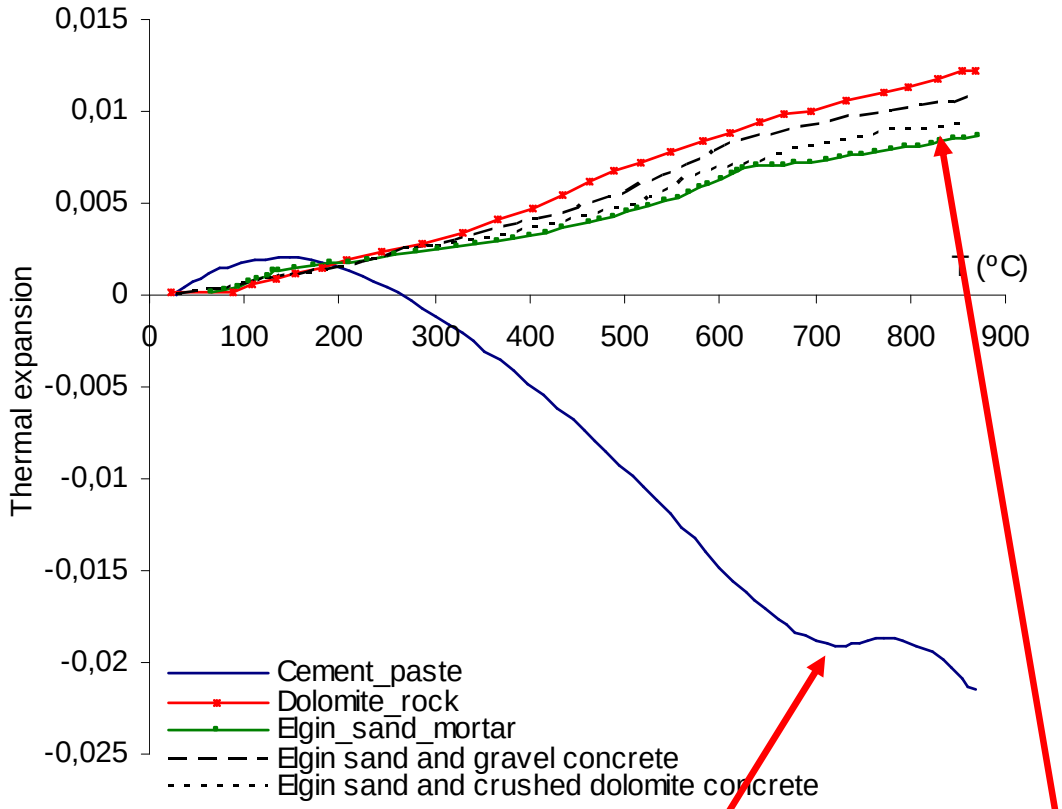
–**FREE EXPANSION** of cement, rock, concrete and mortar specimens

–Small cylindrical specimens 13mm in diameter and 76mm in length (uniform temp assumed !)

–Purely mechanical approach (no consideration of diffusion/flow)

–Temperature range: 27 – 871ºC





CONTRACTION of cement paste….

but OVERALL EXPANSION due to cracking !

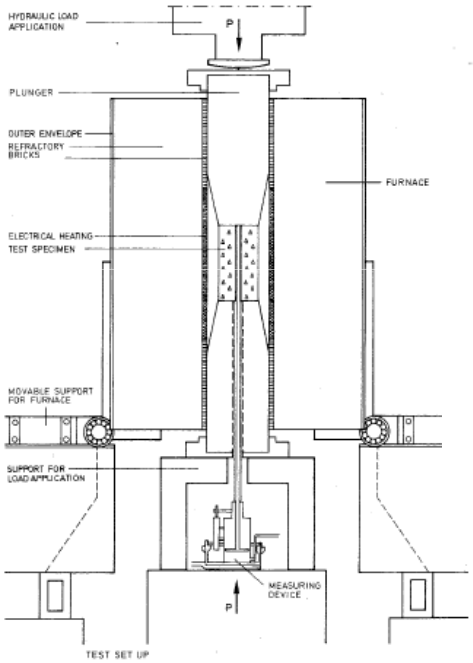
Motivation (cont): EXPERIMENTS BY ANDERBERG AND THELANDERSSON 1976 ("LITS effect")

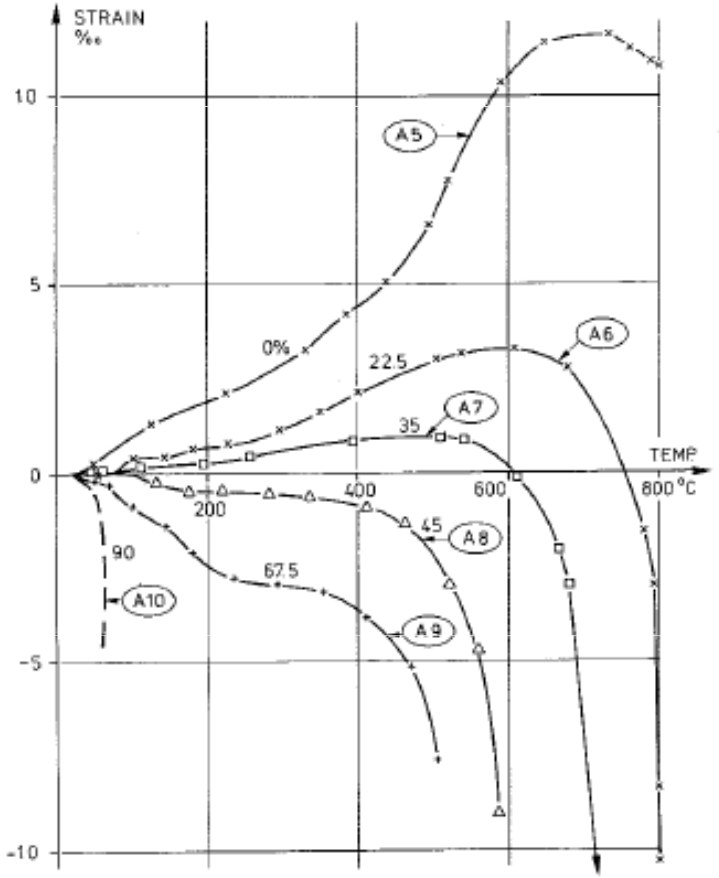
–EXPANSION UNDER CONSTANT STRESS of concrete specimens

–Cylindrical samples 75mm in diameter and 150mm in length

–Purely mechanical approach (no explicit consideration of diffusion/flow)

–Temperature range: 20 – 800ºC





NO SUPERPOSITION PRINCIPLE between applied stress and ΔT !

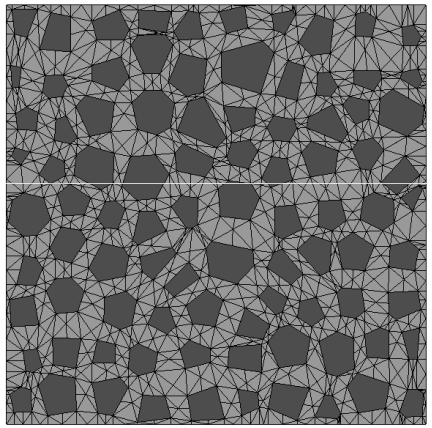
MAIN OBJECTIVES OF THIS STUDY

- General: To extend the existing meso-model to represent high temp effects.
- Initially, consider only mechanical effects of differential expansions, taking as input data the expansion curves by Cruz and Guillen and uniform temp.
- Consider interaction with loadign, see the resulting combined effect on cracking, deformations, comparison to LITS (uniform temp.)
- Consider transient temp, ISO Curve, spalling.

OUTLINE

- Introduction (background, motivation, objectives..)
- Application of the numerical model to the basic known cases
- Numerical simulations of spalling of wall subject to heating.
- Concluding remarks

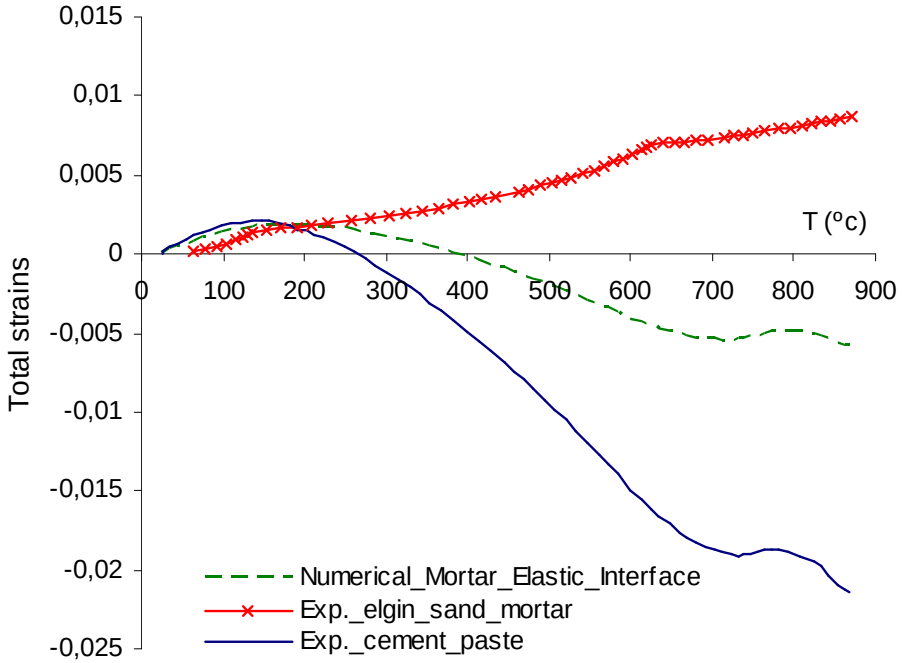
NUMERICAL RESULTS FOR FREE EXPANSION OF MORTAR, UNIFORM TEMP.



- Two-phase composite
- Cement paste with a variable coefficient of thermal expansion, extracted from the experimental cement paste curve.
- Sand with a constant coefficient of thermal expansion
- 12x12 mm square specimens
- Volume fraction of sand: 39%
- Maximum size aggregate: 1.7mm

➢Preliminary Elastic analysis

- Interfaces are not allowed to open or slide
- The changes of expansion to contraction is delayed.



NUMERICAL RESULTS FOR FREE EXPANSION OF MORTAR, UNIFORM TEMP.(2)

➢ Non-linear analysis with cracking

- Interface elements allowed to open/slide if cracking conditions are reached (constitutive model)

Interface constitutive parameters:

E = 70000 MPa (dolomite rock)

E = 25000 MPa (cement paste) and υ= 0.2 (both).

All interfaces:

$K_N = K_T$ = 500000 MPa/mm

$\tan\phi_0$ = 0.90

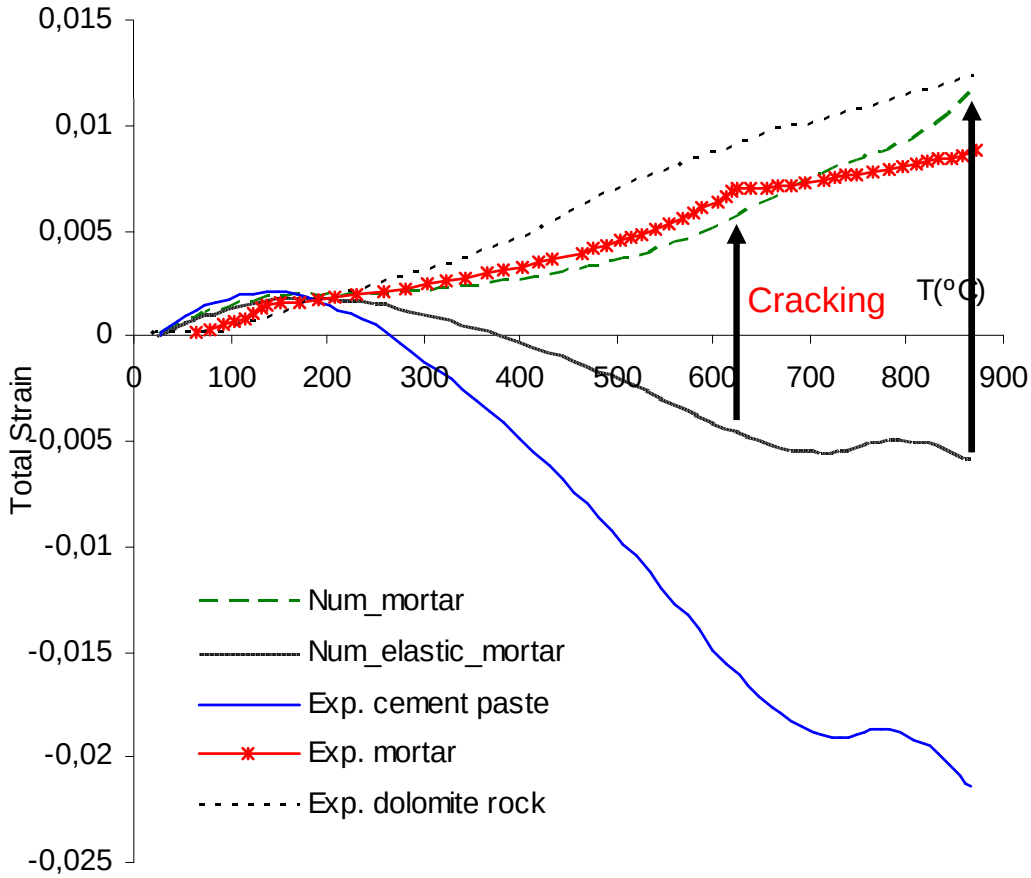
χ_0 =6 MPa

c_0 = 15MPa

G^F_I = 0.025 N.mm, $G^F_{II} = 10G^F_I$

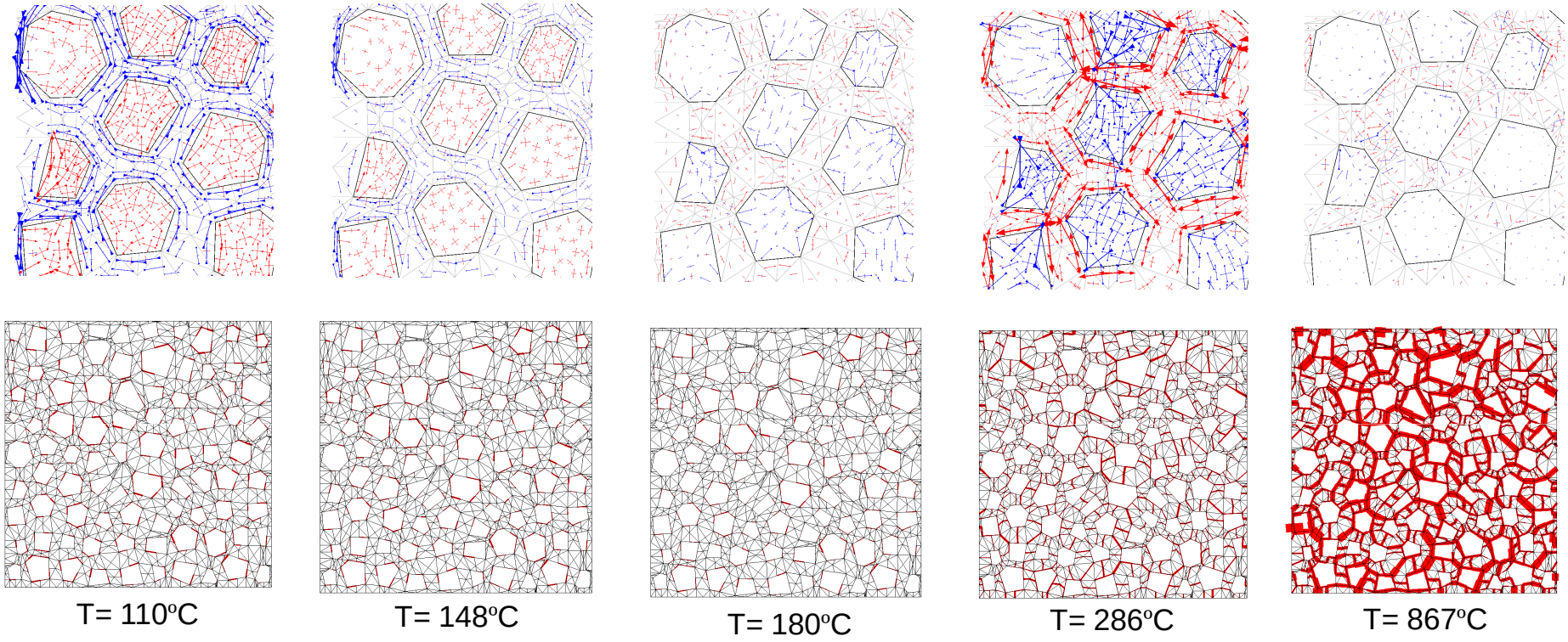
σ_{dil} = 40 MPa

α_d = -2.



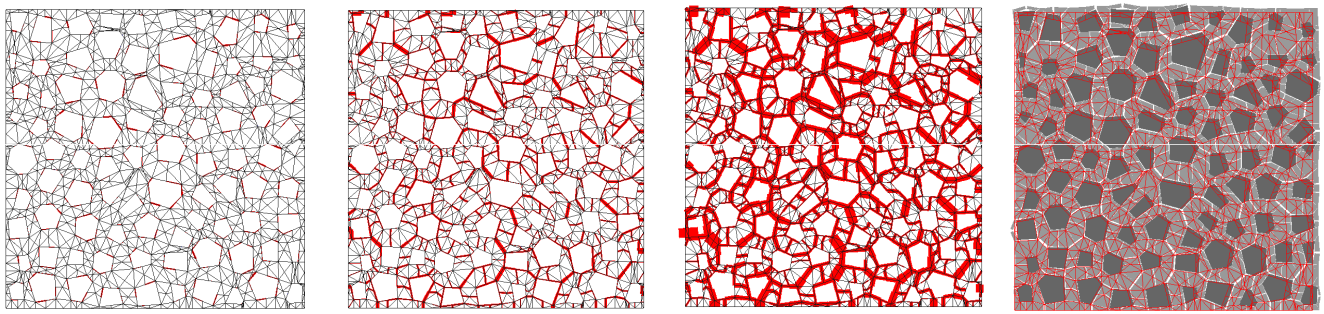
NUMERICAL RESULTS FOR FREE EXPANSION OF MORTAR, UNIFORM TEMP.(3)

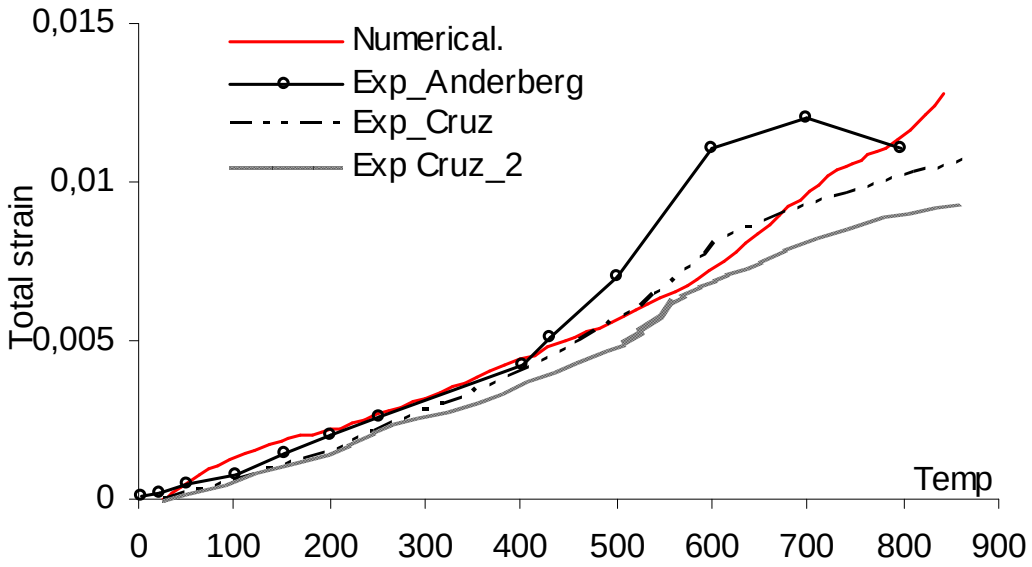
Evolution of continuum stresses and crack opening



NUMERICAL RESULTS FOR FREE EXPANSION OF CONCRETE, UNIFORM TEMP.

- Two-phase composite
- Mortar with a variable coefficient of thermal expansion extracted from numerical mortar curve.
- Large aggregates with a constant coefficie of thermal expansion
- 10x10 cm square specimens
- Volume fraction of sand: 28%
- Maximum aggregate size: 14mm





Material parameters:

E = 70000 MPa (dolomite rock)

E = 29000 MPa (mortar) and υ= 0.2 (both).

Aggregate-mortar interfaces:	Mortar-mortar interfaces:
$K_N = K_T$ = 500000 MPa/mm	$K_N = K_T$ = 500000 MPa/mm
$\tan\phi_0$ = 0.90	$\tan\phi_0$ = 0.90
χ_0 =4 MPa	χ_0 =6 MPa
c_0 = 15MPa	c_0 = 20MPa
G^F_I = 0.025 N.mm, $G^F_{II} = 10G^F_I$ $G^F_{II} = 10G^F_I$	G^F_I = 0.030 N.mm,
σ_{dil} = 40 MPa	σ_{dil} = 40 MPa
α_d = -2	α_d = -2

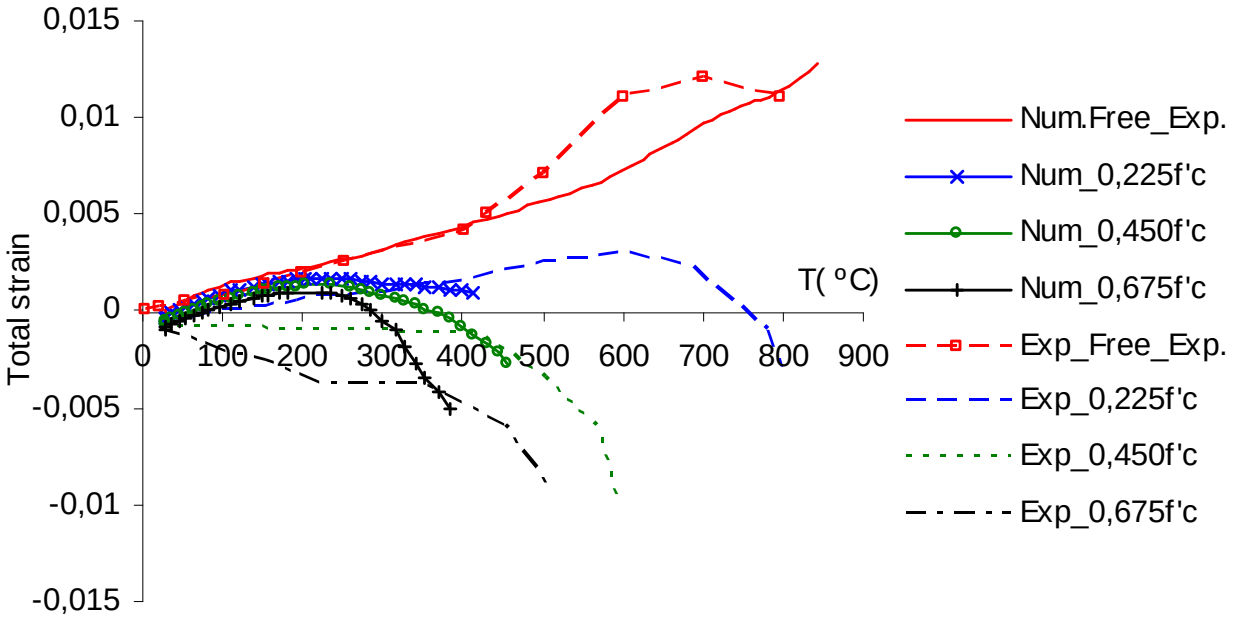
THERMAL EXPANSION OF CONCRETE UNDER UNIFORM TEMP + APPLIED STRESS (LITS EFFECT)

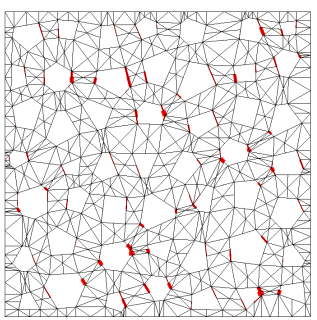
- The specimens were loading to a certain vertical stress level and then heated to 800ºC

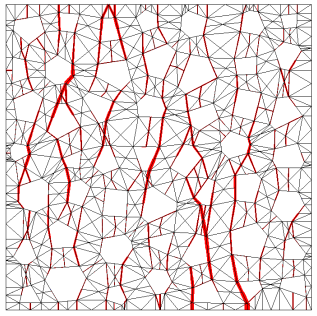
- The stress level is given as a percentage of compressive strength of the material

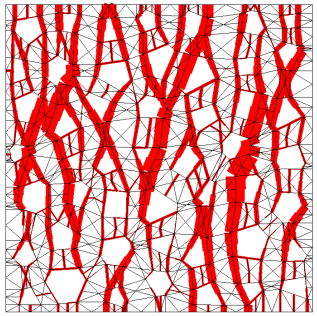
- Three cases were analyzed

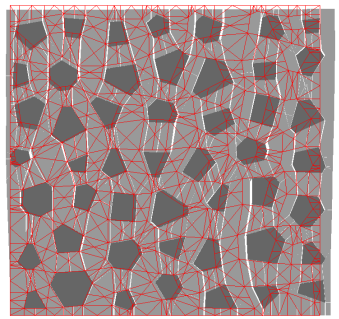
- Experimental curves were moved to the origin after the pre-compression (as it was done in exp. curves)




T = 157ºC


T = 352ºC


T = 494ºC


T = 494ºC

EXPANSION OF MORTAR UNDER UNIFORM TEMP+APPLIED STRESS (numerical only)

- The mesh used is the same as the one used for previous mortar analysis

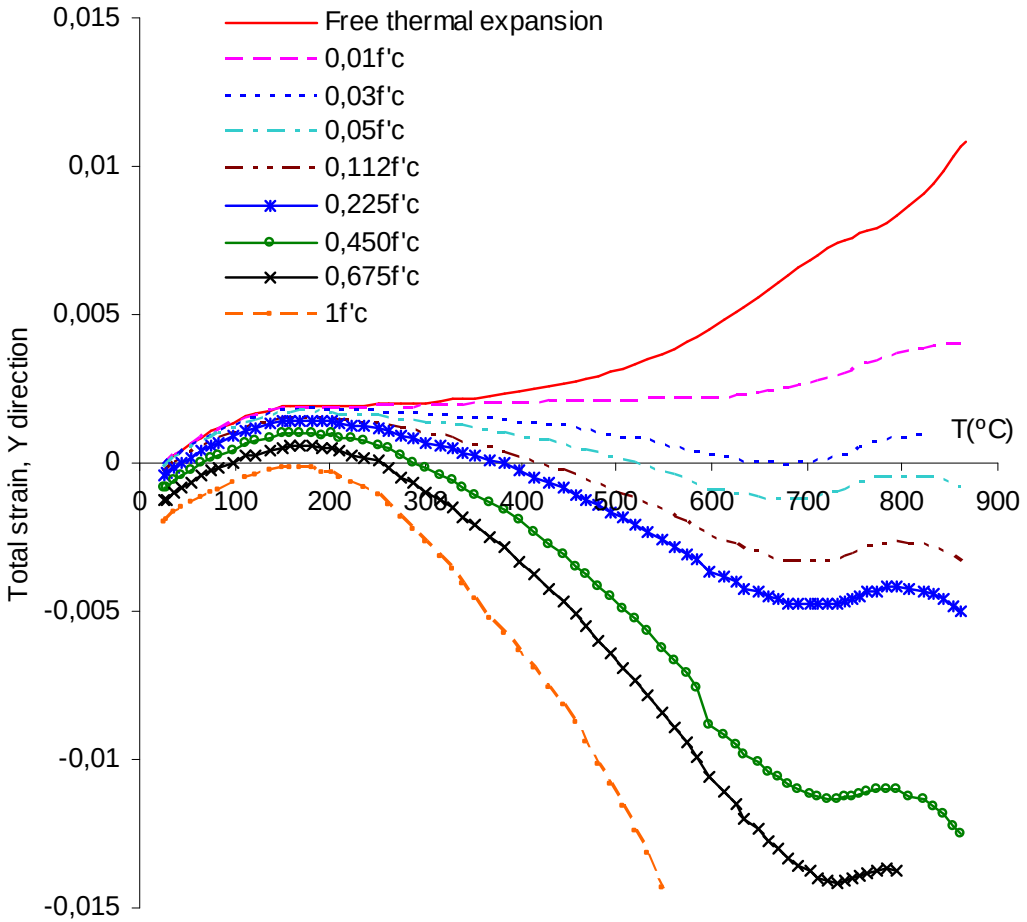
- Ten cases were analyzed

- Experimental curves were not corrected to the origin

- The effect of compression is reflected by the shift downwards of each curve (not moved here)

- For T < 200 ºC aprox, both effects loading and thermal, could be simply superimposed

-For higher temperature, the curves tend to follow the matrix compression, cracking and overall deformation are delayed



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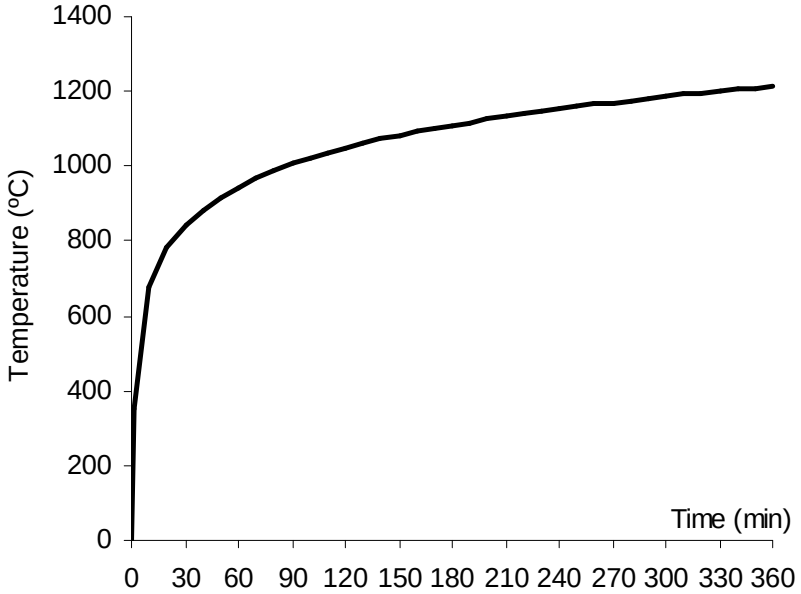
TIME-DEPENDENT IMPOSED TEMPERATURE VALUES on boundary (ISO 834), TRANSIENT THERMAL ANALYSIS ON THE SAME MESH

$$T = 345 Log10(8t + 1) + 20$$



Thermal parameters		
	Mortar	Aggregate
Thermal conductivity [J/min cm ºC]	*0,66*	*1,1*
Density [Kg/cm3]	*0,0023*	*0,0026*
Specific heat [J/KgºC]	*1,17E+03*	*7,11E+02*
Difussivity [cm2/min]	*0,24*	*0,60*
Thermal Expansion coeff. [1/ºC]	*variable*	*cte. = 0,0000125*

Material parameters:

E = 70000 MPa (aggregate)

E = 29000 MPa (cement paste) and υ= 0.2 (both).

Aggregate-cement paste interfaces:

$K_N = K_T$ = 500000 MPa/mm

$\tan\phi_0$ = 0.90

χ_0 =4 MPa

c_0 = 15MPa

G^F_I = 0.03 N.mm, $G^F_{II} = 10G^F_I$

σ_{dil} = 40 MPa

α_d = -2.

Cement-cement interfaces:

$K_N = K_T$ = 500000 MPa/mm

$\tan\phi_0$ = 0.90

χ_0 =6 MPa

c_0 = 22.5MPa

G^F_I = 0.06 N.mm, $G^F_{II} = 10G^F_I$

σ_{dil} = 40 MPa

α_d = -2.

EVOLUTION OF CRACKING, ELEMENT REMOVAL AFTER $W_{cr}=G_f^I$

T = 420ºC
t = 1.67 min

T = 640ºC
t = 7.70 min

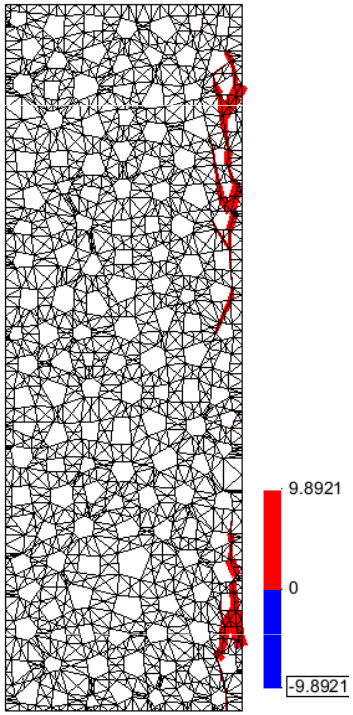
T = 660ºC
t = 8.82 min

T = 680ºC
t = 10.10 min

T = 700ºC
t = 11.56 min

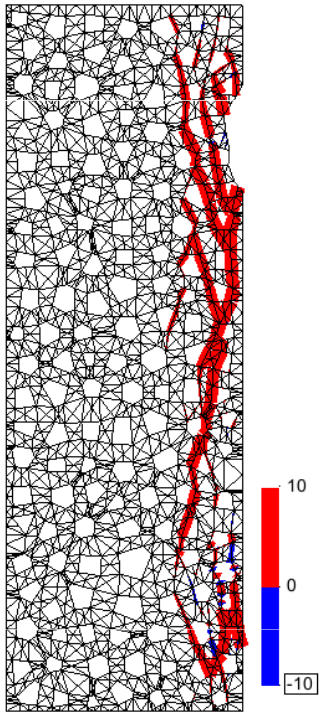
T = 720ºC
t = 13.23 min

Wcr/Gfl



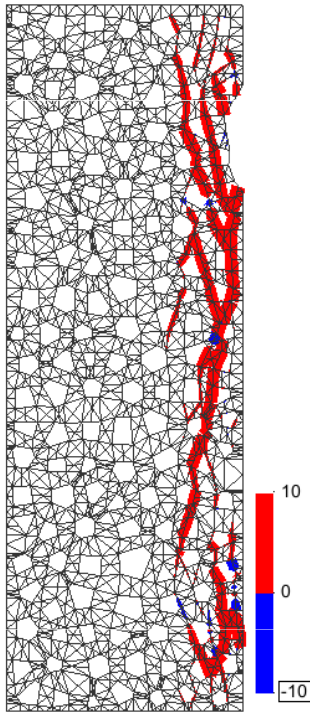
T = 420ºC

t = 1.67 min



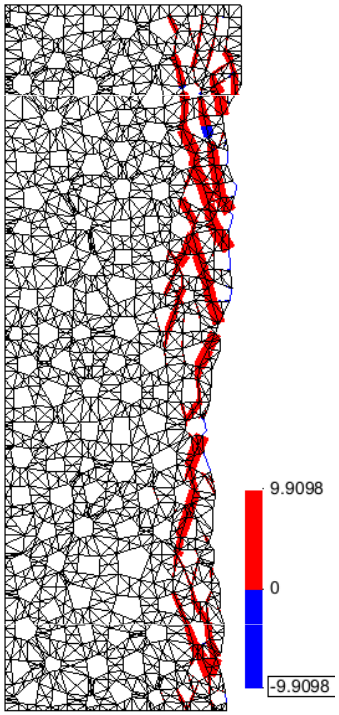
T = 640ºC

t = 7.70 min



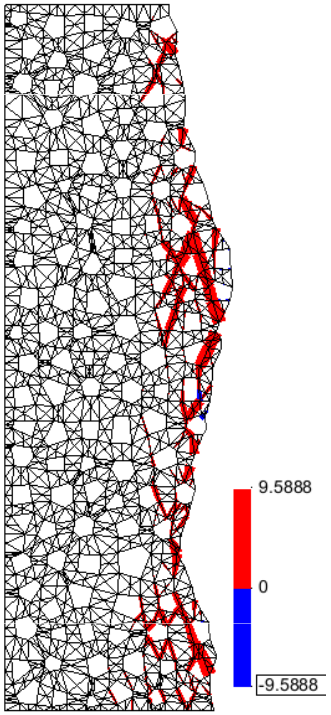
T = 660ºC

t = 8.82 min



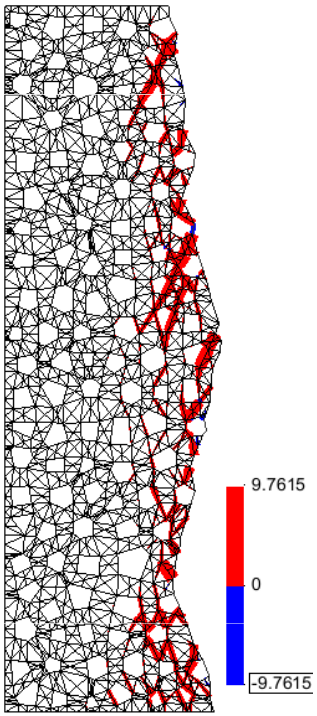
T = 680ºC

t = 10.10 min



T = 700ºC

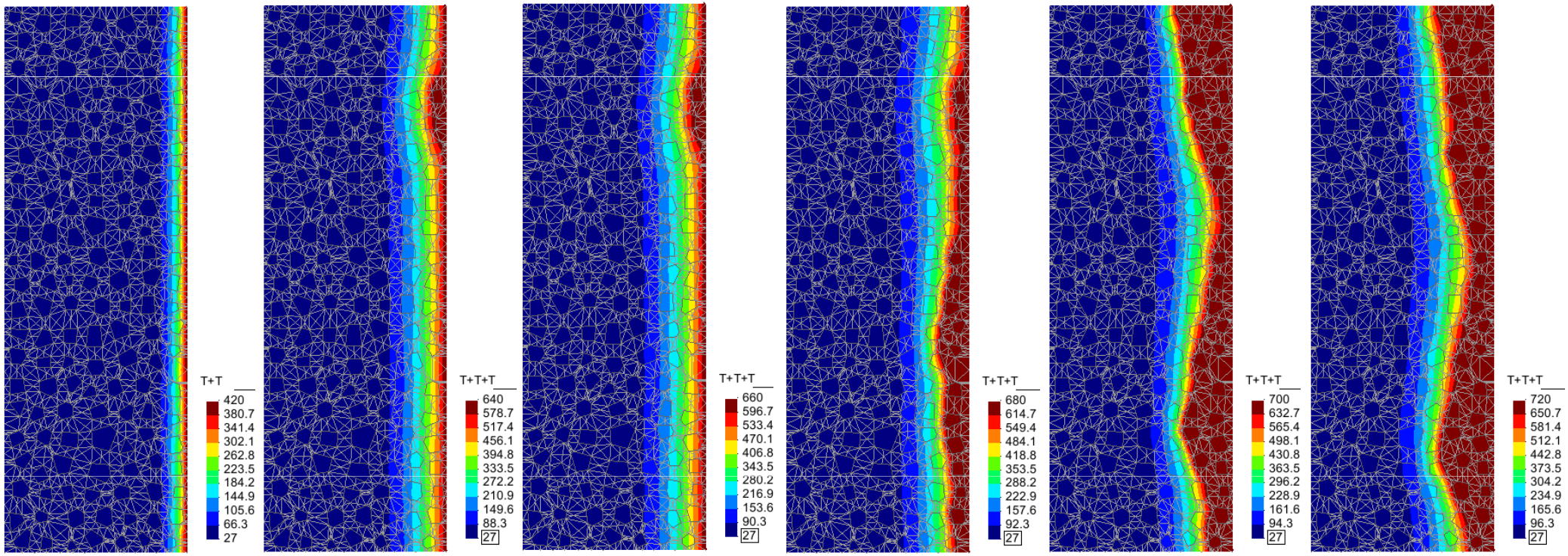
t = 11.56 min



T = 720ºC

t = 13.23 min

TIME-DEPENDENT IMPOSED TEMPERATURE VALUES (ISO 834), APPLIED ON SPALLED SURFACE(!)



T = 420ºC

t = 1.67 min

T = 640ºC

t = 7.70 min

T = 660ºC

t = 8.82 min

T = 680ºC

t = 10.10 min

T = 700ºC

t = 11.56 min

T = 720ºC

t = 13.23 min

CONCLUDING REMARKS

- In spite of simplistic assumptions, the meso-model seems to capture the main trends of classical high temperature experimental observations on concrete and mortar.
- Free expansion tests are dominated by the expanding aggregates, while in pre-compressed tests cracking perpendicular to the stress is reduced or prevented altogether, leading to LITS.
- Removal of concrete pieces leads to clear spalling, progressing into specimen.
- Updating Temp. B.C to spalled surface actually introduces T-M COUPLING. However, effect may be too drastic, since spalling does not stop, eventually erodes totally the cross-section. In reality probably pieces stay, slows down BC penetration.
- On-going work aims at combining this purely mechanical description with a diffusion model for the heat transfer and humidity migration within cement paste,
- …as well as 3D extension.

Thanks for your Attention!

NON-UNIFORM TEMPERATURE DISTRIBUTION ANALYSIS

Thermal diffusion model. DRACFLOW → Temperature distribution for each time increment → Thermal deformation $\varepsilon = \alpha \Delta T$ → Meso-mechanical Model. DRAC

- The mesh used is the same as the one used for previous mortar and concrete analysis.

-The same expansion .vs. temperature law that in previous mortar and concrete uniform temperature are used.

- Thermal parameters are the same for concrete and mortar.

-An imposed temperature value of 400ºC is applied on the four faces of the specimens.

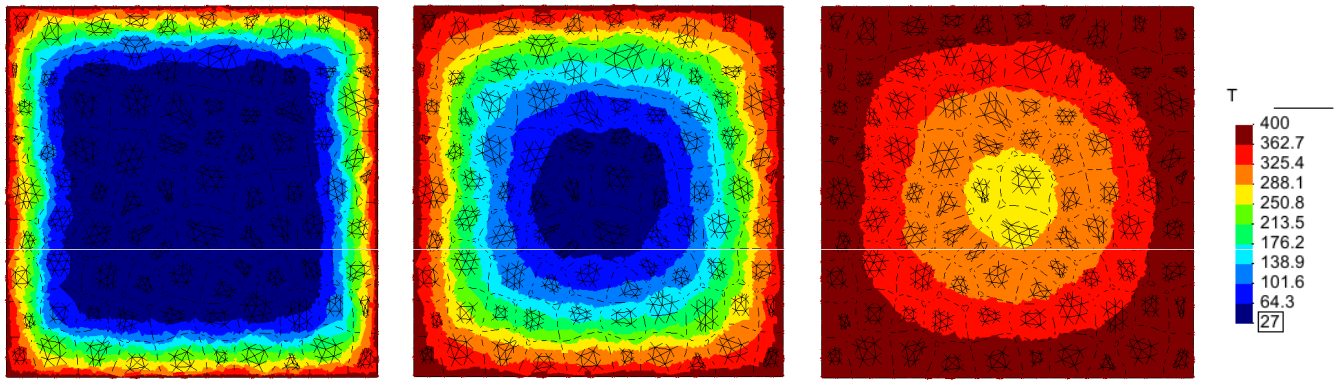
Thermal parameters		
	Mortar	Aggregate
Thermal conductivity [J/min cm ºC]	*0,84*	*1,44*
Density [Kg/cm3]	*0,0023*	*0,0026*
Specific heat [J/KgºC]	*1,17E+03*	*7,11E+02*
Difussivity [cm2/min]	*0,31*	*0,77*
Thermal Expansion coeff. [1/ºC]	*variable*	*cte. = 0,0000125*

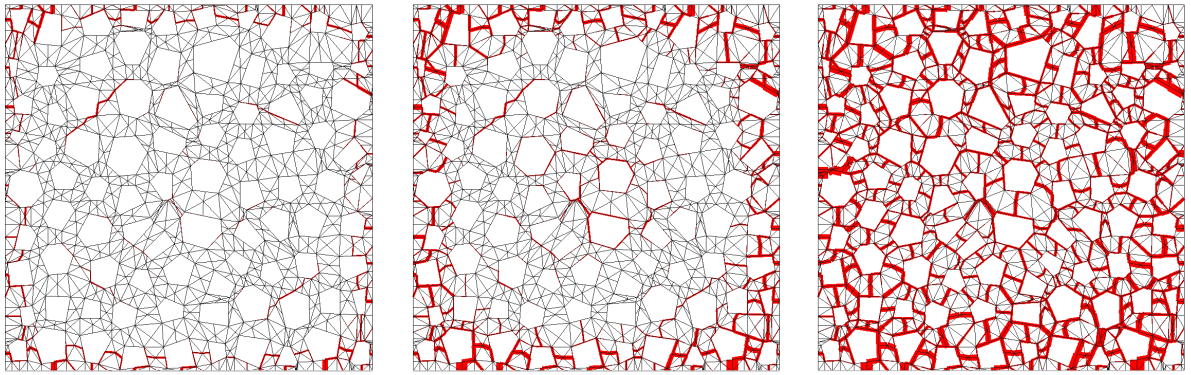
MORTAR SPECIMEN, FREE THERMAL EXPANSION (presc.fixedTemp on boundary)

- The temperature fronts move toward the center of the specimens in a not perfectly uniform manner due to the different diffusion coefficient for the two phases.

- In correspondence with the temperature changes, some microcracking is generated.

-Microcracking starts on the specimens surface and propagates inward until it becomes more or less uniform.





3 sec. 6 sec. 25,8 sec.

Material parameters:

E = 70000 MPa (dolomite rock)

E = 25000 MPa (cement paste) and υ= 0.2 (both).

Dolomite sand-cement interfaces:

$K_N = K_T$ = 500000 MPa/mm

$\tan\phi_0$ = 0.90

χ_0 =3 MPa

c_0 = 7,5MPa

G^F_I = 0.03 N.mm, $G^F_{II} = 10G^F_I$

σ_{dil} = 40 MPa

α_d = -2.

Cement-cement interfaces:

$K_N = K_T$ = 500000 MPa/mm

$\tan\phi_0$ = 0.90

χ_0 =6 MPa

c_0 = 15MPa

G^F_I = 0.06 N.mm, $G^F_{II} = 10G^F_I$

σ_{dil} = 40 MPa

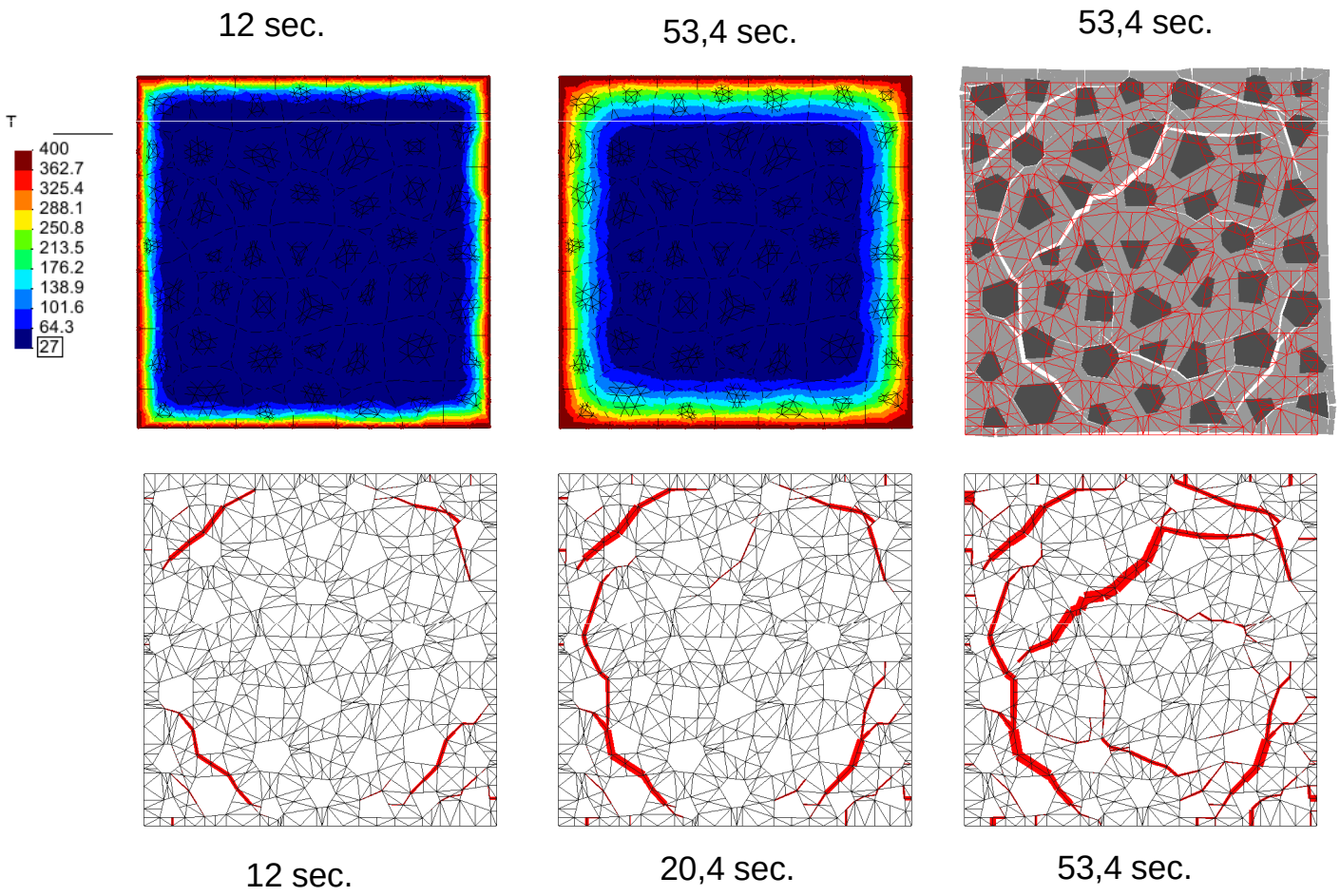
α_d = -2.

CONCRETE SPECIMEN, FREE THERMAL EXPANSION

- The same mechanical parameters as in previous cases are used

- Cracks start at the corners of specimens along aggregate-matrix contacts, and they develop a perimeter crack (spalling).

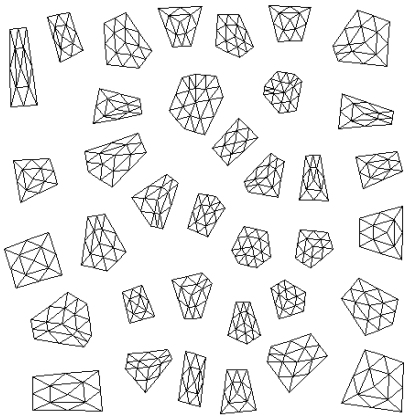
- For higher temperature values, additional cracks form in the center of the specimen.



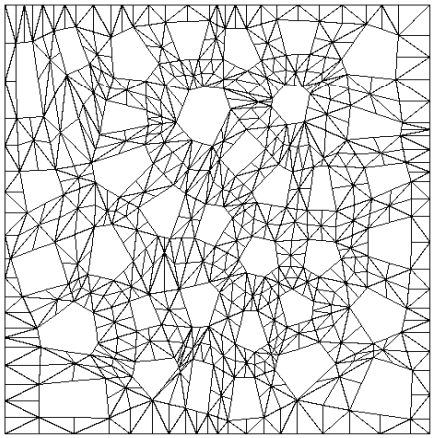
MESO-MECHANICAL MODEL IN 2D

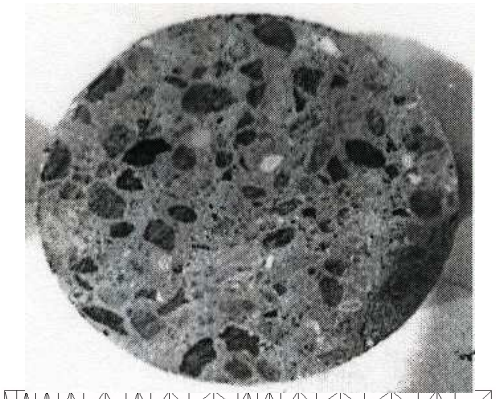
Continuum
(triangular elements)

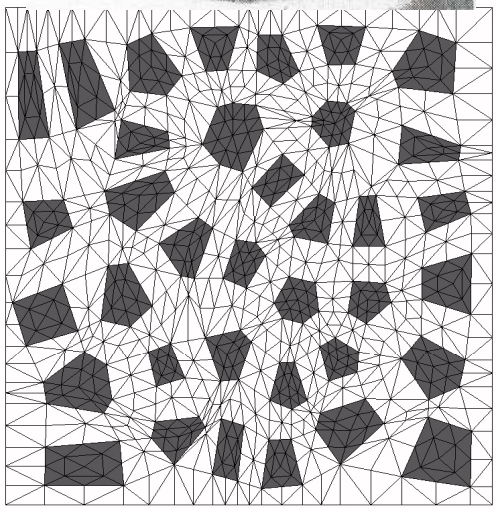
AGGREGATES



MATRIX CONT.



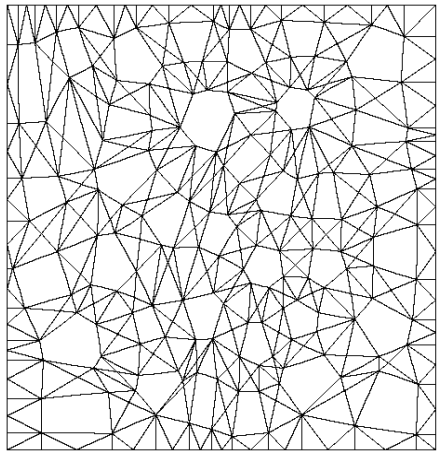




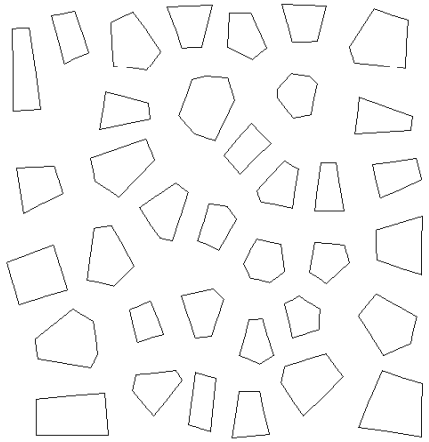
Voronoi/Delaunay's mesh
generation process

Interfaces elements
(zero-tickness)

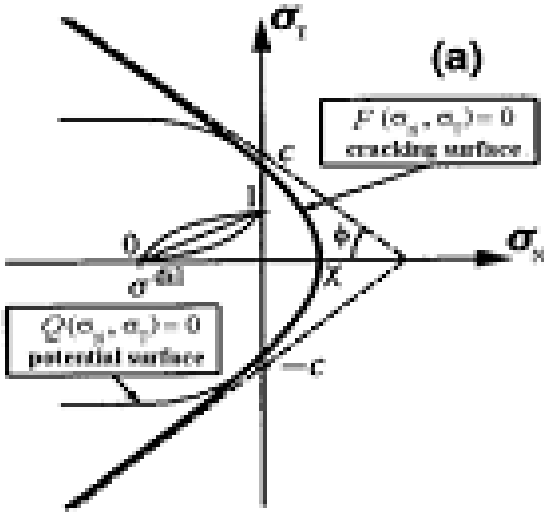
MATRIX

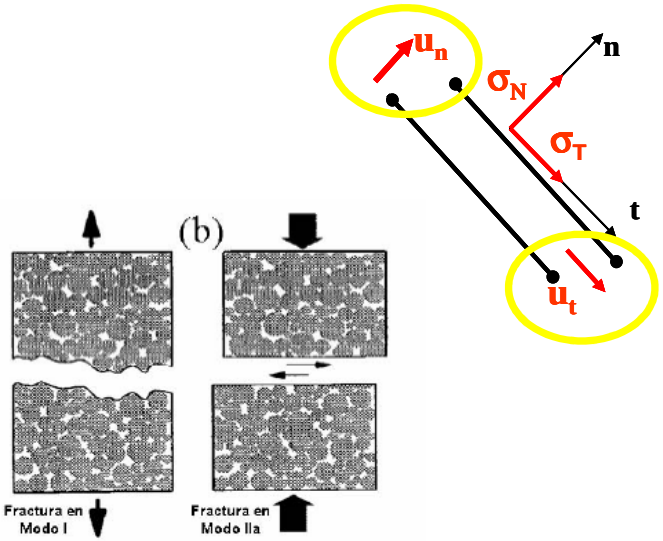


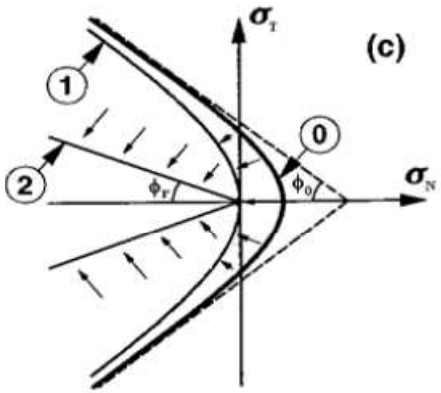
AGGR.-MATRIX

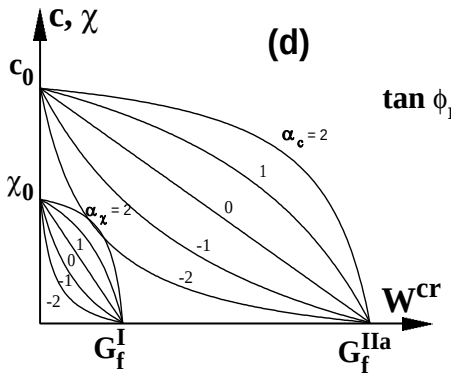


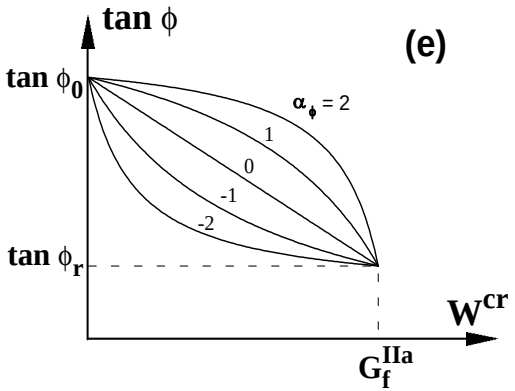
INTERFACE MODEL











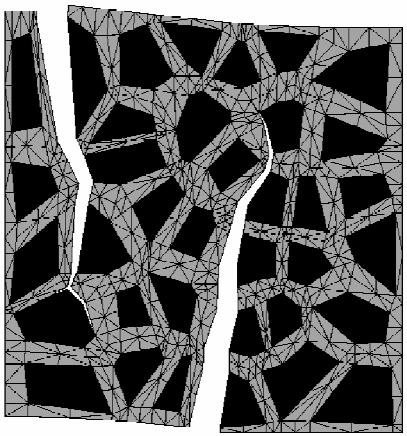
- Elasto-plastic constitutive law Incorporates concepts of fracture mechanics and fracture energies

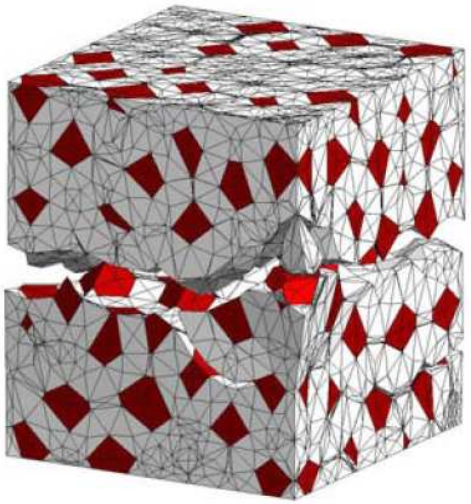
- Behavior formulated in terms of normal and shear components of the stress on the interface plane $\sigma = (\sigma_N, \sigma_T)^T$ and the corresponding relative displacement $u = (u_N, u_T)^T$

SOME PREVIOUS RESULTS

TENSILE TEST

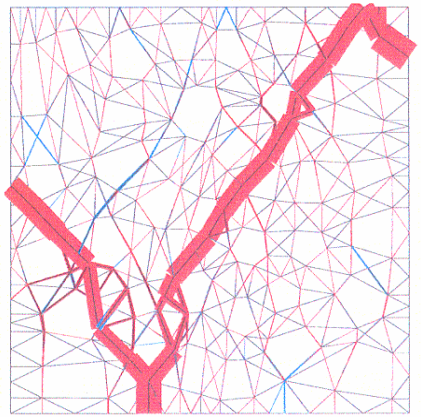
(2D AND 3D)

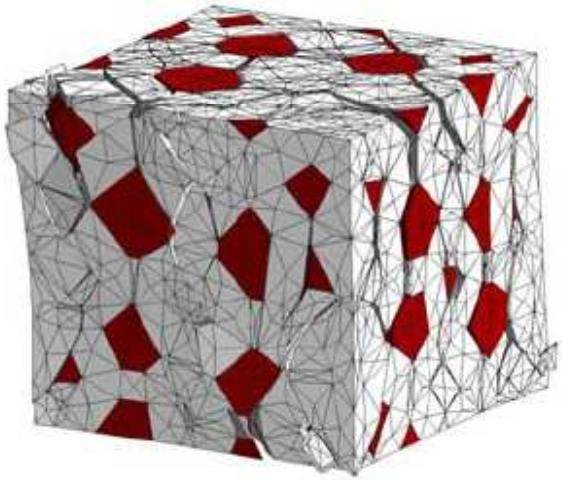




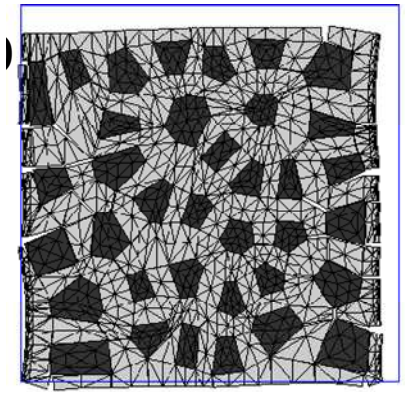
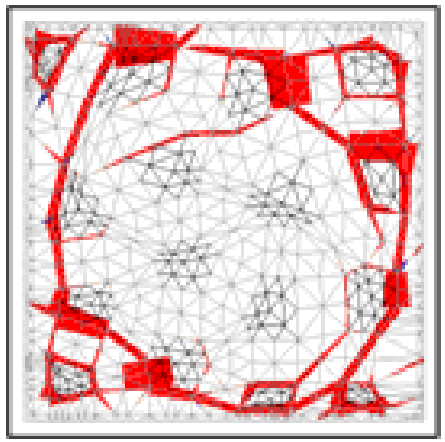
COMPRESSION TEST

(2D AND 3D)





DRYING SHINKAGE



EXTERNAL SULPHATE ATTACK