Recent Advances on Bio-based Cement Composites and Concrete (View from Brazil)

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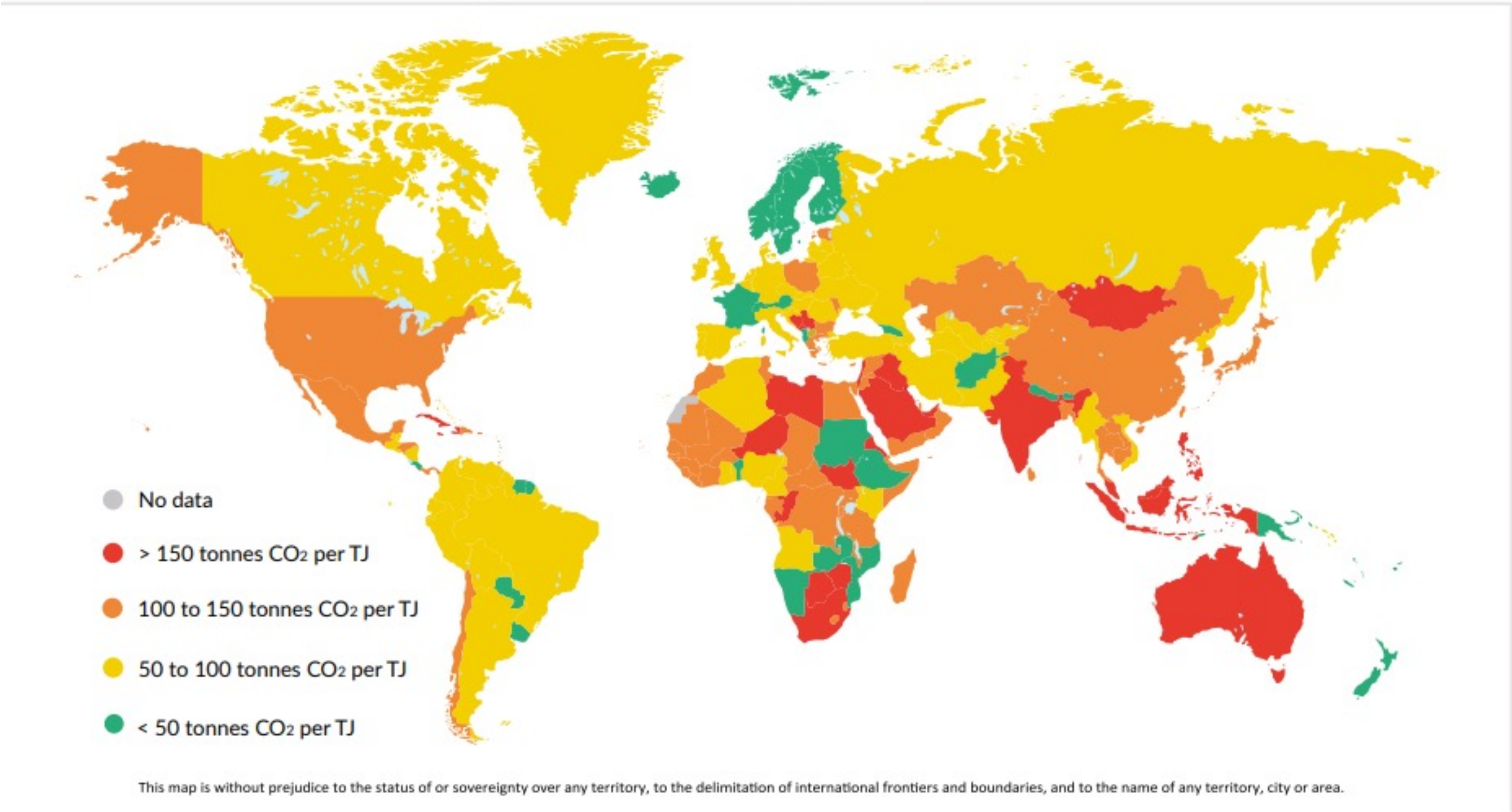
PEC/COPPE/UFRJ
Laboratório de Estruturas e Materiais
Prof. Lobo Carneiro

Buildings energy-carbon intensities

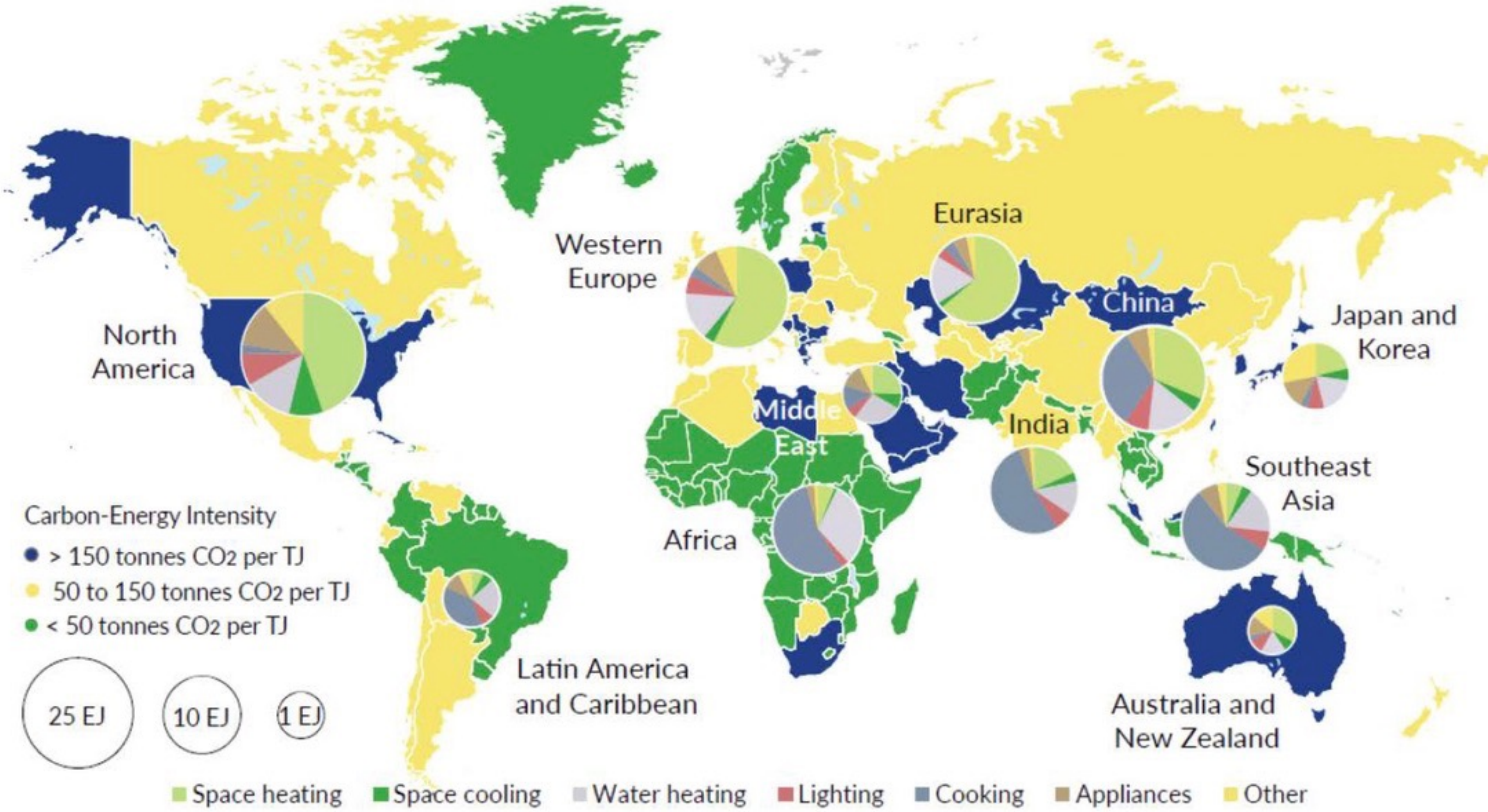
Current buildings energy-carbon intensities are far from the 20 tonnes CO_2 per TJ needed by 2050 to meet ambitions for a 2°C world or below



Buildings sector energy-carbon intensities by country, 2015
Source: UN (2017) apud Energy Technology Perspectives 2017, IEA/OECD

Buildings energy-carbon intensities

Energy efficient buildings per regions of the world



Courtesy: Prof. Guillaume Habert – ETH Zurich

Building Materials Demand

Building materials stock will double in the coming years to maintain and improve existing buildings and to build new infrastructure to accommodate urban migration

Time	GDP (trillion 2012 USD)	Population (billion)	Households (million)	Average persons per household	Residential floor area (billion m^2)	Average m^2 per person
2011	80.8	6.95	1894	3.6	164	24
2030	161.4	8.36	2840	2.9	266	30
2050	272.7	9.48	3518	2.7	354	37

Courtesy: Prof. Guillaume Habert – ETH Zurich

Role of fast-growing Bio-Based Materials (BBM) such as bamboo, natural fibres, straw…?

Benefits of the use of fast-growing Bio-Based Materials (BBM) in Construction

- Can storage CO_2;
- Can be avaliable as a renewable and fast source;
- Have adequate hygrothermal properties for using as building elements – walls, roofs, slabs, shadings, etc.
- Can be designed in a circular way promoting the bio circular economy;
- Reusability/recyclability, Design for Disassembling (DfD) approach and Building Information Modeling (BIM) + LCA implementation
- Least developed countries can be important players due to their climate conditions and social needs;
- Can make use of traditional techniques and materials for the development of more industrialized processes – social aspects

SDGs

Bio-based materials solutions under investigation at NUMATS/UFRJ and **biomass intensity content**:

a) High Performance Vegetable Fibre-Cement Based Composites (V_f < 10%)

b) Bio-based sandwich systems using bio-aggregates and vegetable fibres

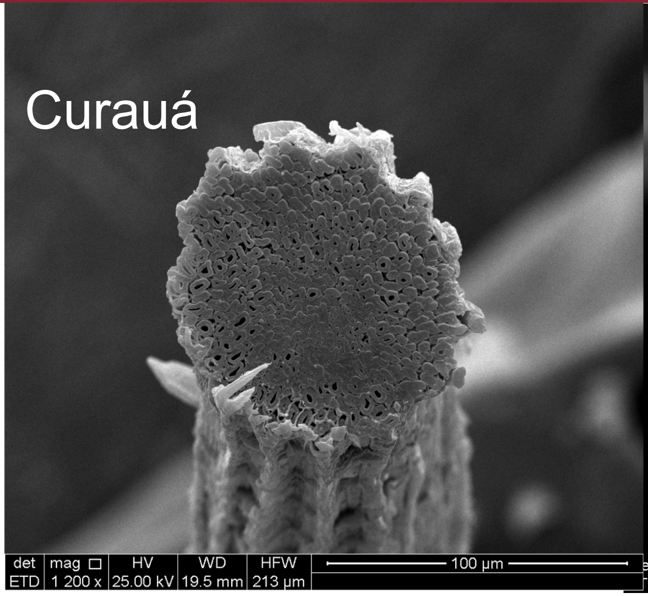
(Biomass Volume: 25-70% e Vf: 6-10%)

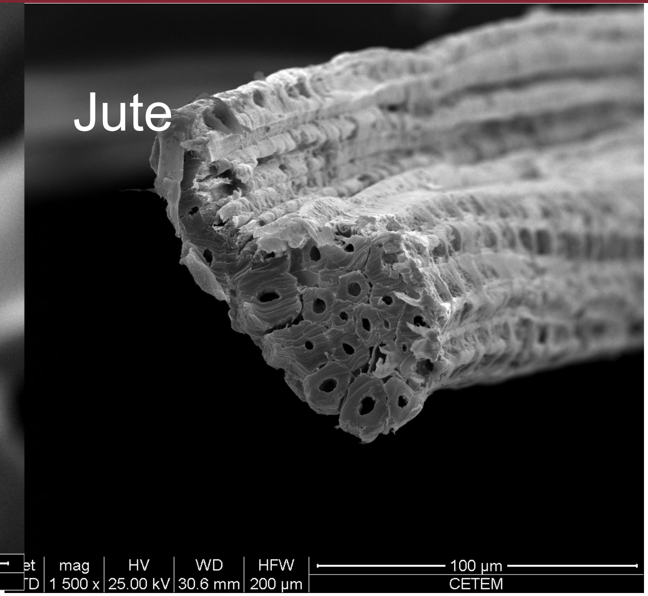
c) Bamboo-Bioconcrete Building Systems (Biomass Volume: 25-70% e V_{bamboo}: 6-10%)

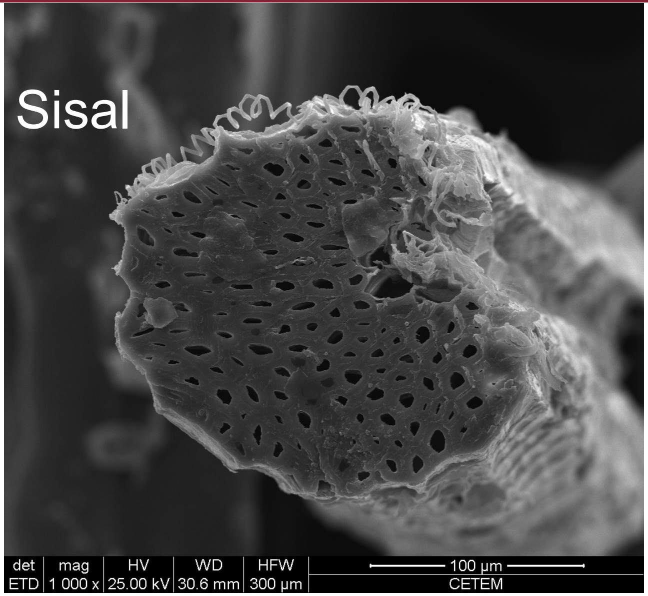
d) Pole Bamboo and Industrialized Bamboo as building material (V_{bamboo} > 95%)

High Performance Vegetable Fibre Cement Based Composites

High Performance-Vegetable Fibres

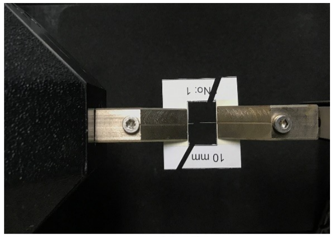




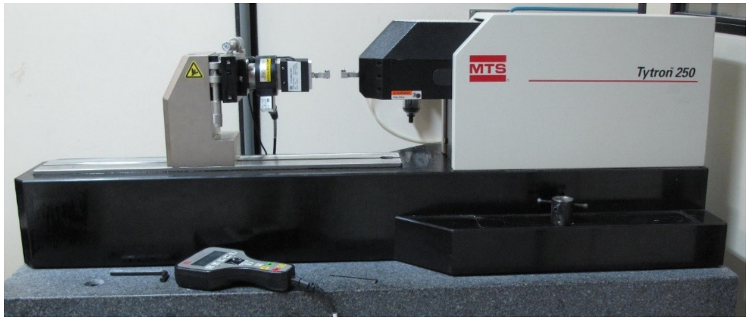


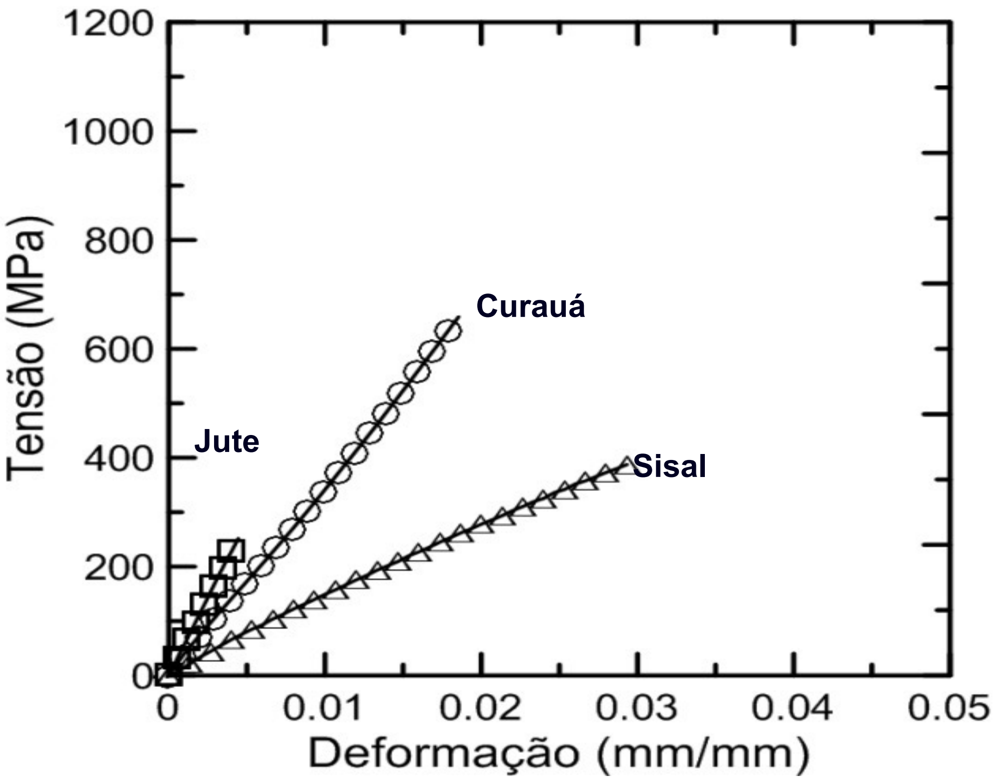
Fibers	Thickness S2 (µm)	∅ lumen (µm)	N° fibrercells	MF angle (º)	Total area (mm^2)
Curauá	1.81	0.8	300	18	0.008
Sisal	2.60	8.2	144	22	0.023
Jute	2.5	6.7	26	17	0.004

Mechanical Behavior of High Performance Vegetable Fibres



Testing





Fibers	Tensile strength (MPa)	E (GPa)	Strain (%)
Curauá	632 ± 138	38.1 ± 18	2 ± 0.4
Sisal	484 ± 135	19.5 ± 4.5	3.3 ±1.6
Juta	249 ± 89	43.9 ± 12.3	0.6 ± 0.2

Design of of High Performance VFRC

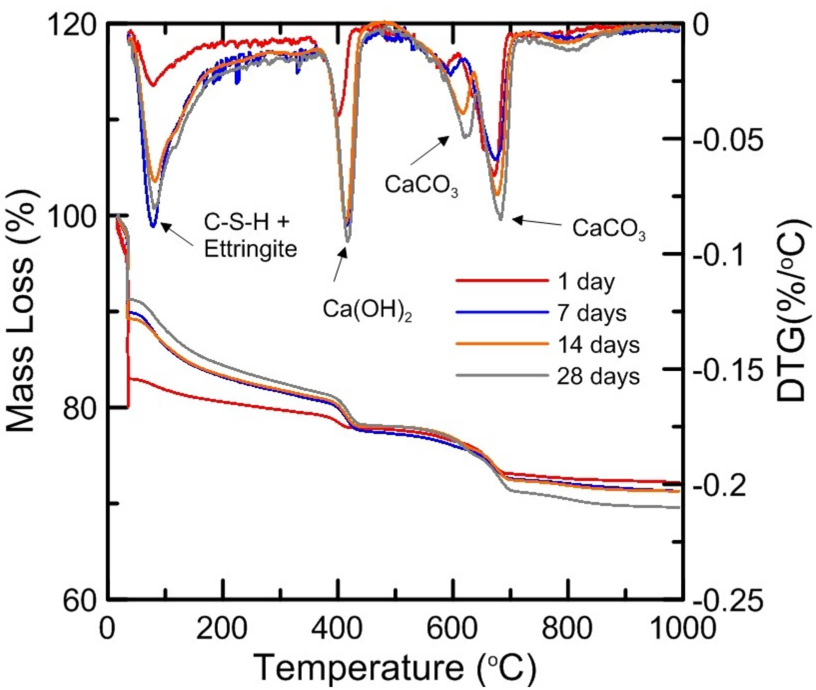
Driven criteria: Durability

How to create a compatible environment for the vegetable fibers in cement based composites?

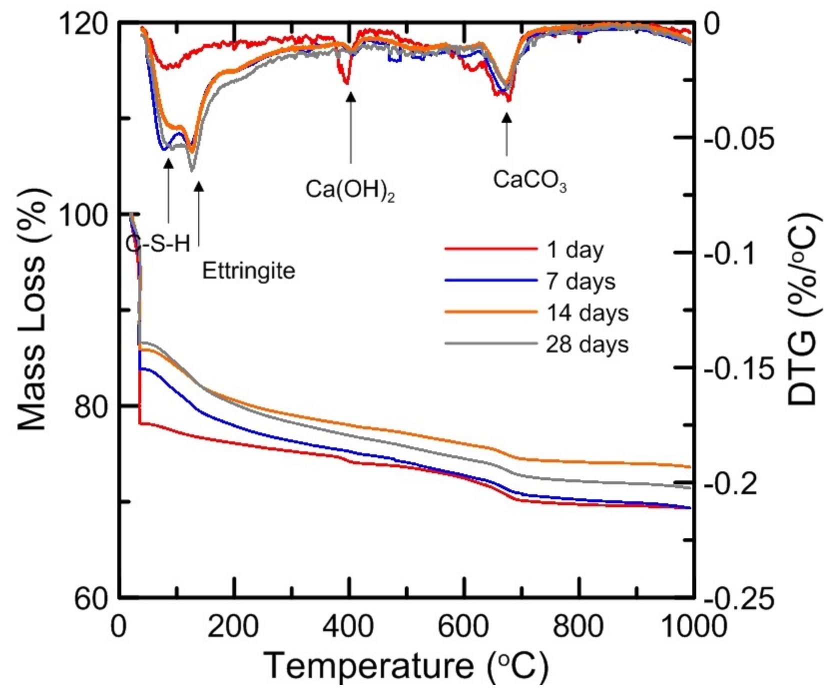
Use of cement matrices free of CH

DURABILITY: CH FREE MATRICES

TG and DTG analysis



PC matrix



CH Free (MK) matrix

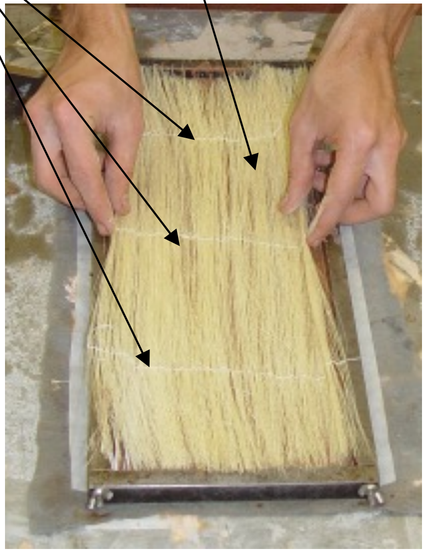
Mechanical response of sisal fibre reinforced mortar composites (SFRMC): unidirectional reinforcement

Composite production: Hand lay up technique

Mixing process

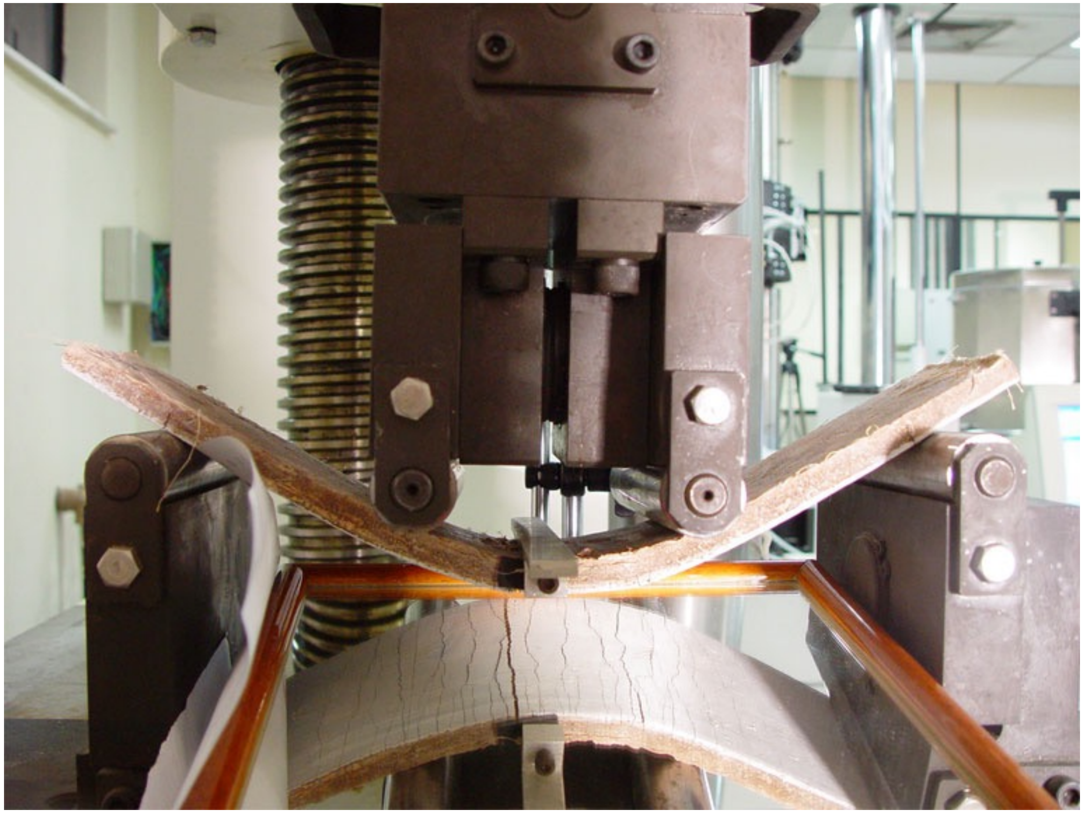
"n" layers of fibers

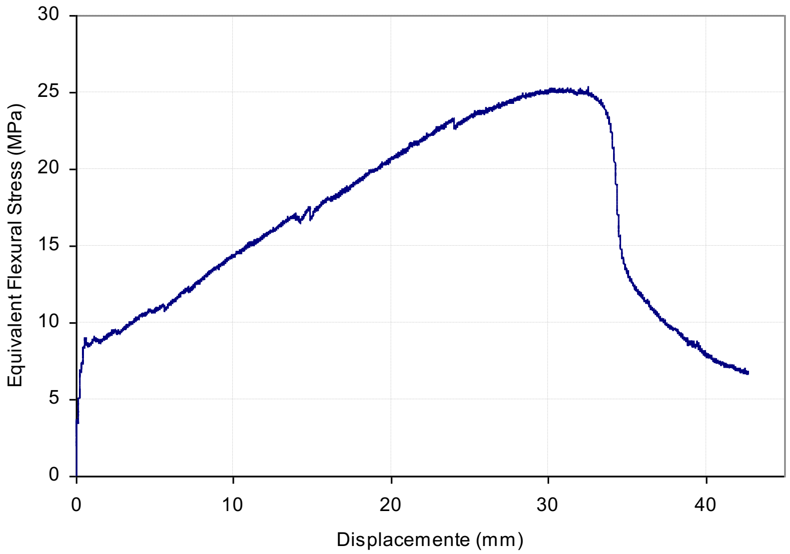
Stitches



Bending behaviour of the laminate

Load-deflection-cracking development curve

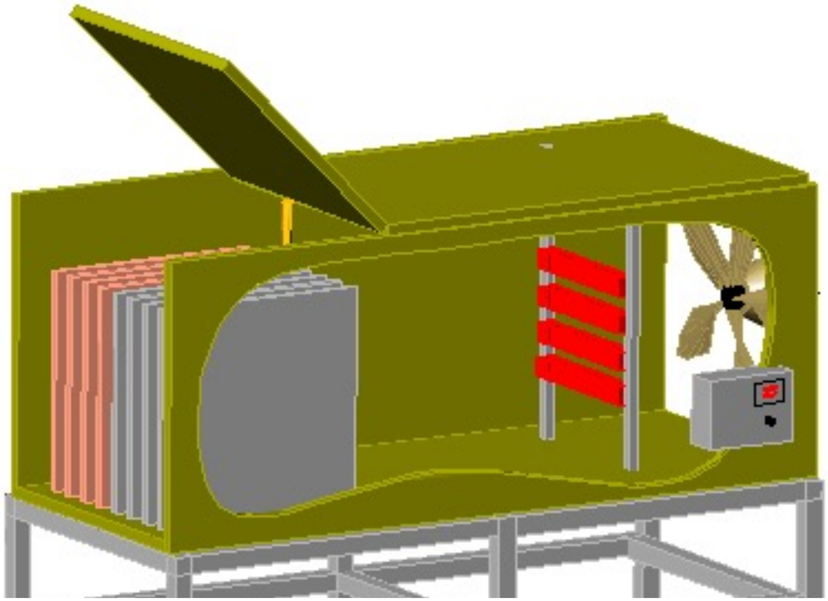




Durability Tests: "accelerated" aging in the Laboratory

Wetting and drying cycles
Hot water Immersion: 6 months at 60 ^{o}C.

Cycles: 24 hours wetting and 48 hours drying in the forced air flow chamber.



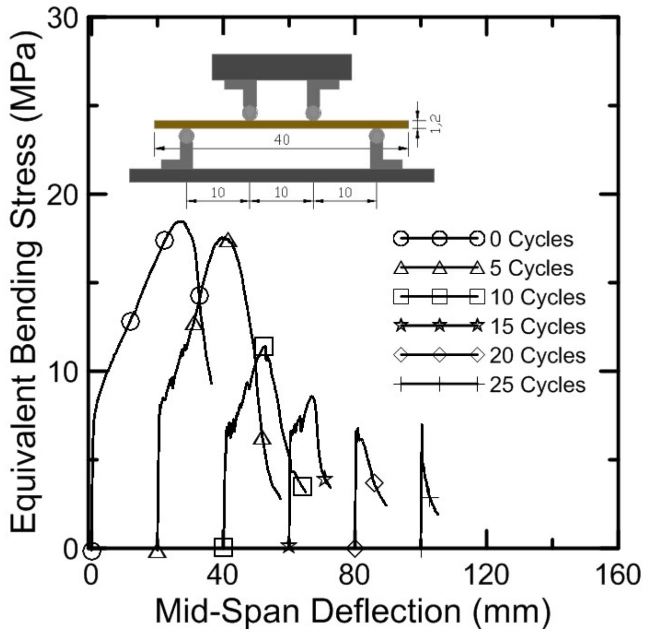
Temperature of drying: 36 ± 1 ^{0}C

Wind velocity: 0.5 m/s

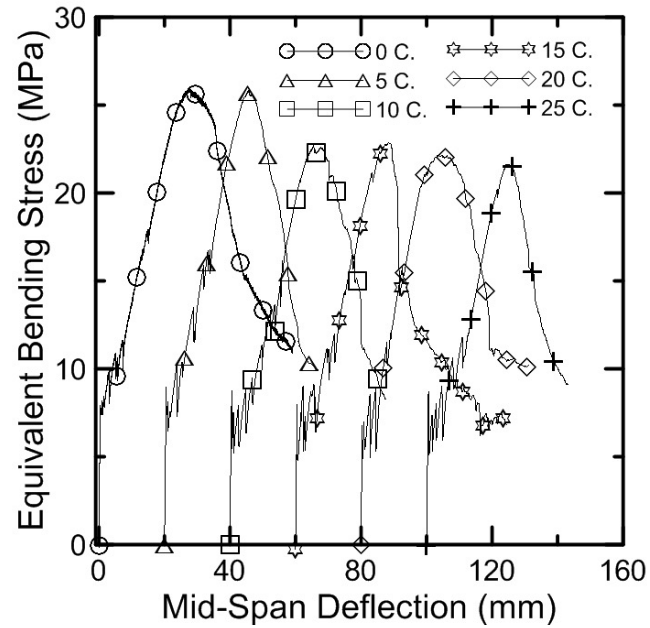
Water temperature: 30 ± 1 ^{0}C

Durability studies

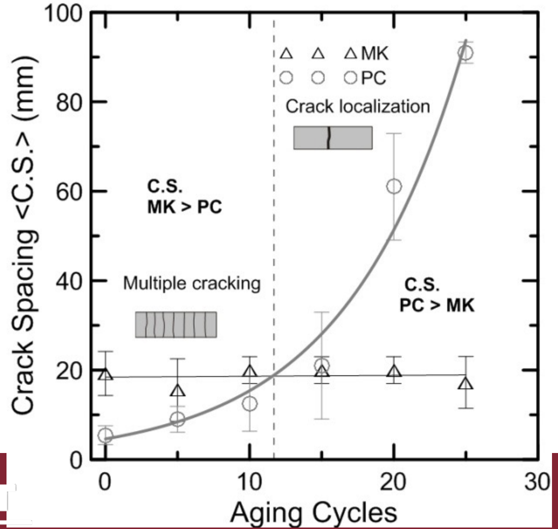
PC and CH FREE MATRICES



PC matrix

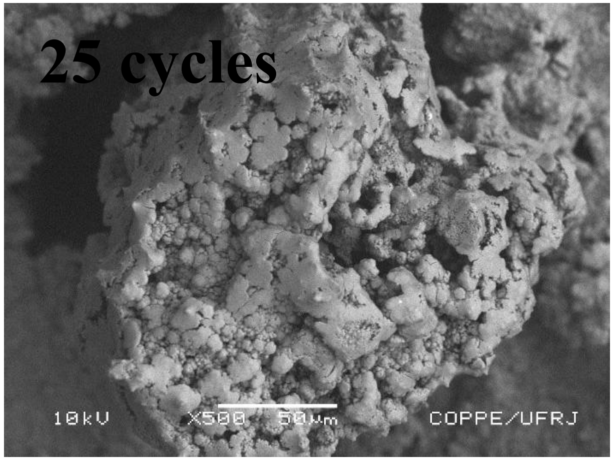


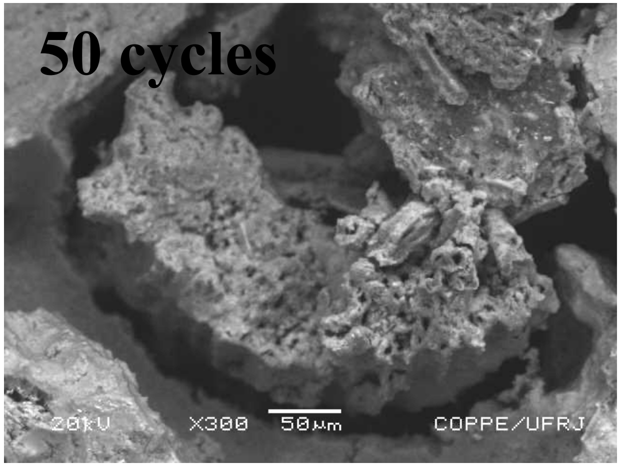
CH Free (MK) matrix

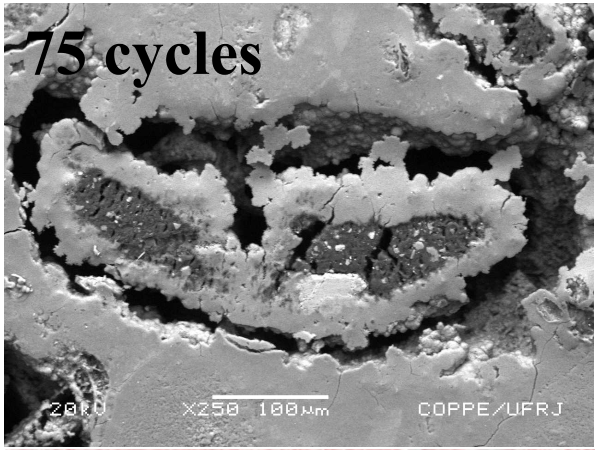


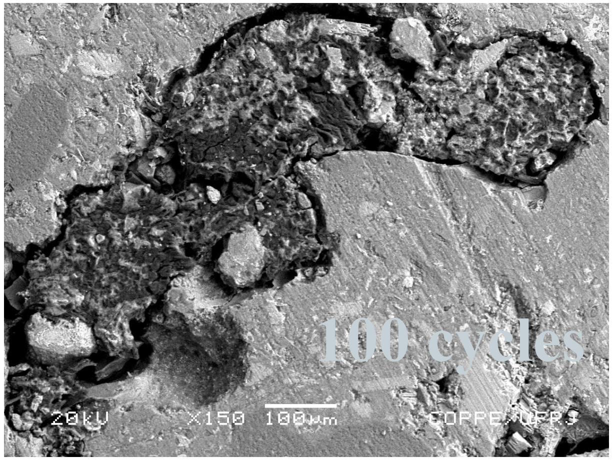
Durability concerns

Microstructure after cycles of wetting and drying

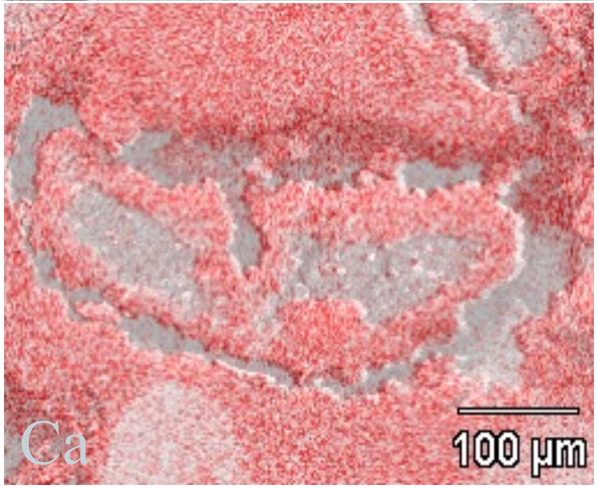






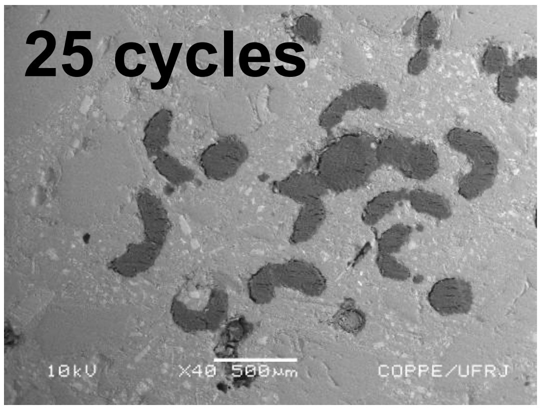


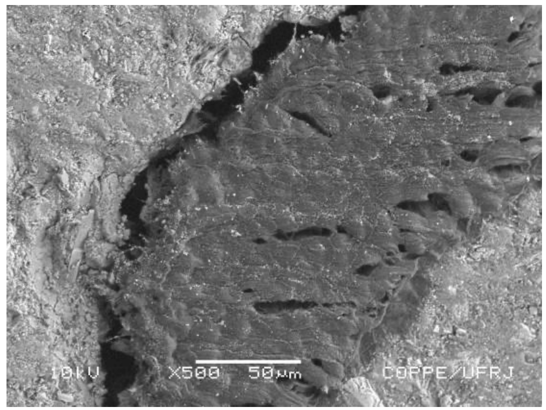
PC composites

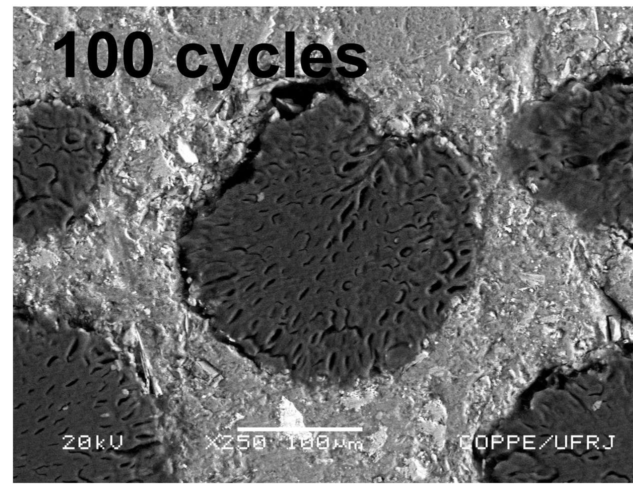


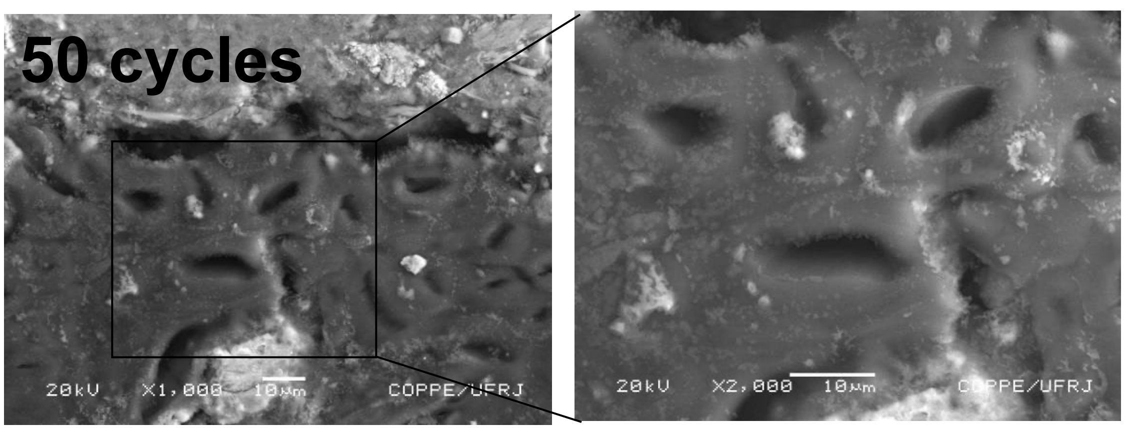
Durability concerns

CH Free Specimens after 25, 50 and 100 cycles of wetting and drying



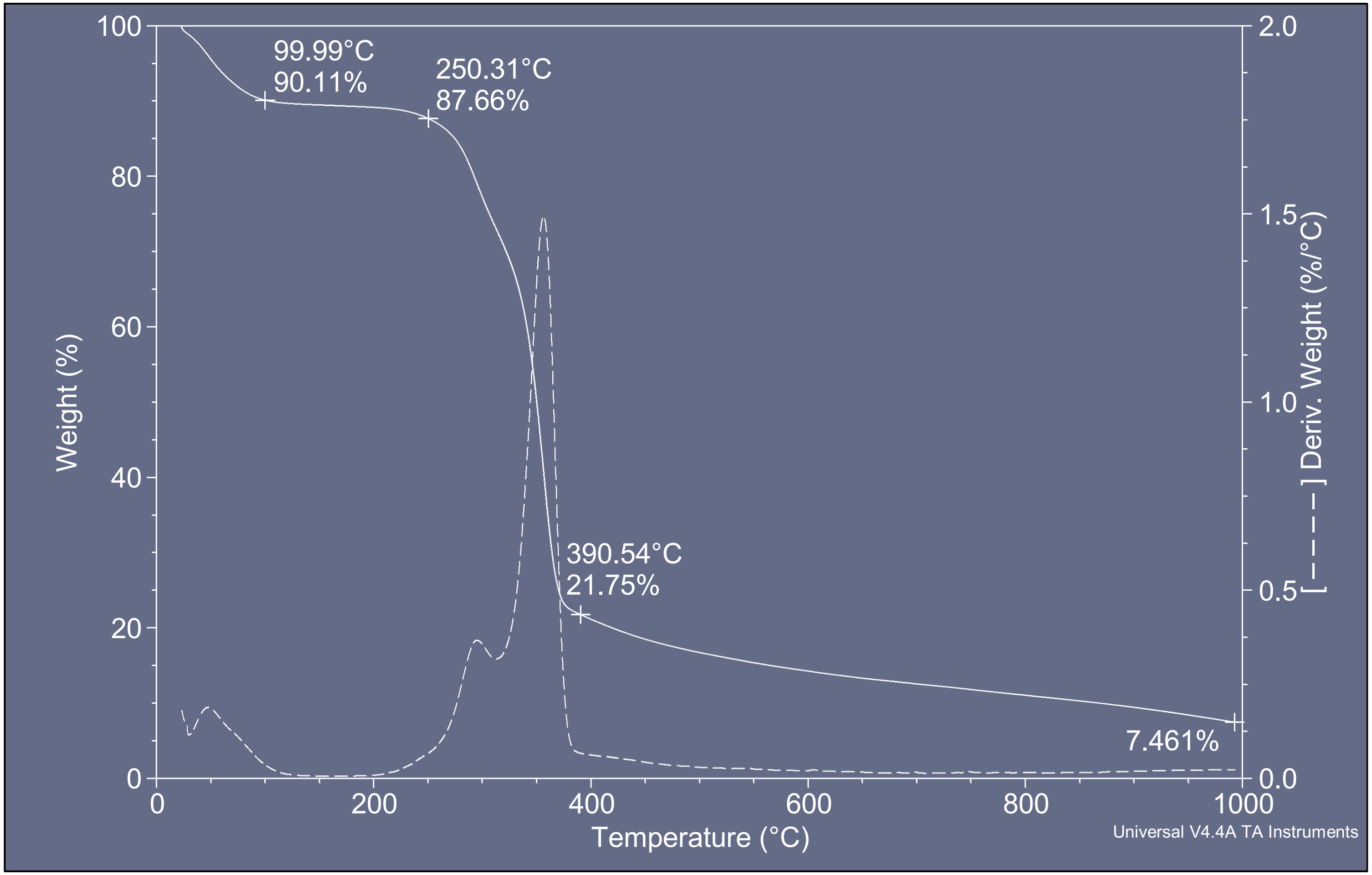






Durability: Thermal loads

Sisal Fibre – TG/DTG test

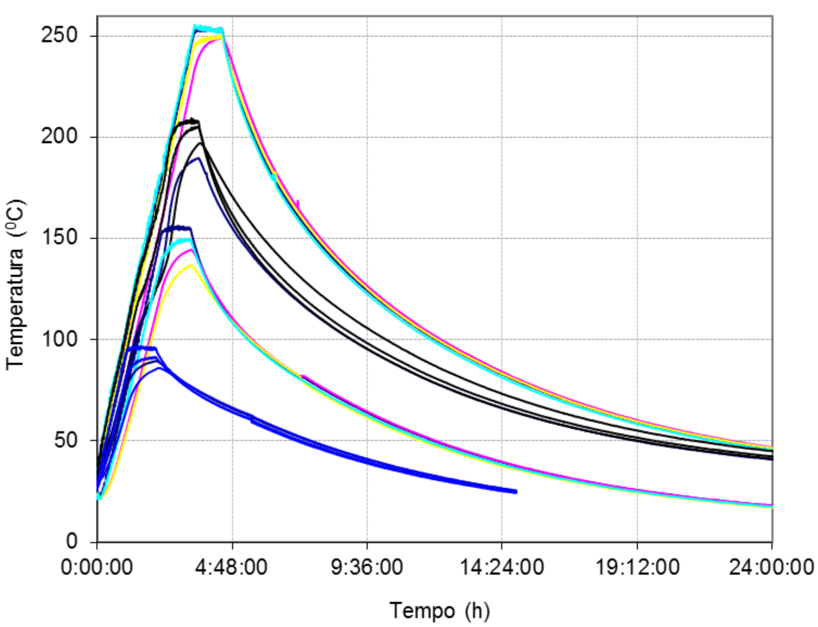


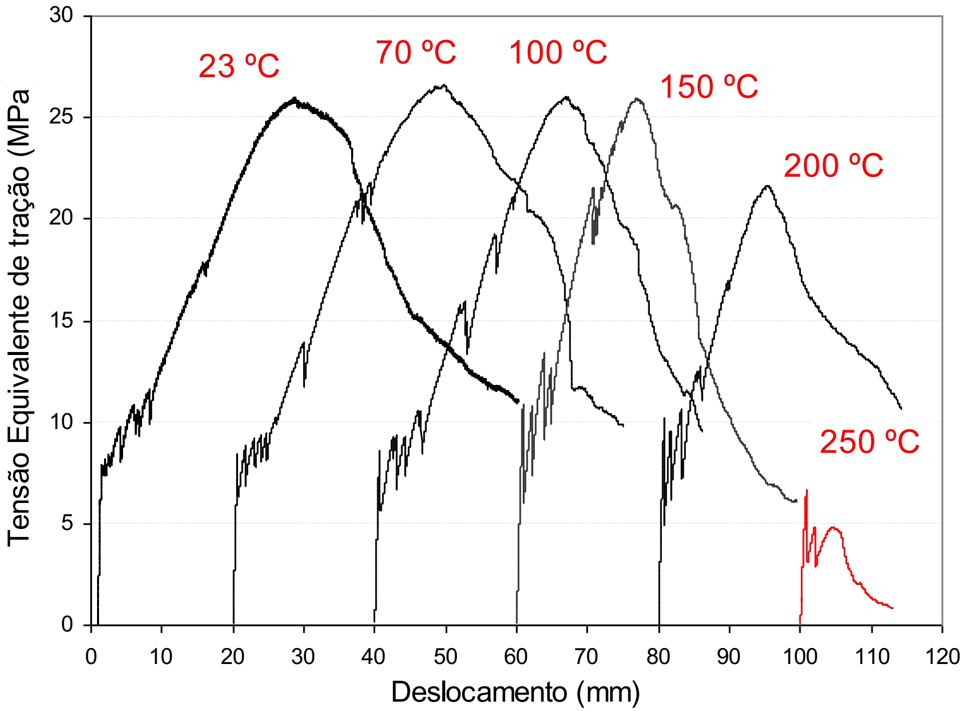
Durability of HPVFRC at high temperature

T: 70ºC, 100ºC, 150ºC, 200ºC e 250ºC

Heating rate: 1ºC/min

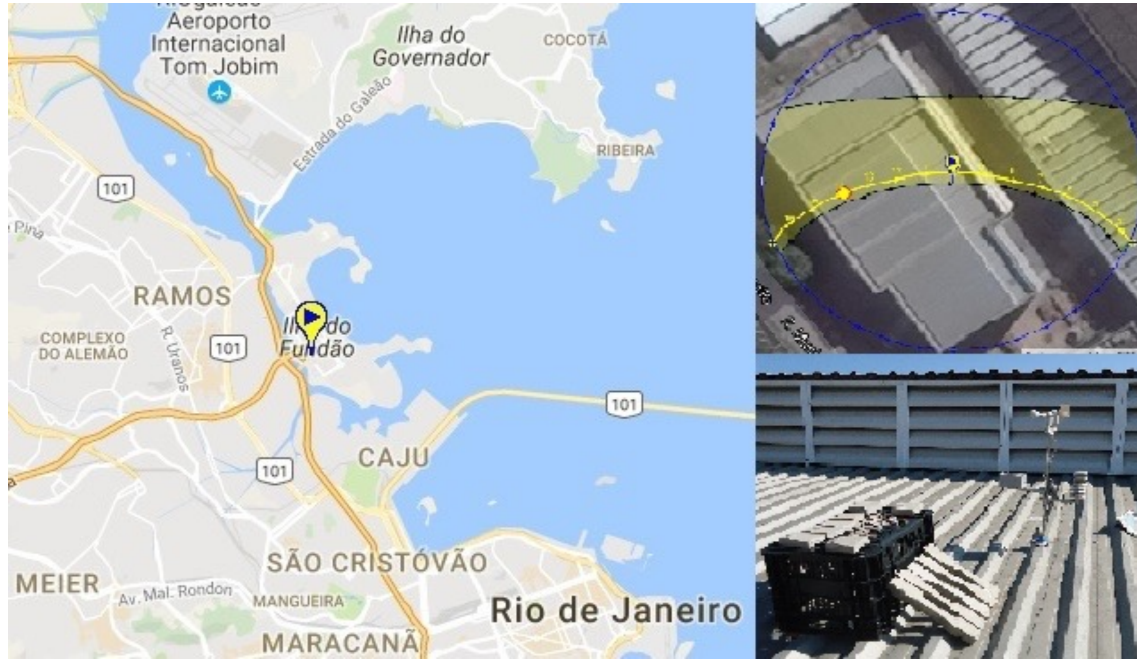
Residence time: 1h





Outdoors durability tests carried out on VFRHC and bio-concrete

Natural weathering

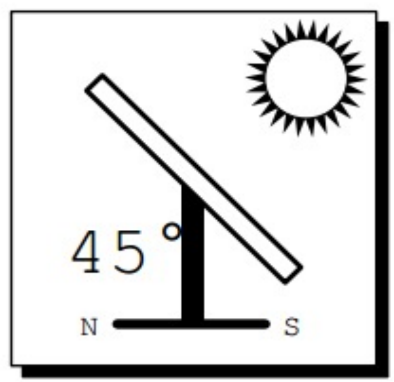


Test
Verification of strain-hardening behavior's durability of the composite exposed to natural weathering conditions with high fluctuation of temperature, humidity and rainfall over time.

Location
Rio de Janeiro - Roof of the laboratory building

Specimens
Dog-bones, pull-out

Time periods
3, 6, 9 and 12 months



Fonte: Q-Lab (2011)

Natural weathering

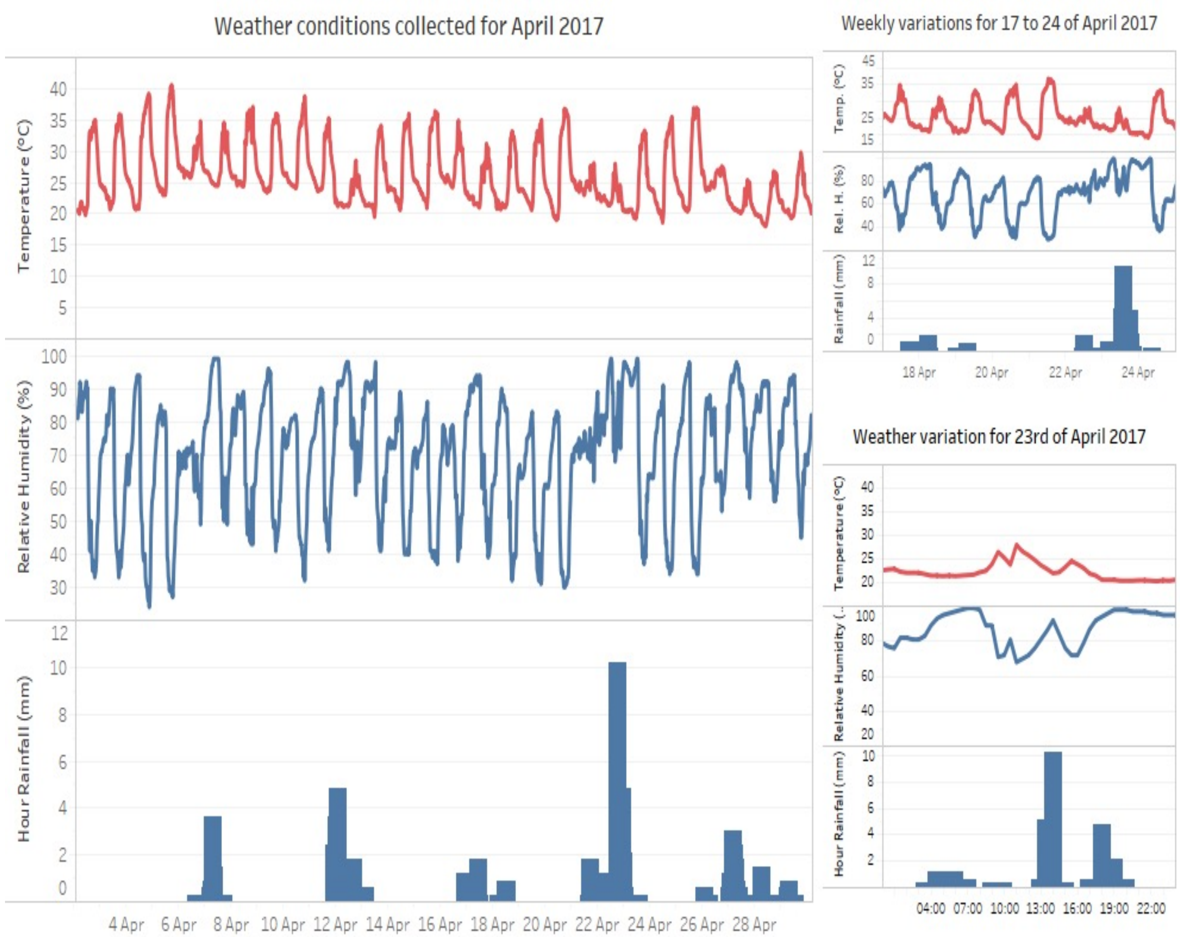
Weather analysis
Weather station measurements, each 30 minutes.

“Cycle”
The temperature and humidity variation.

Macrocycle
Monthly weather variation.

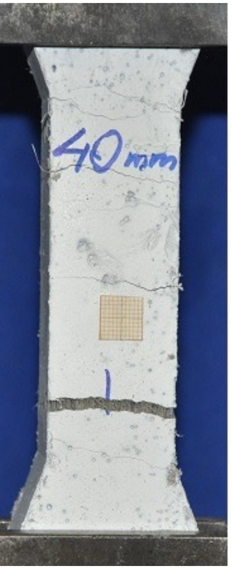
Mesocycle
Weekly variation.

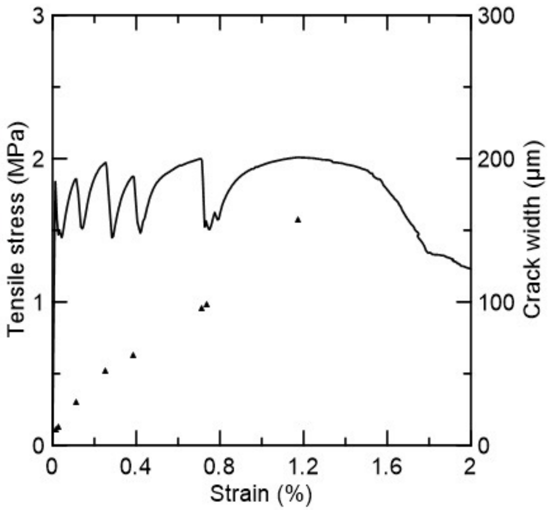
Microcycle
Daily weather variation.

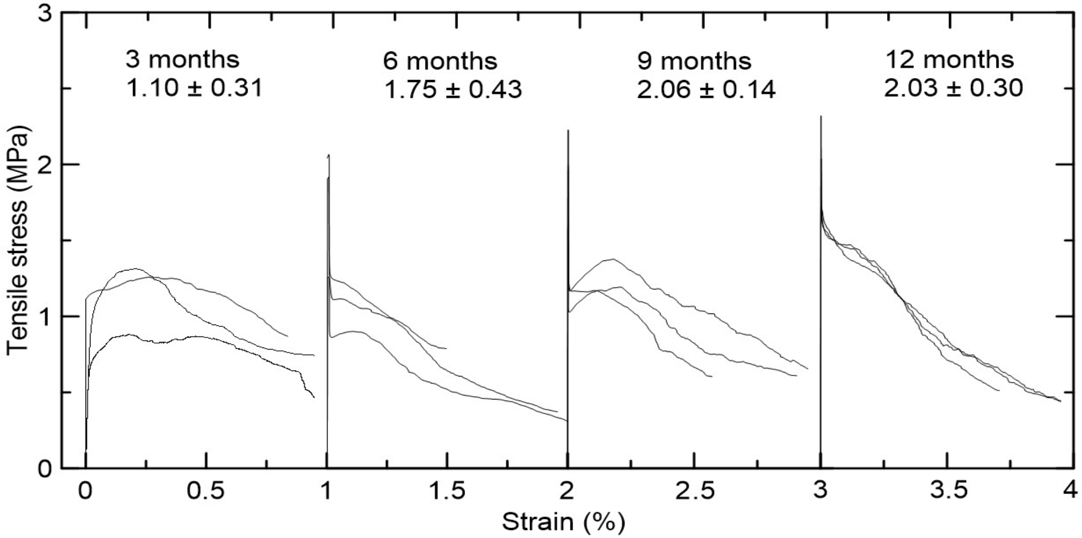


April 2017

Natural weathering: Curaua fiber cement based composite

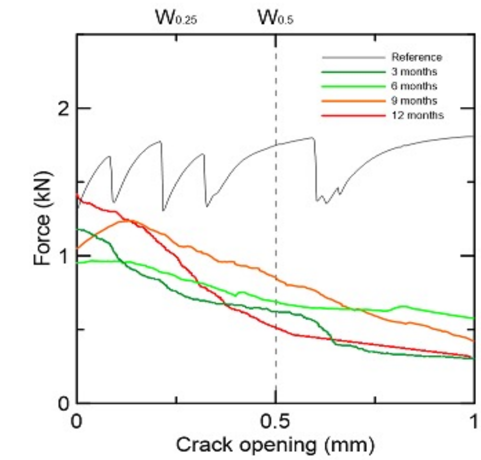






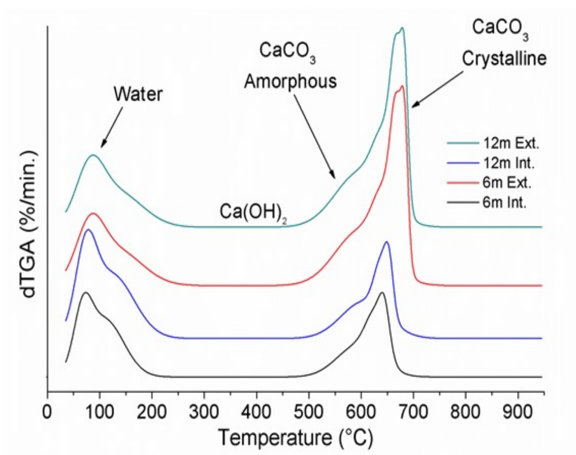
6, 9 an 12 months
The strain hardening did not occur, but the fibers presented bridging capacity.

Work indexes
The work indexes proved bridging capacity (lower in comparison to 28 days composite) but the fiber is still able to work inside the composite and was not petrified

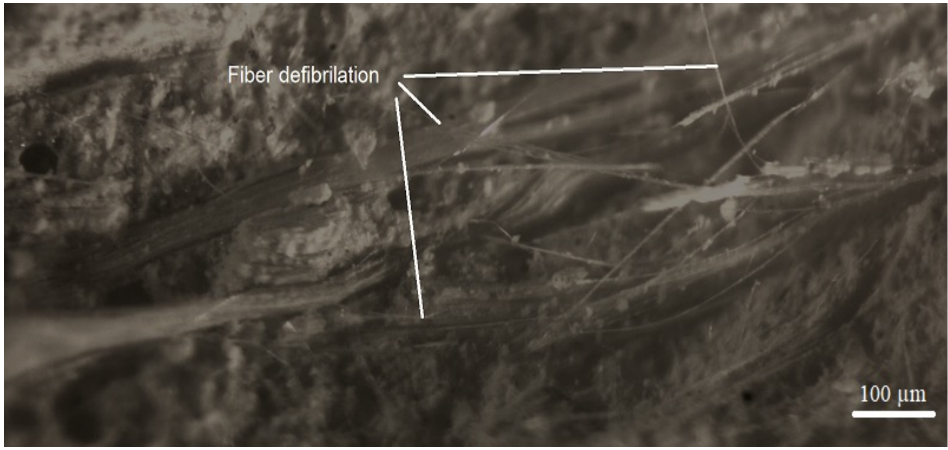


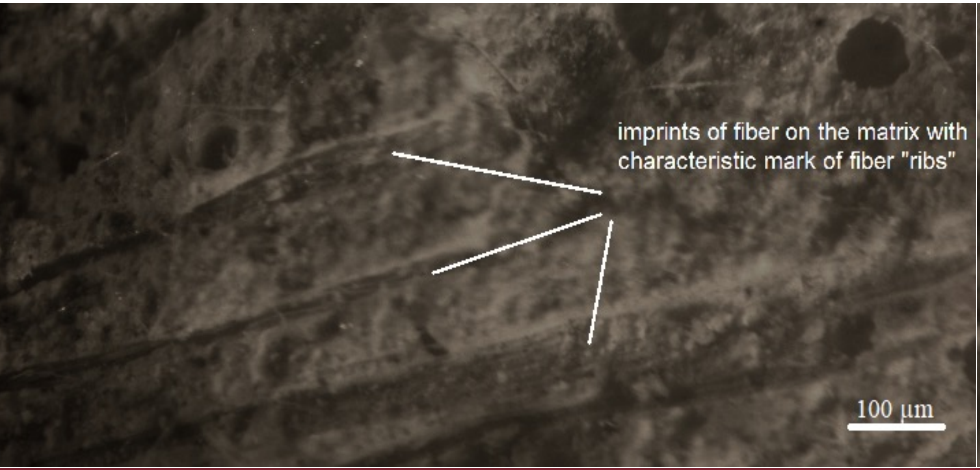
Natural weathering

TG Tests
The calcium hydroxide present was not confirmed.

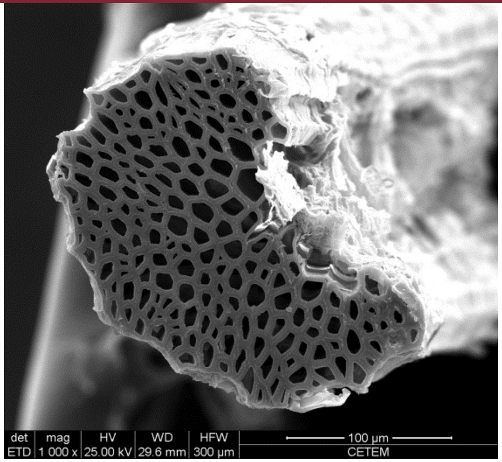


Microstructural observations:

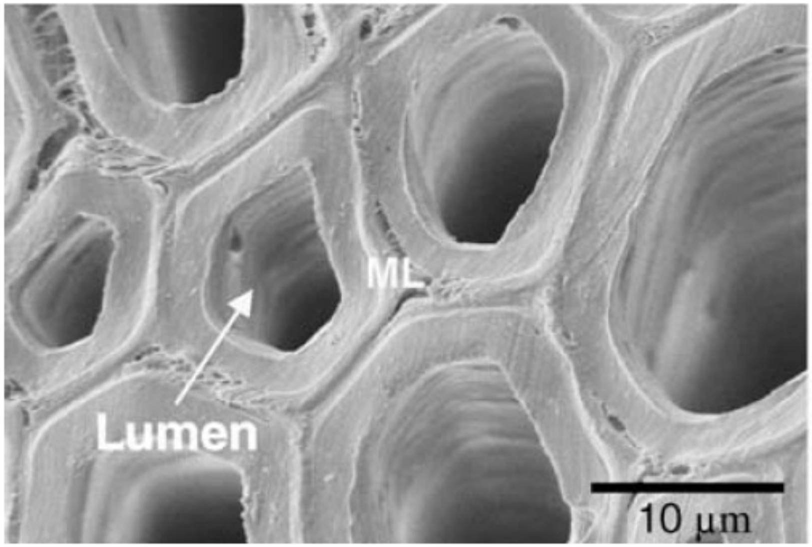


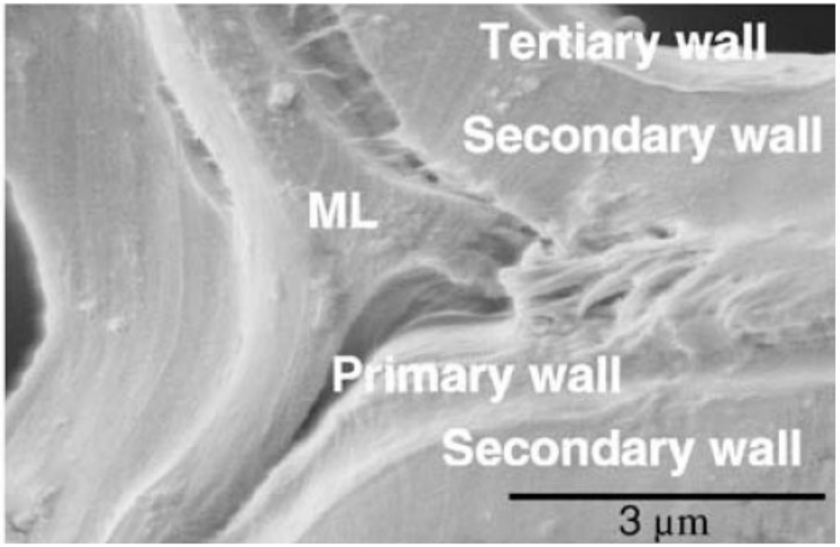


Use of cellular (sisal) fibers as healing agent in UHPFRC



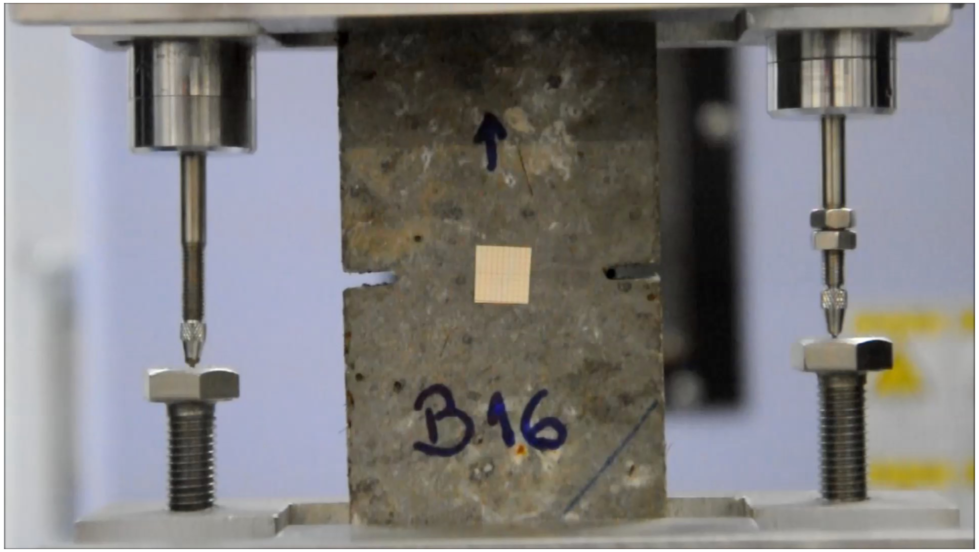
Cellular structure of vegetable (sisal) fiber



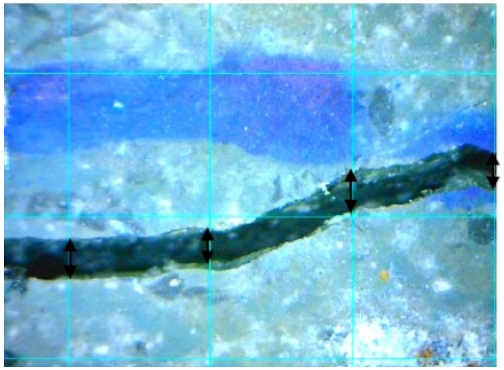


Pre-cracking under tensile load

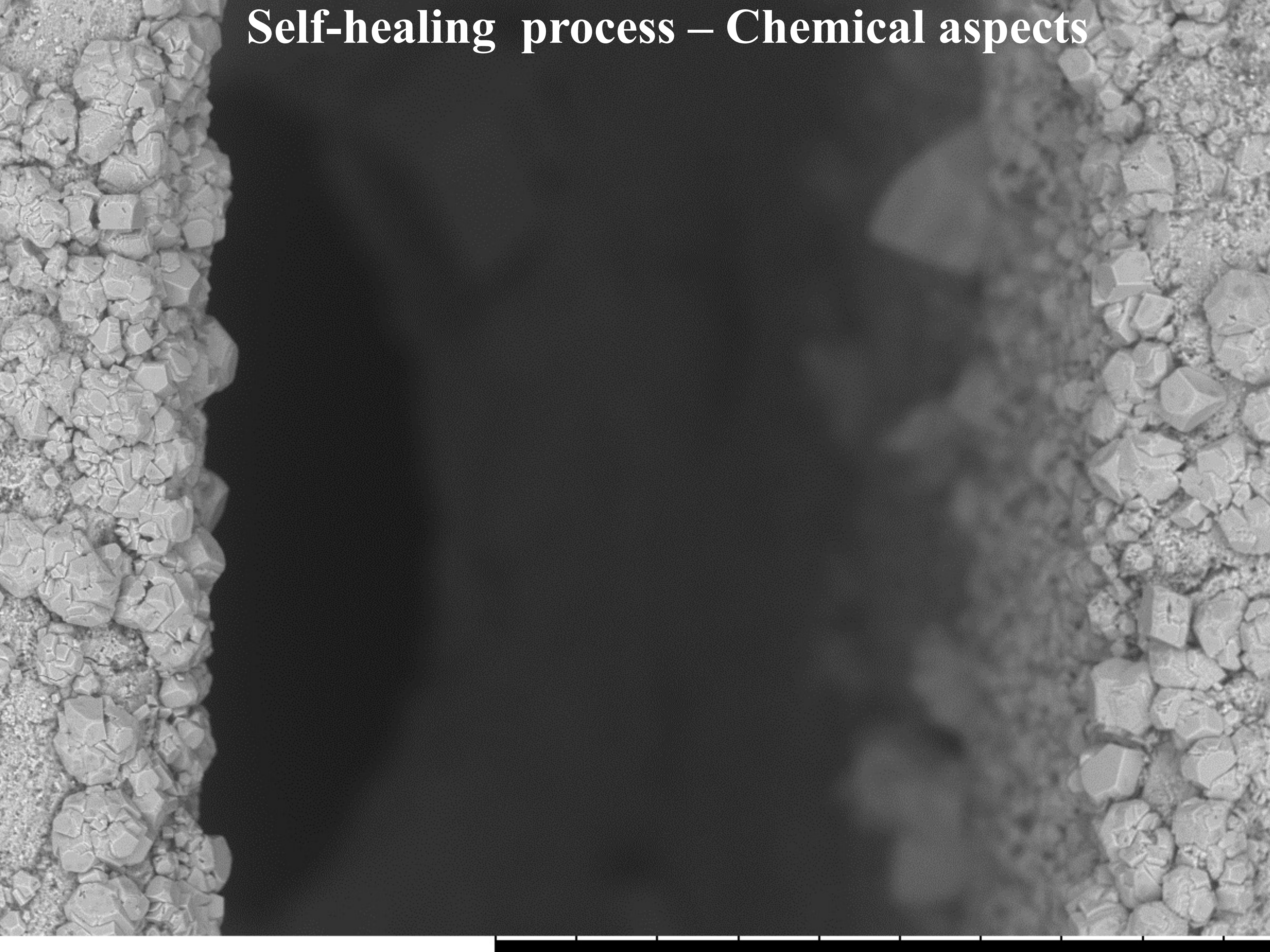
Age: 28 days
Crack width ~ 200µm
Rate = 0,01 mm/min
Notch – 10mm



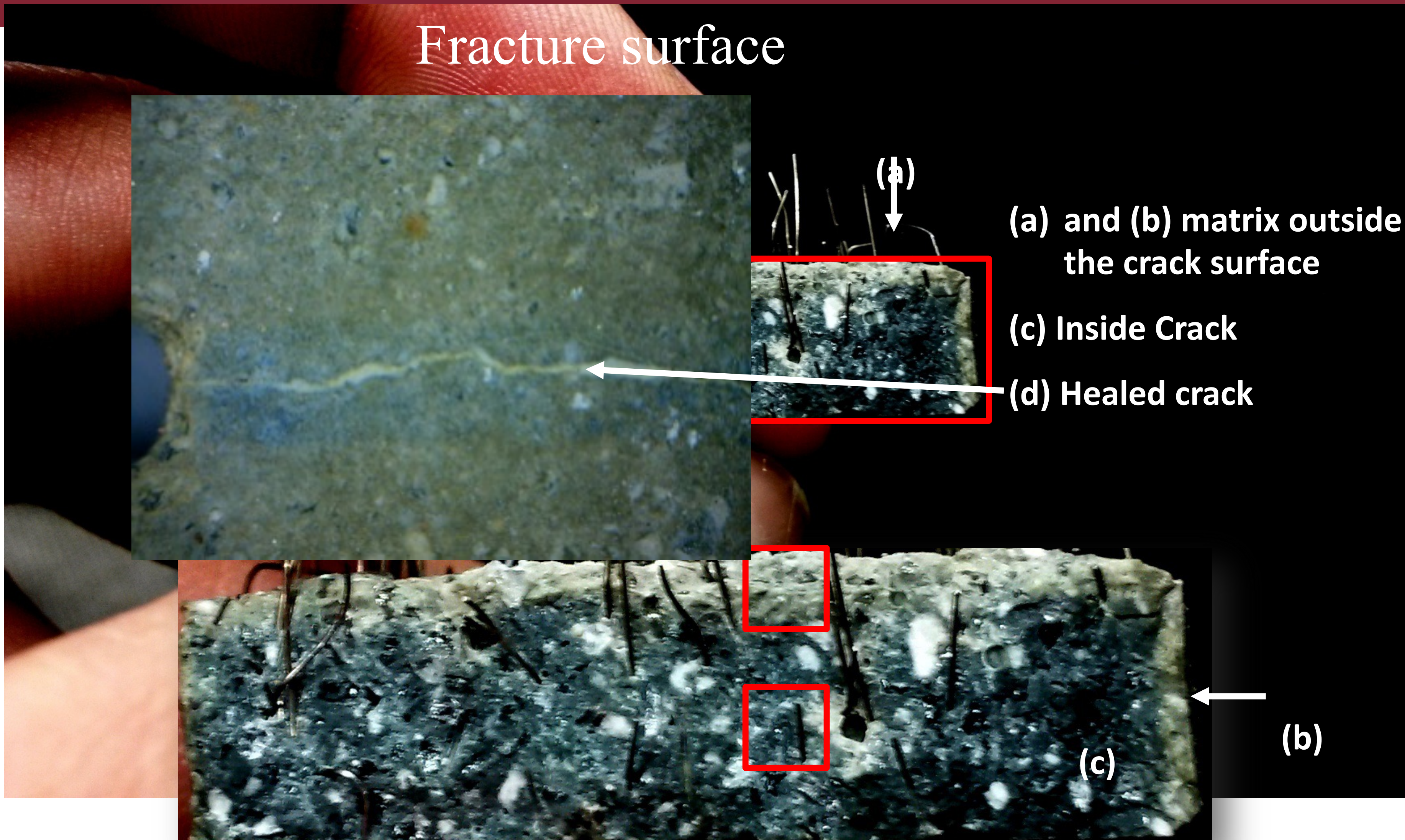
Crack open measurement



Self-healing process – Chemical aspects

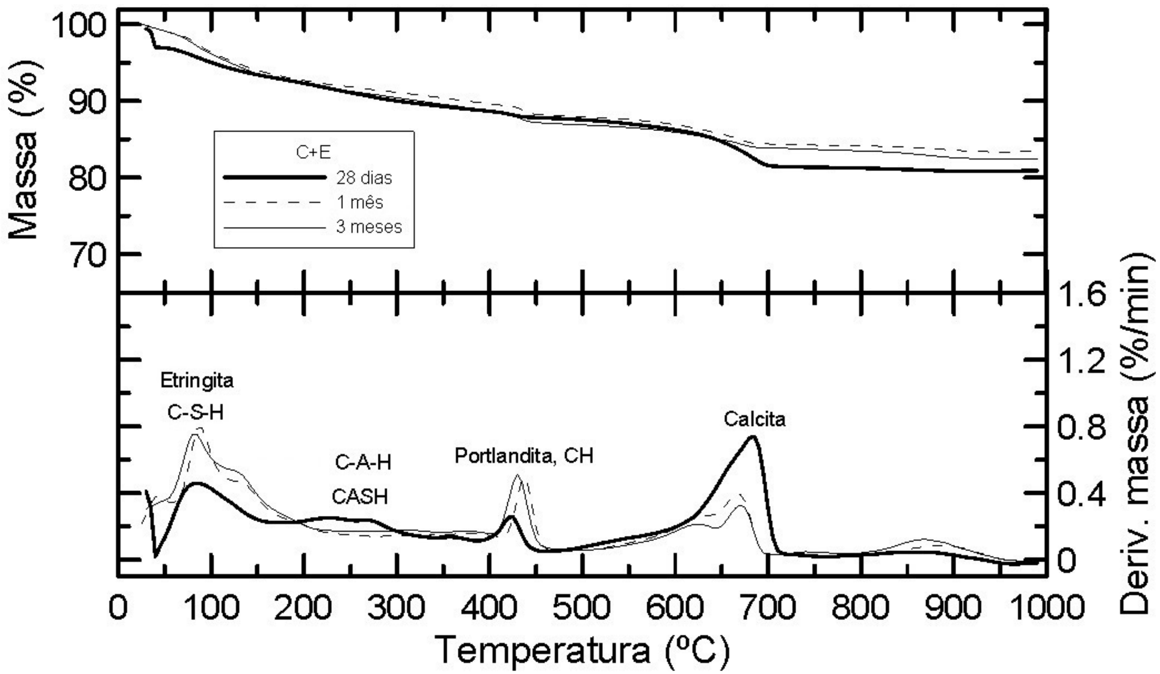


Self-healing process – Chemical aspects



Hydration products of aging matrix

Cement + slag paste



Produtos	28d [%]	28d+2m [%]	28d+3m [%]
Etringita e C-S-H	2,22	3,03	3,23
Portlandita	0,55	0,75	0,98
Carbonato de cálcio	5,43	2,86	2,07

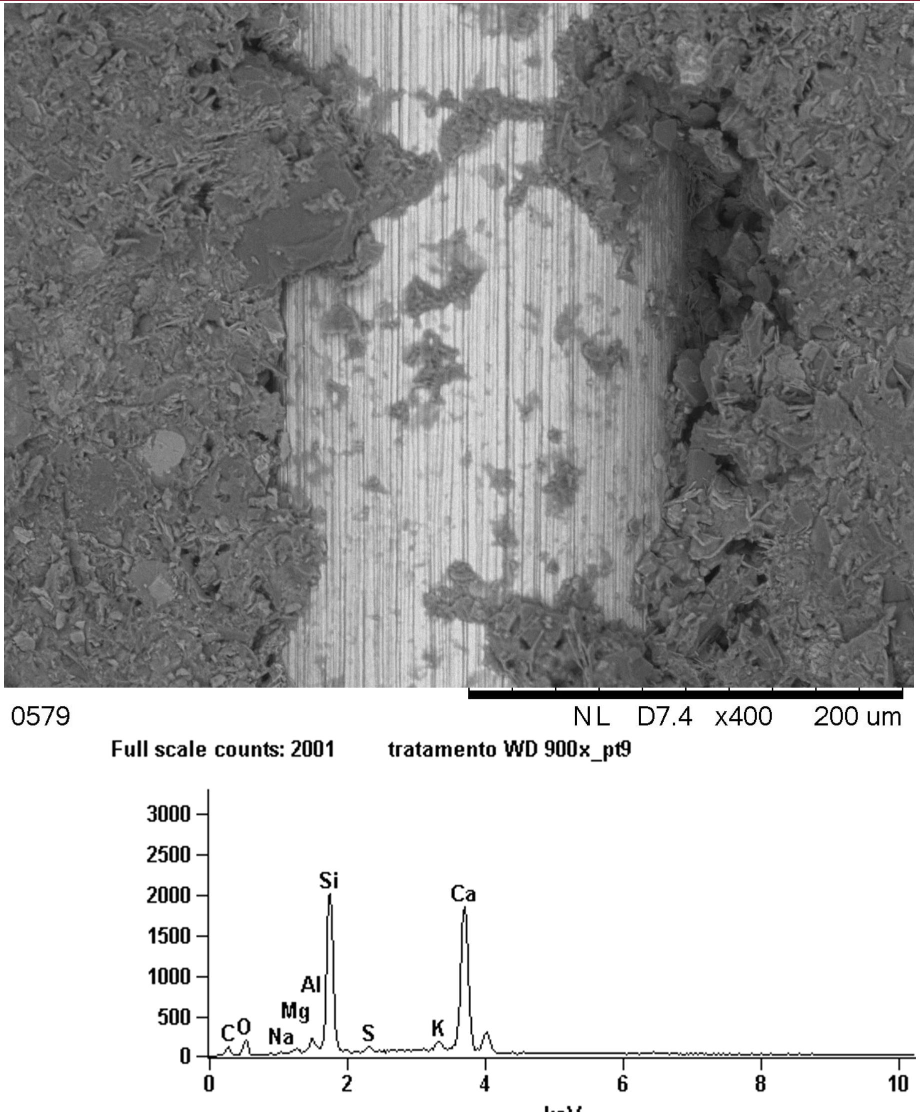
Healing of cracks at the interface

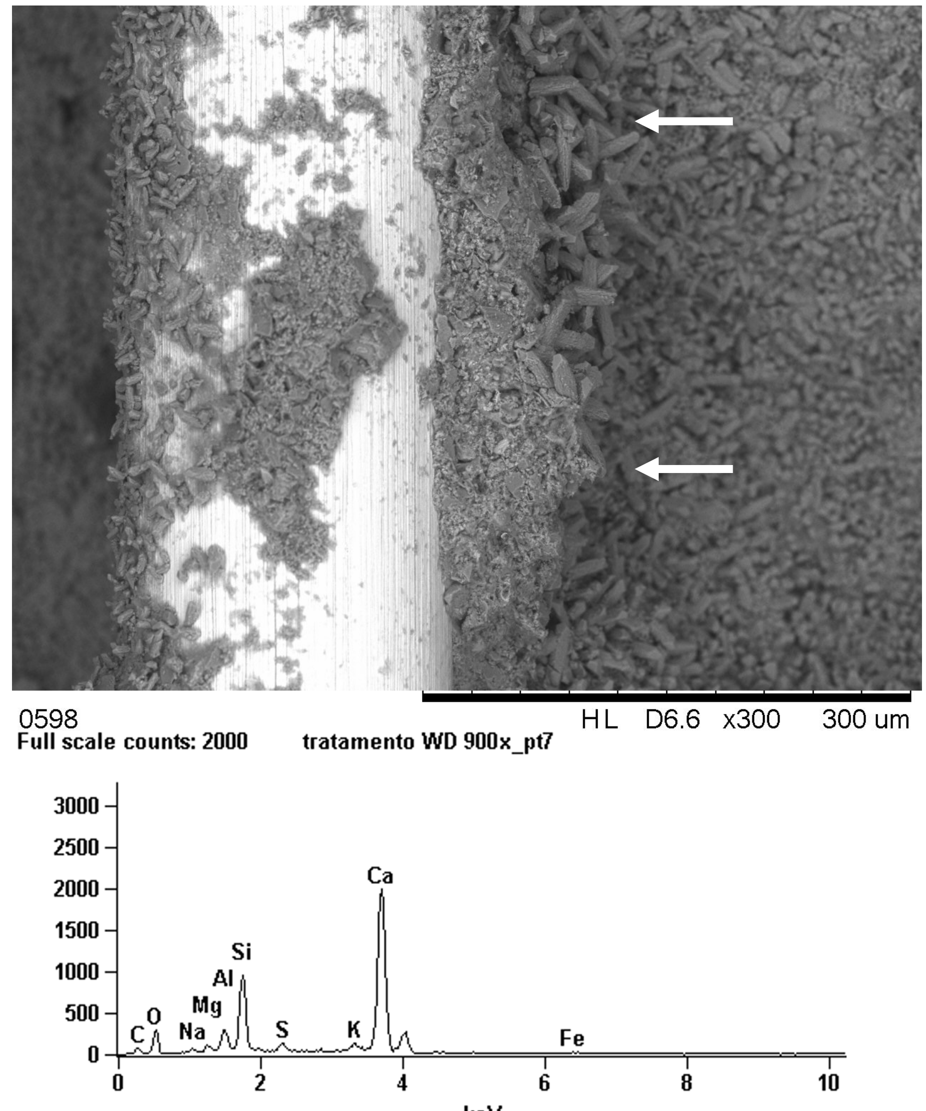
Products accumulated in the fiber

28 days: pre-slip

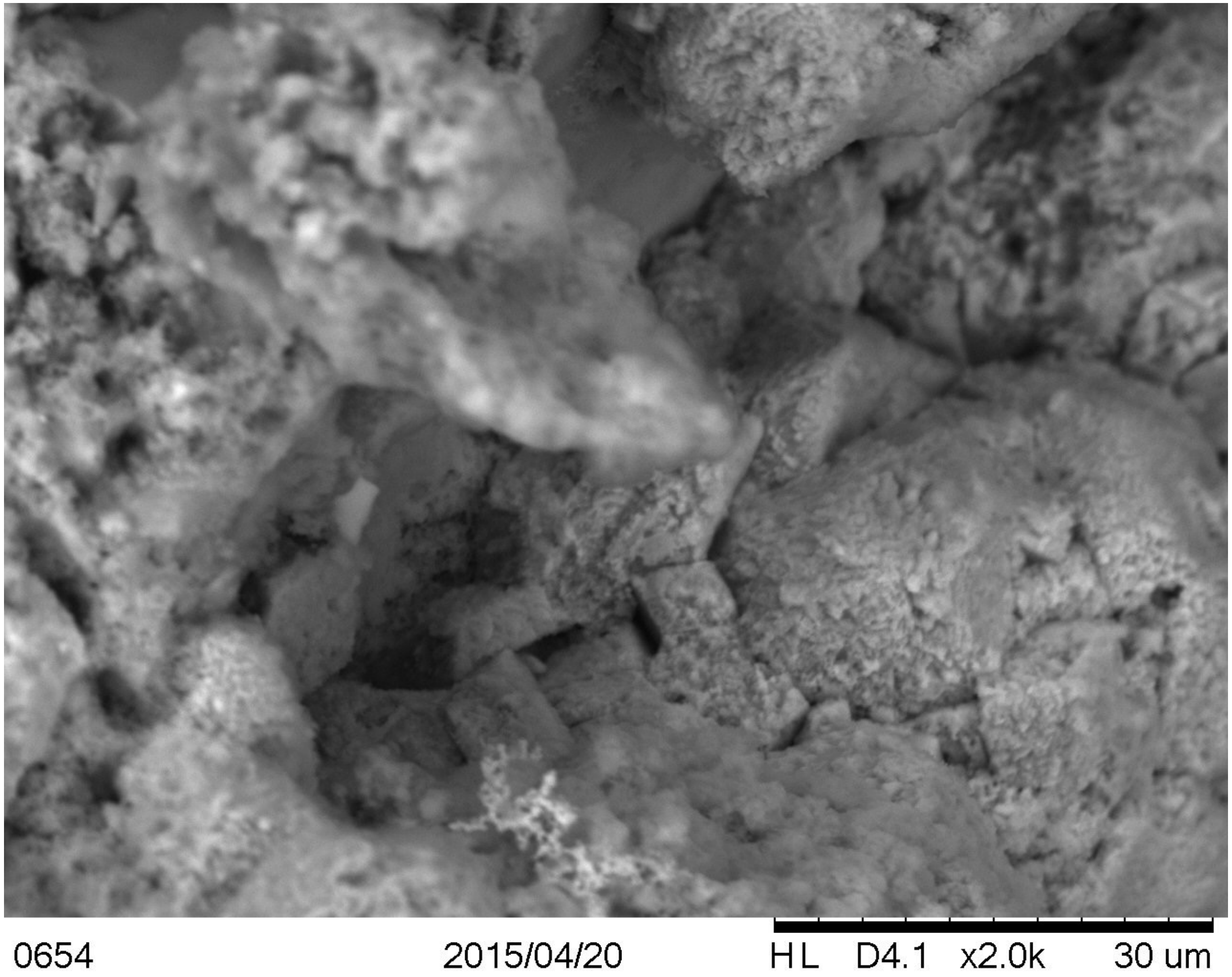
After 2 months of W&D (total slip)

Healing the small cracks at the Interfacial zone



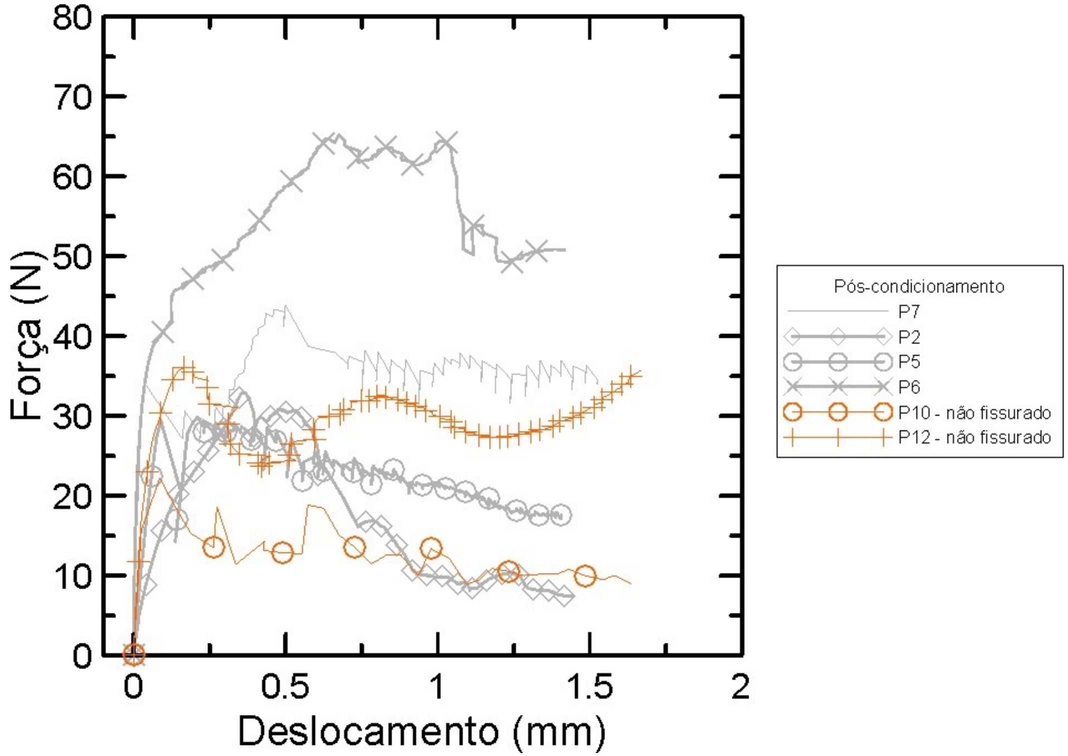


Healing the small cracks at the Interfacial zone



Healing of cracks at the interface: pull-out results

Comparative: control specimen and pre-cracked, both with two months of WD cycles



Pre-cracked specimen

$Force_{max.}$ = 44,23±14,10 N

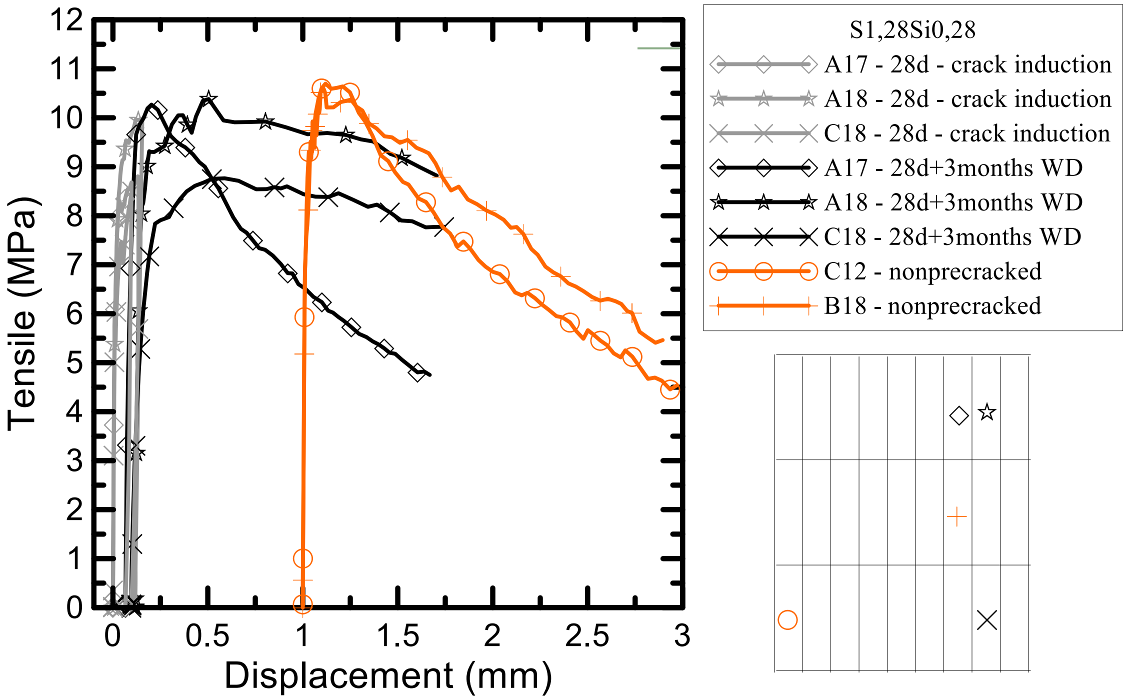
Control samples

$Force_{max.}$ = 30,48±11,51 N

Recovery: 138%

Stress x displacement behavior after conditioning: M1 [A1,28A0,28] 3M – W&D

M1 [A1,28S0,28] – 3 months submitted to wet/dry cycles



Bio-based cementitious systems using bio-aggregates and vegetable fibres

Biomass Materials Used in the Study

Bamboo Particles (BP)

Apparent density:
0.58g/cm^3

Rice Husk (Rhu)

Apparent density:

0.30 g/cm^3

Wood Shavings (WS)

Apparent density:

0.55 g/cm^3

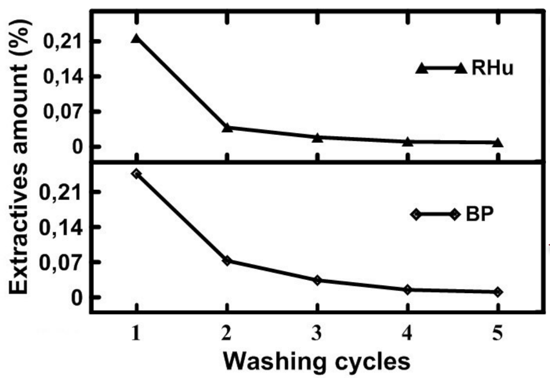
- In 2015 the logging industry generated 46.8 million tons of solid waste, of which 33.0 million of this total was generated by forestry activities and 13.8 million by industries (IBÁ, 2016)

- The estimated value of the rice husk for 2016 was 48.27 milion tons.

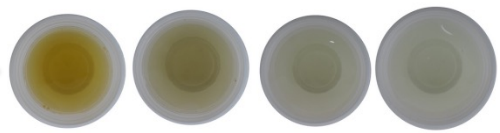
- Residues from the processing of bamboo corresponds to approximately 45-55% from the extraction of the raw material

Water soluble extractives measurement

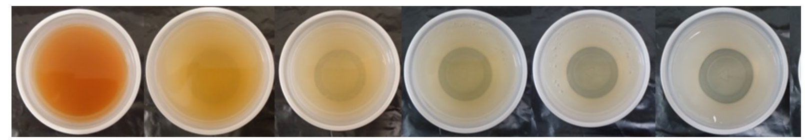
Extractives amount and color of the waste water
after multiple washing cycles

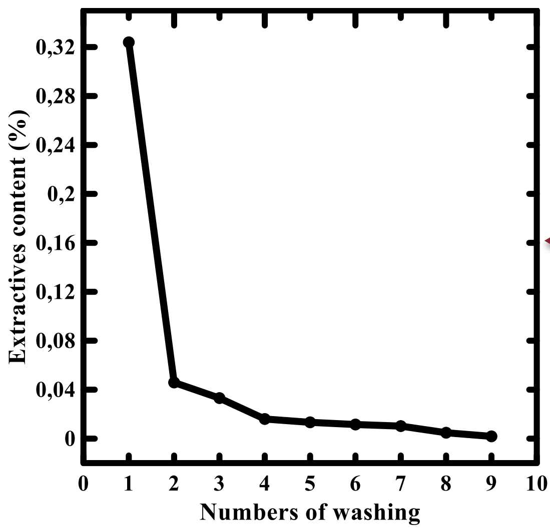


Rice Husk

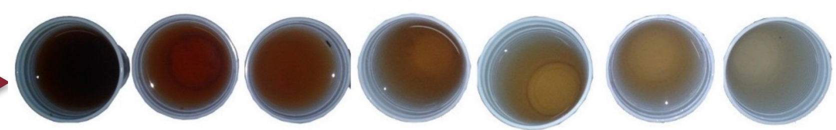


Bamboo Particles





Wood Shavings



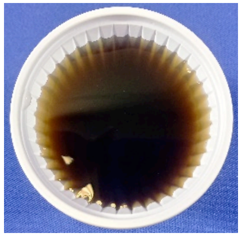
Rice Husk	Bamboo Particles	Wood Shavings
0.89%	1.35%	3.02%

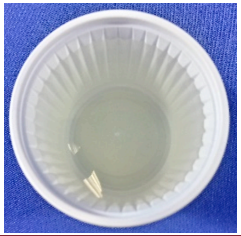
Total extractives content

Membrane separation processes

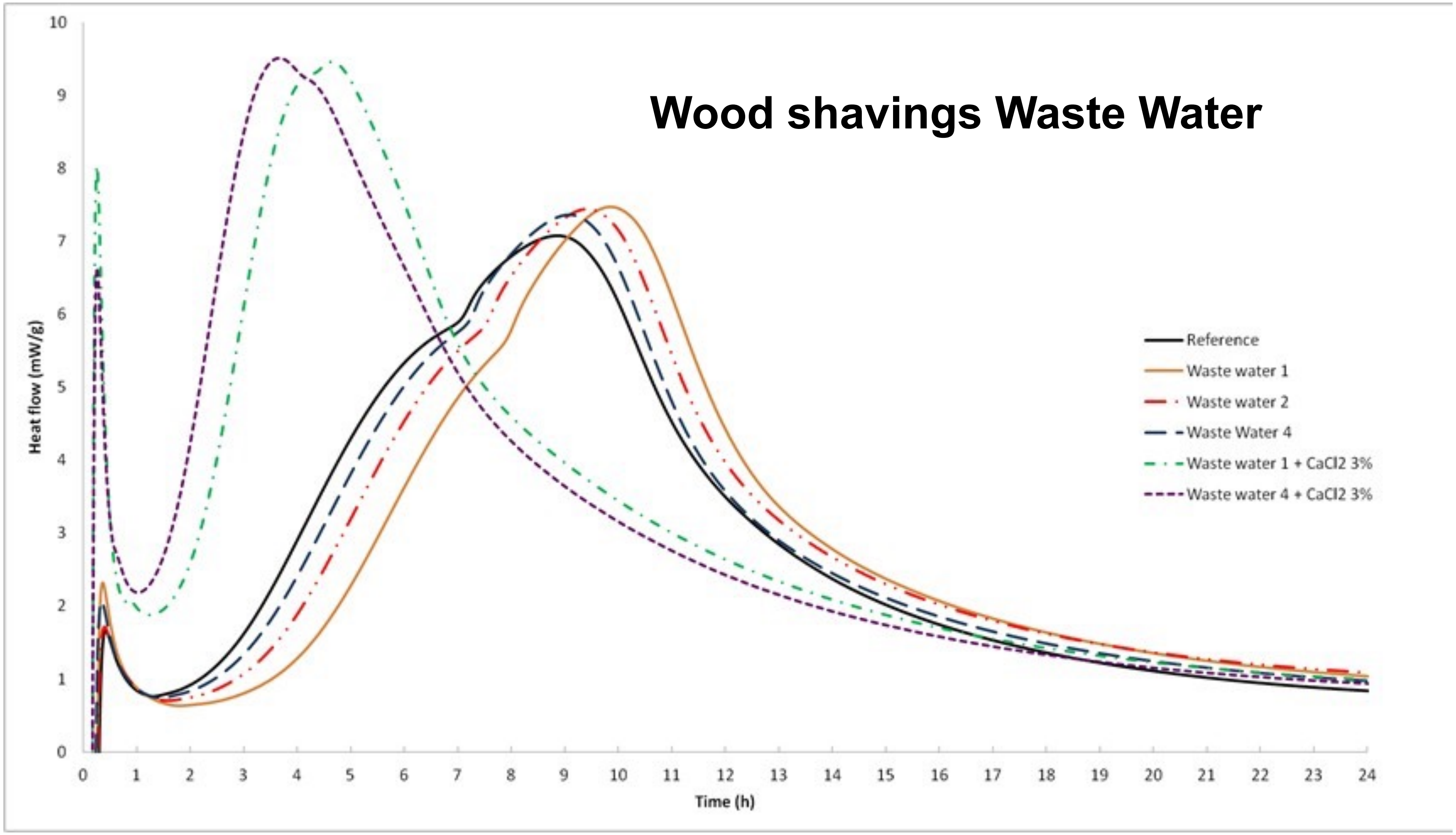
- Reverse Osmosis

Bamboo/water mass ratio: 1/2.5

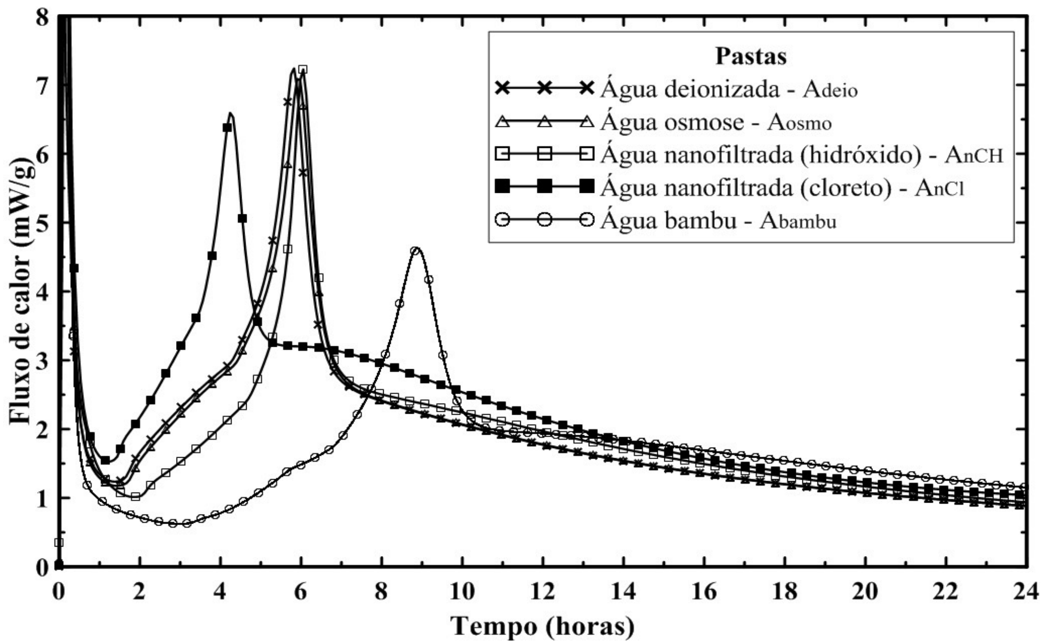




Effect of the extractives on the cement hydration through isothermal calorimetry



Effect of the extractives on the cement hydration through isothermal calorimetry

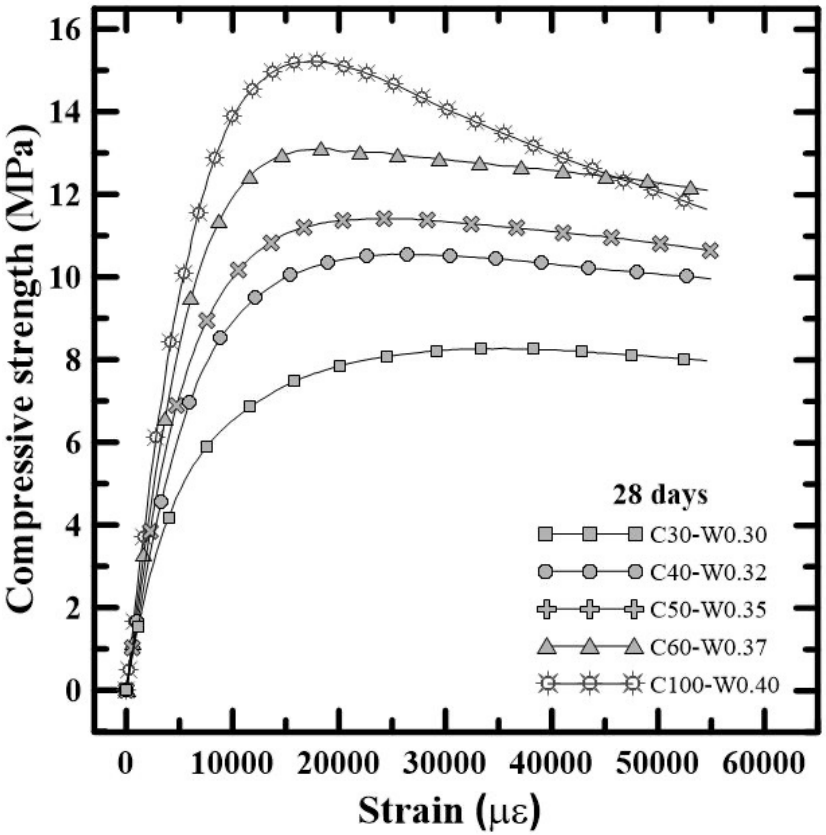


Cement Paste produced using the water containing bamboo particles extractives

New production approach – workable mixtures

Demonstrate the feasibility of producing bio-based cementitious composites with adequate workability using bamboo biomass in order to keep traditional concrete technology mixture procedures

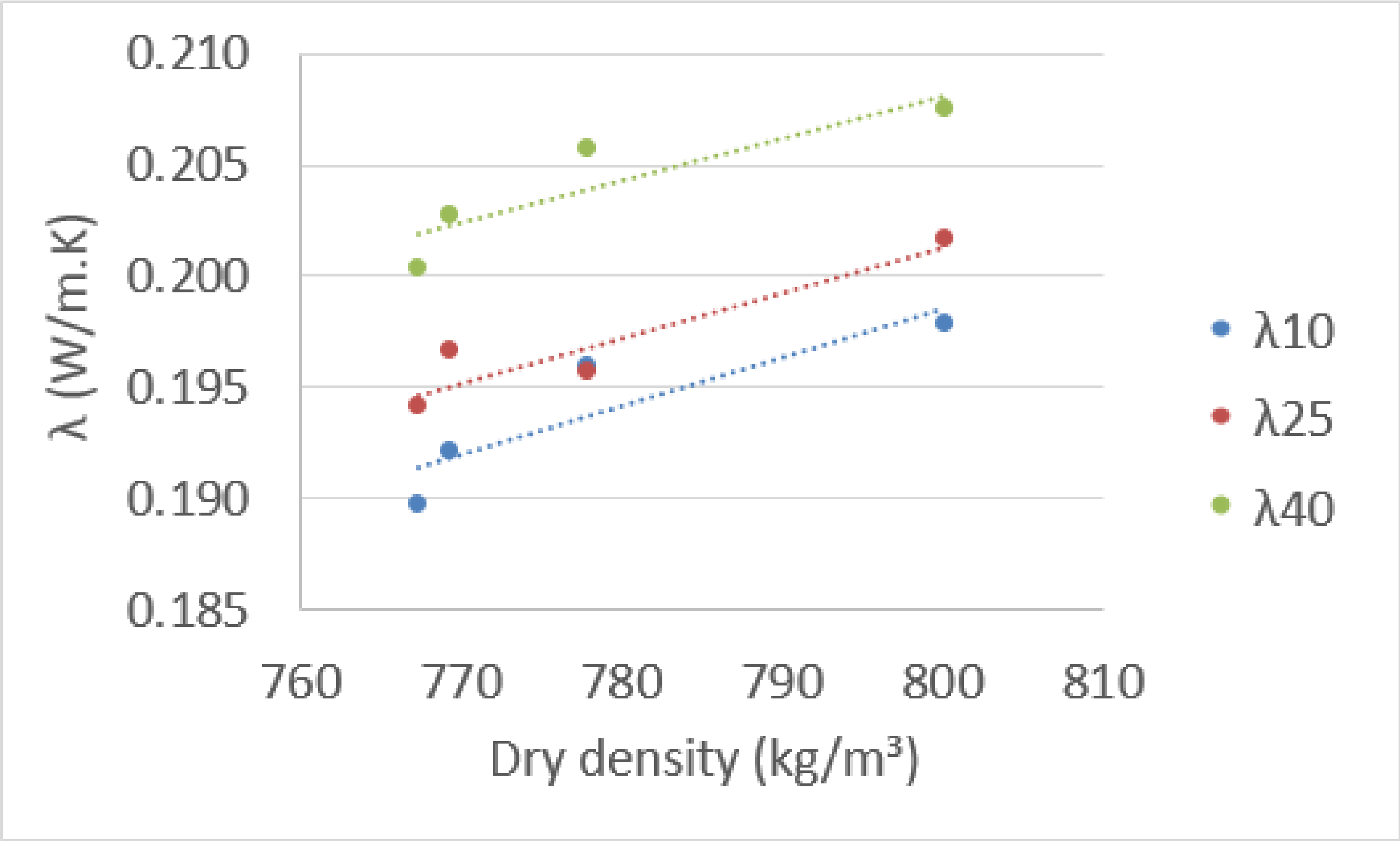
High Strength Bamboo Bioconcrete – Stress-strain Behaviour



Bio - concrete	Compressive strength (MPa)	Young Modulus (GPa)
C30-W0.30	8.46 (2.89)	1.55 (6.96)
C40-W0.32	10.63 (3.13)	1.48 (4.74)
C50-W0.35	10.96 (6.45)	1.55 (5.50)
C60-W0.37	13.39 (0.14)	1.95 (4.07)
C100-W0.40	14.75 (3.51)	2.15 (7.68)

Thermal performance Bamboo bioconcrete

Thermal conductivity – Bamboo Bioconcrete



Thermal conductivity for different temperatures and densities.

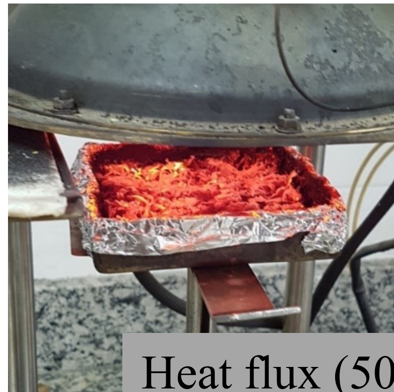
Aerated bioconcrete for retroffitting





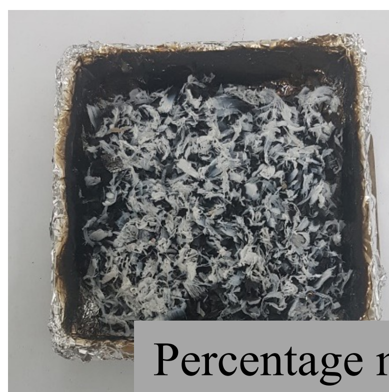
Combustion properties of wood biomass from cone calorimeter tests

Sample initial mass (29 g)



Heat flux (50 kW/m²)

About 14 seconds to ignition



Percentage mass lost of 87,33%

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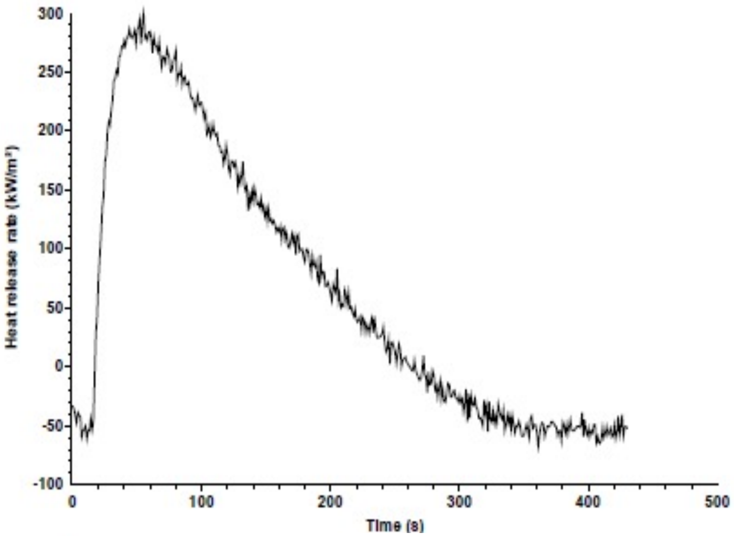
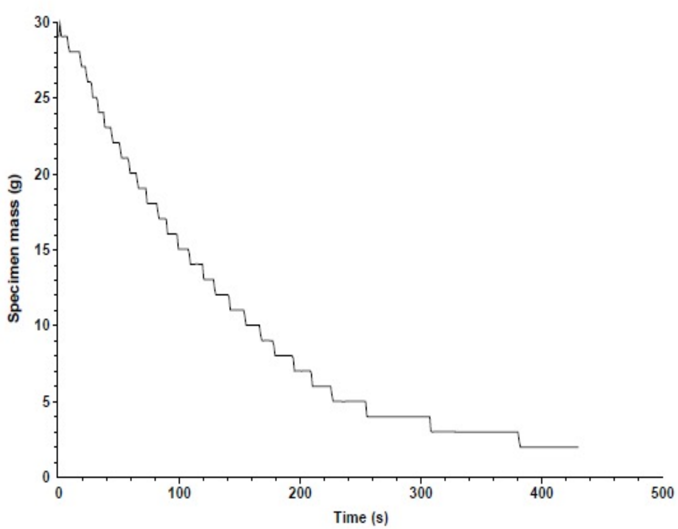
LabEST PEC/COPPE/UFRJ Laboratório de Estruturas e Materiais Prof. Lobo Carneiro

COPPE UFRJ

Combustion properties of wood biomass from cone calorimeter tests

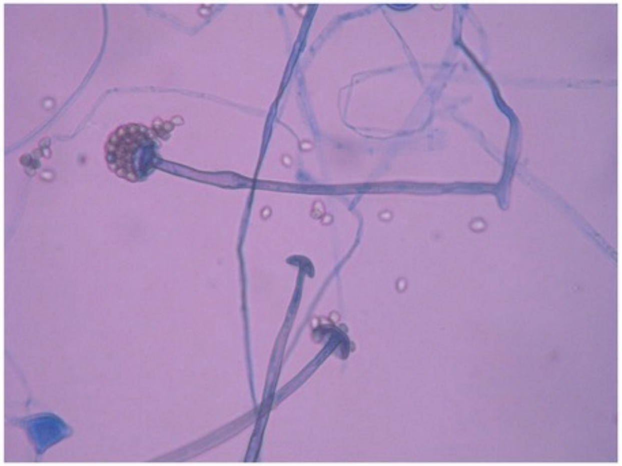




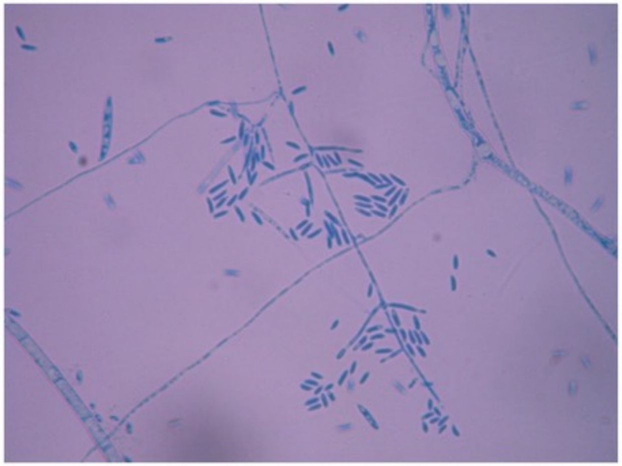
Combustion Properties	Average Results
Time to ignition	14 sec
Ignition temperature	359 °C
Time to flameout	297 sec
Total heat release	42,4 MJ/m²
Heat release rate (mean/peak)	146,44 kW/m² 316,17 kW/m²
Effective heat of combustion	14,69 MJ/kg
Percentage mass lost	87,33 %
Mass loss rate	0,09 g/s

Biological attack: fungi identification present in the biomass

Biological attack: fungi identification

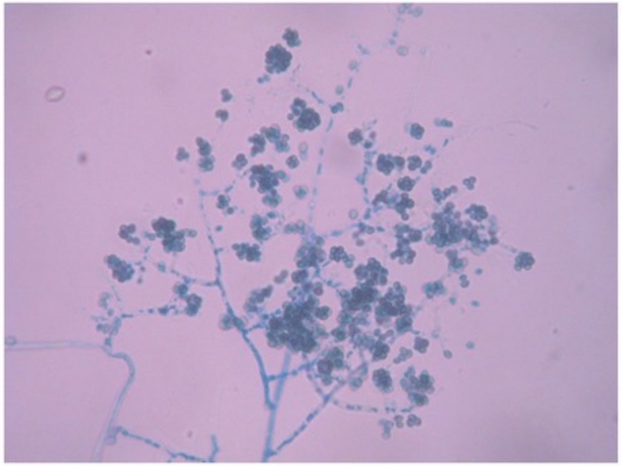


(a) *Rhizopus microsporus* var. *oligospurus*.



(b) *Fusarium* sp.

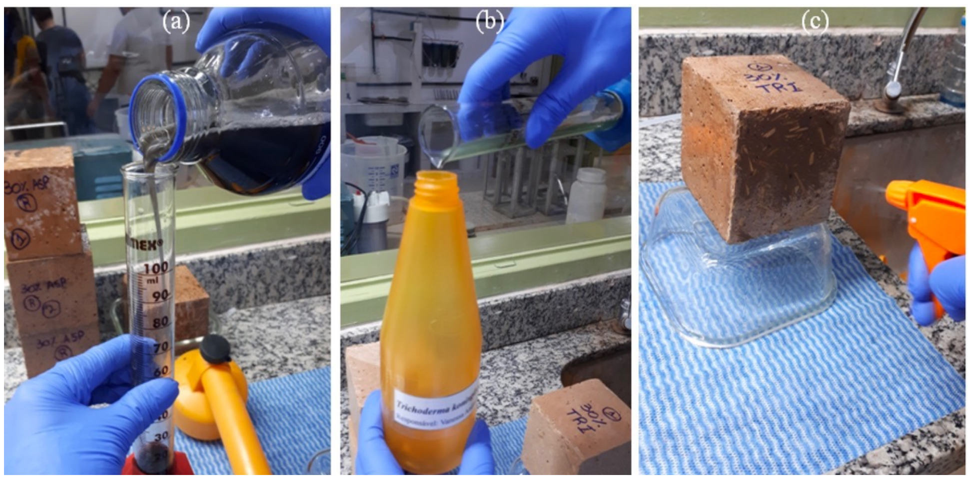
(c) *Rhizopus microsporus* var. *rhizopodiformis*.



(d) *Trichoderma koningii*

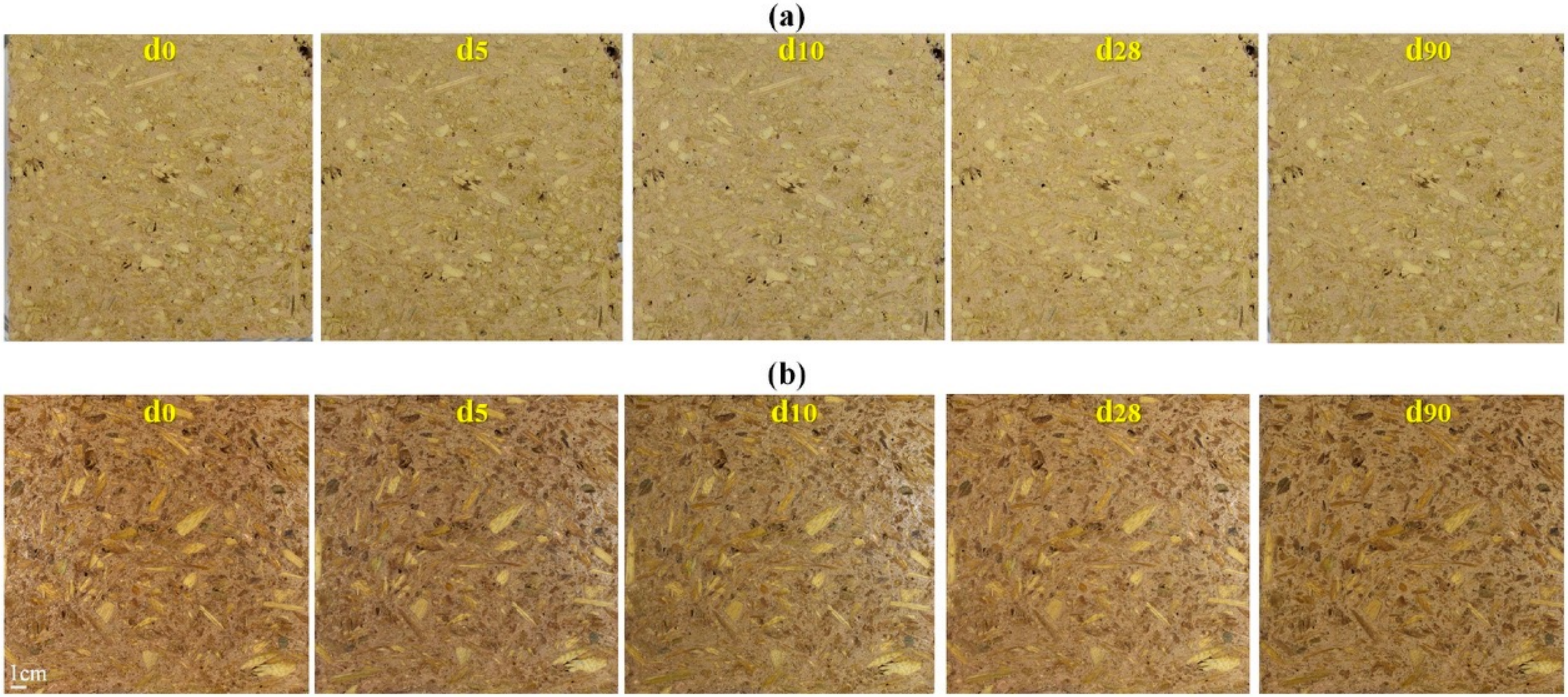
Biological fungal attack

Trichoderna koningii inoculation



T = 34º C and RH = 76% up to 90 days

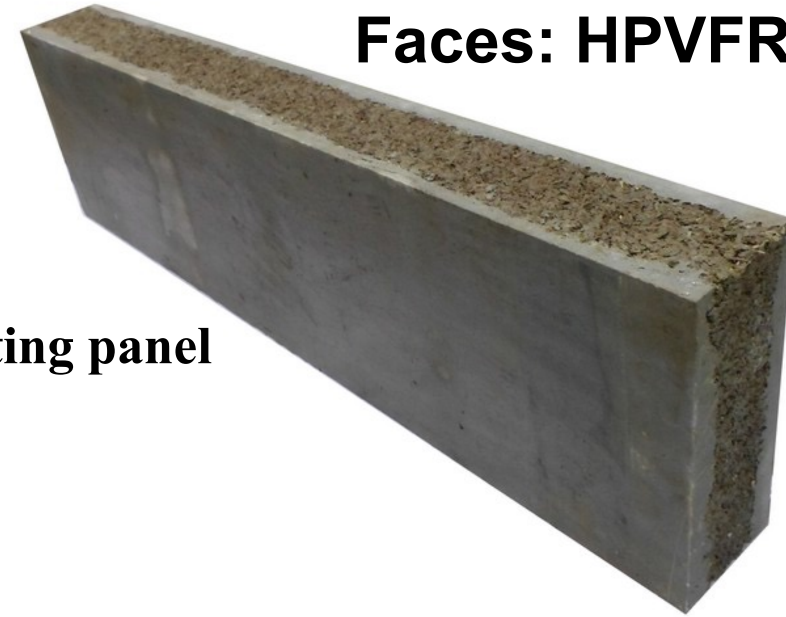
Biological fungal development over time



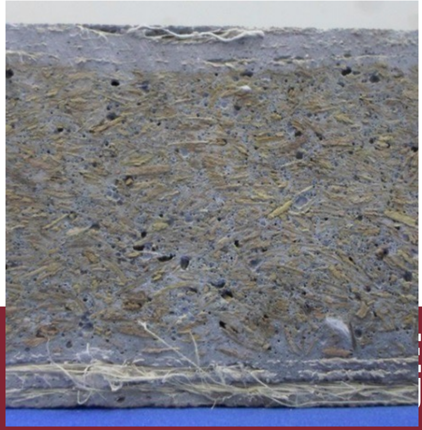
HPVFRC- bio concrete Sandwich panels

Core: bio-concrete
Faces: HPVFRC

Retrofitting panel

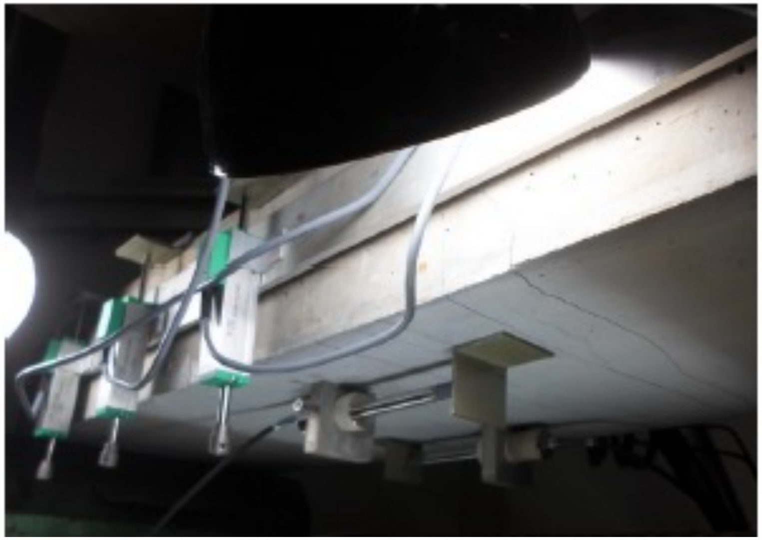


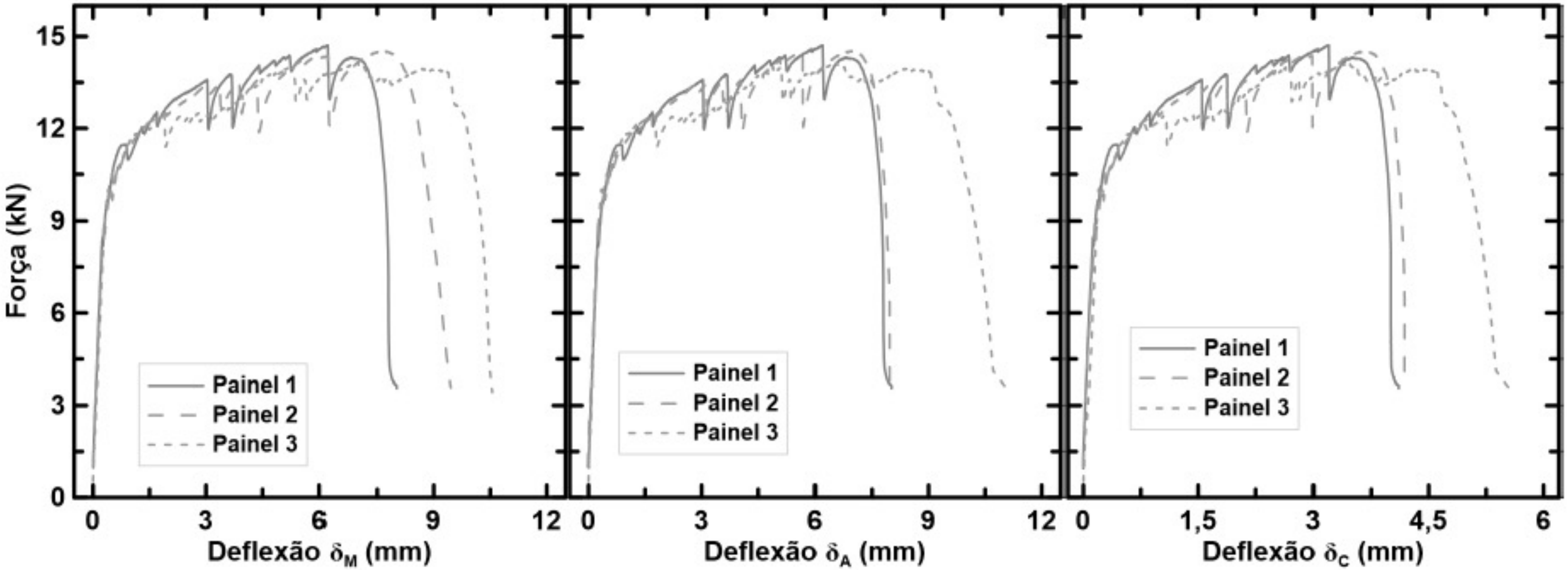
Panel for structural application



HPVRFC- bio concrete Sandwich panels

Behavior under Bending



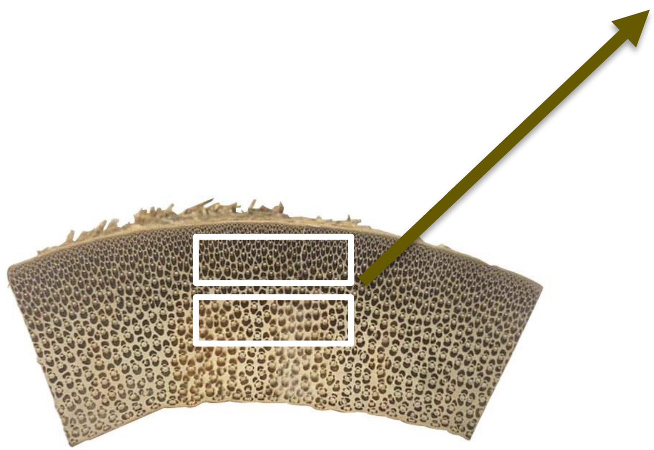


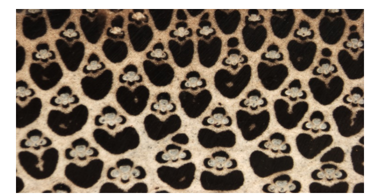
Bamboo reinforced Bioconcrete

Bamboo Segments Mechanical Behaviour

Functionally graded material

Bamboo segments





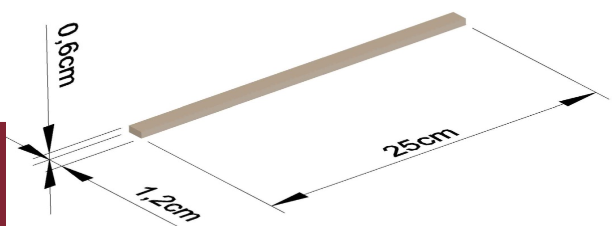
Outer part: V_f = 54,7 %

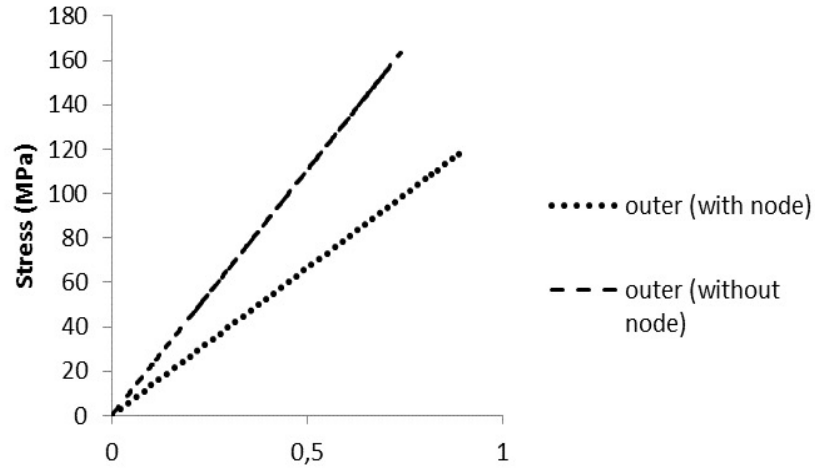
Inner part: V_f = 40,7%

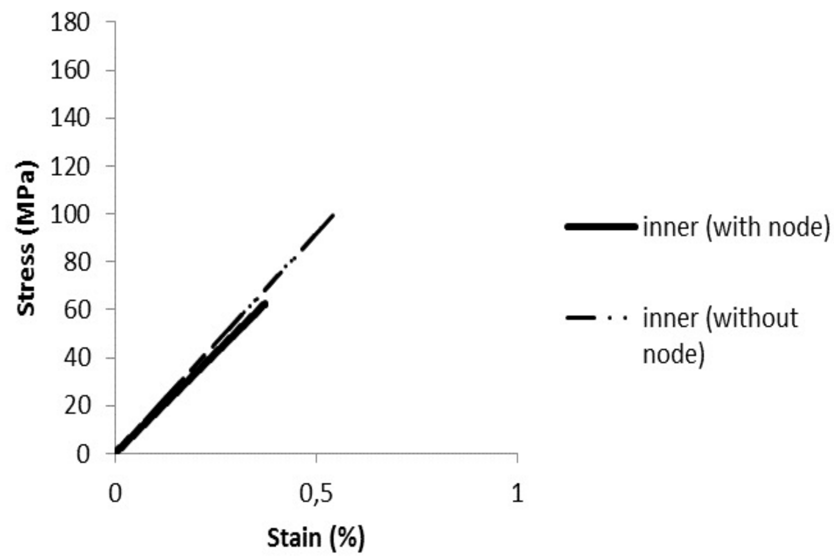
Bamboo Segments Mechanical Behaviour

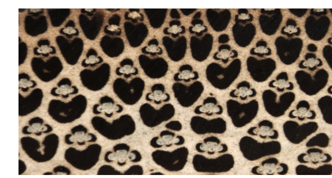
Bamboo Segments Mechanical Behaviour

Functionally graded material







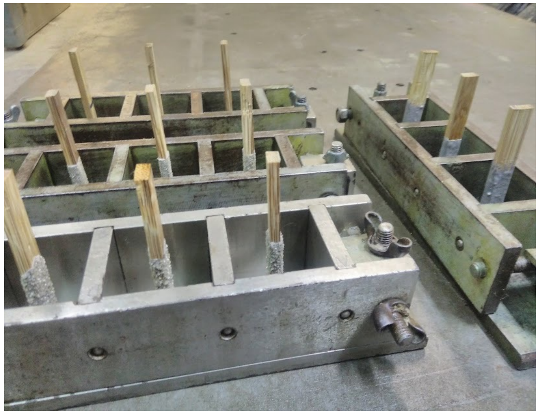


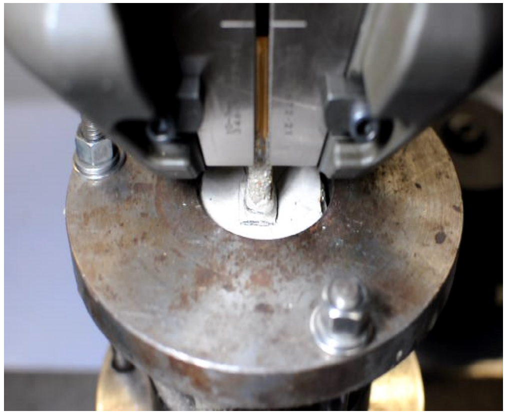
Outer part: V_f = 54,7 %

Inner part: V_f = 40,7%

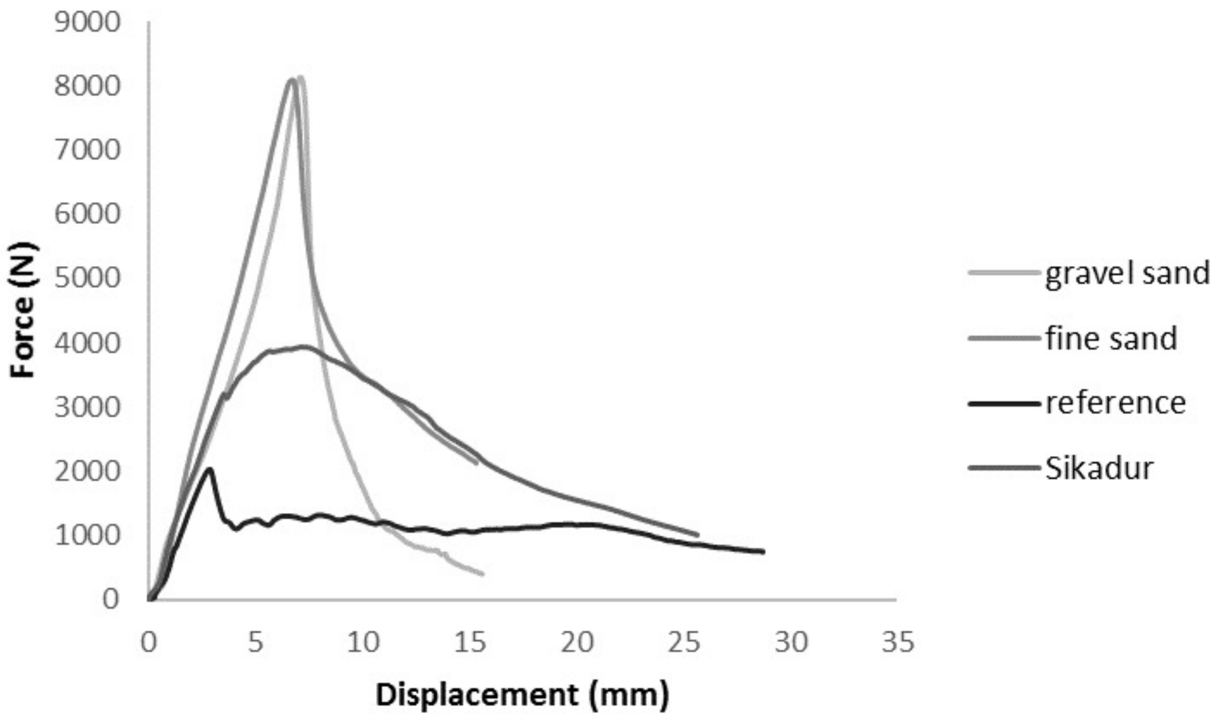
Bamboo Segments as Reinforcement of Bamboo Bio-Concrete

PULL-OUT TEST



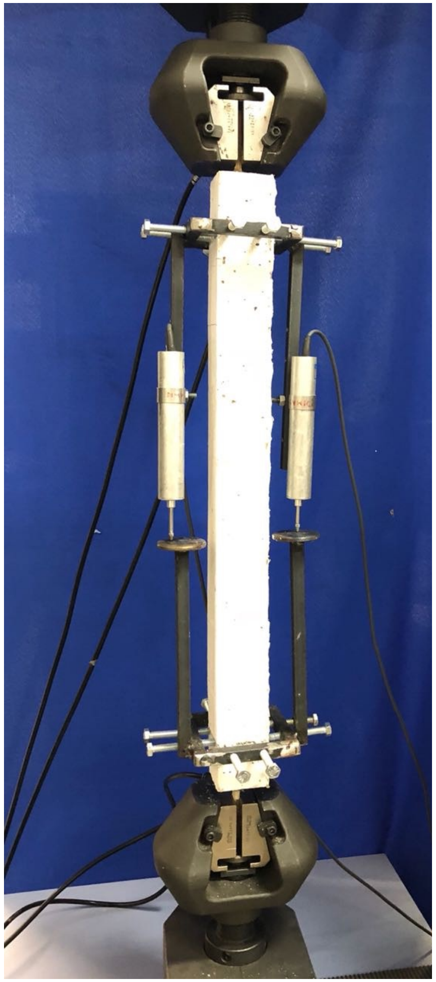


Pullout test results

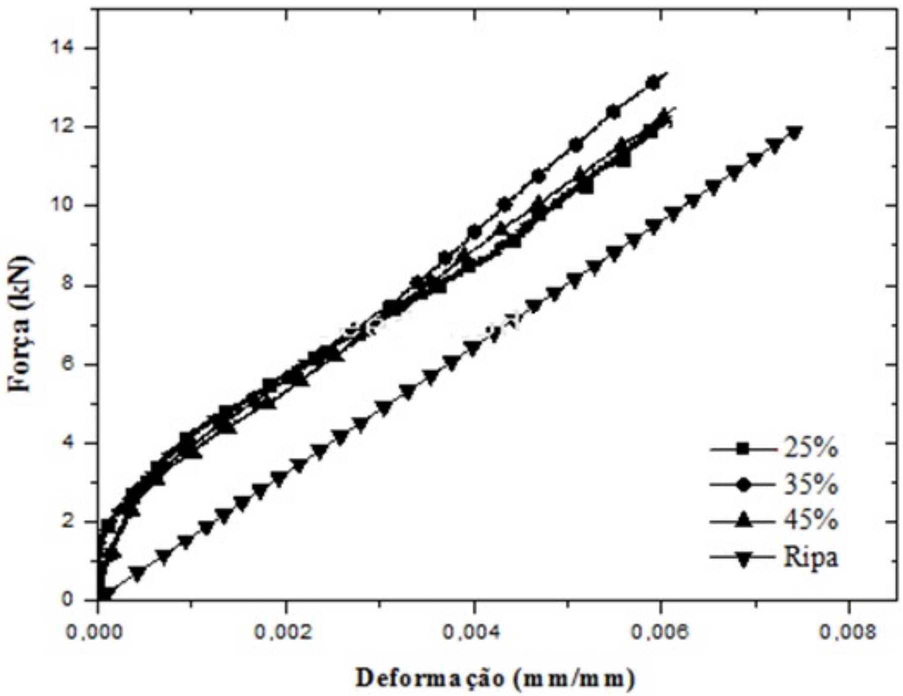


Tratamento	Forca Máxima (N)	Tensão de Aderência (Mpa)
Natural(Referência)	2028,83	1,12
Sikadur	3932,90	1,98
Areia Fina	8090,67	4,49
Areia Grossa	8418,95	3,98

Tension Stiffening of Bamboo Segments-Bamboo Bio-Concrete




Tension Stiffening of Bamboo Segments-Bamboo Bio-Concrete

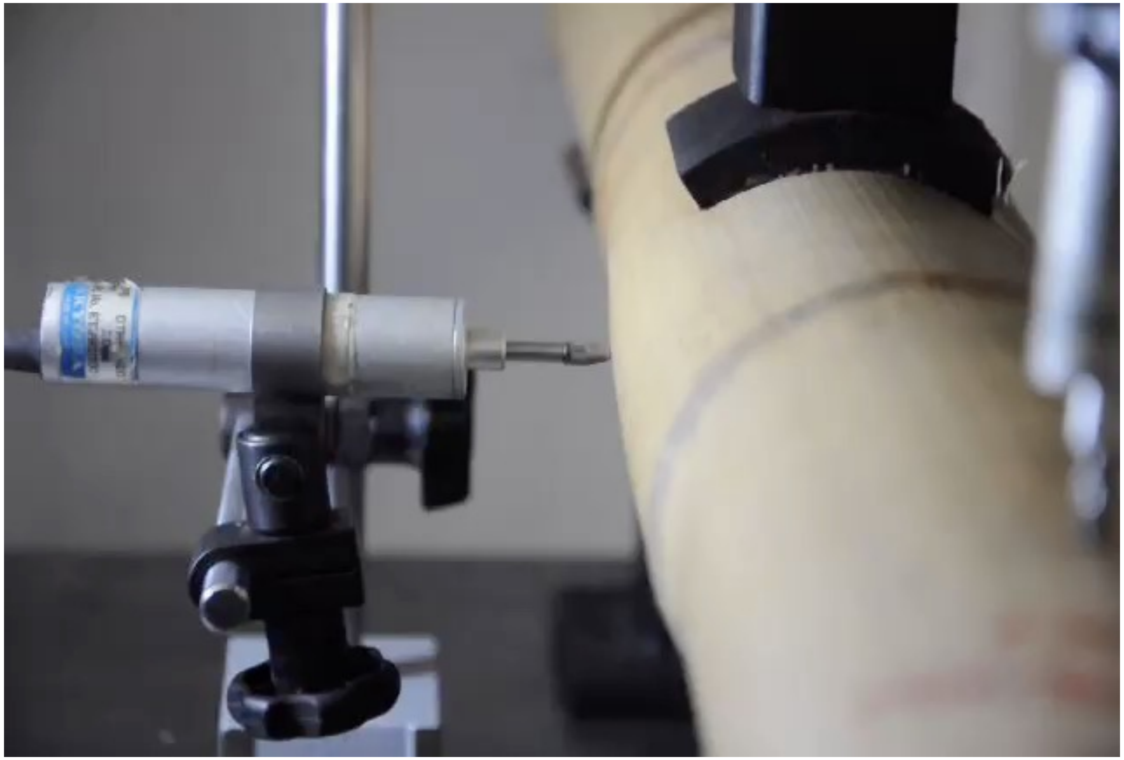


BAMBOO CONSTRUCTION: POLE AND INDUSTRIALIZED BAMBOO

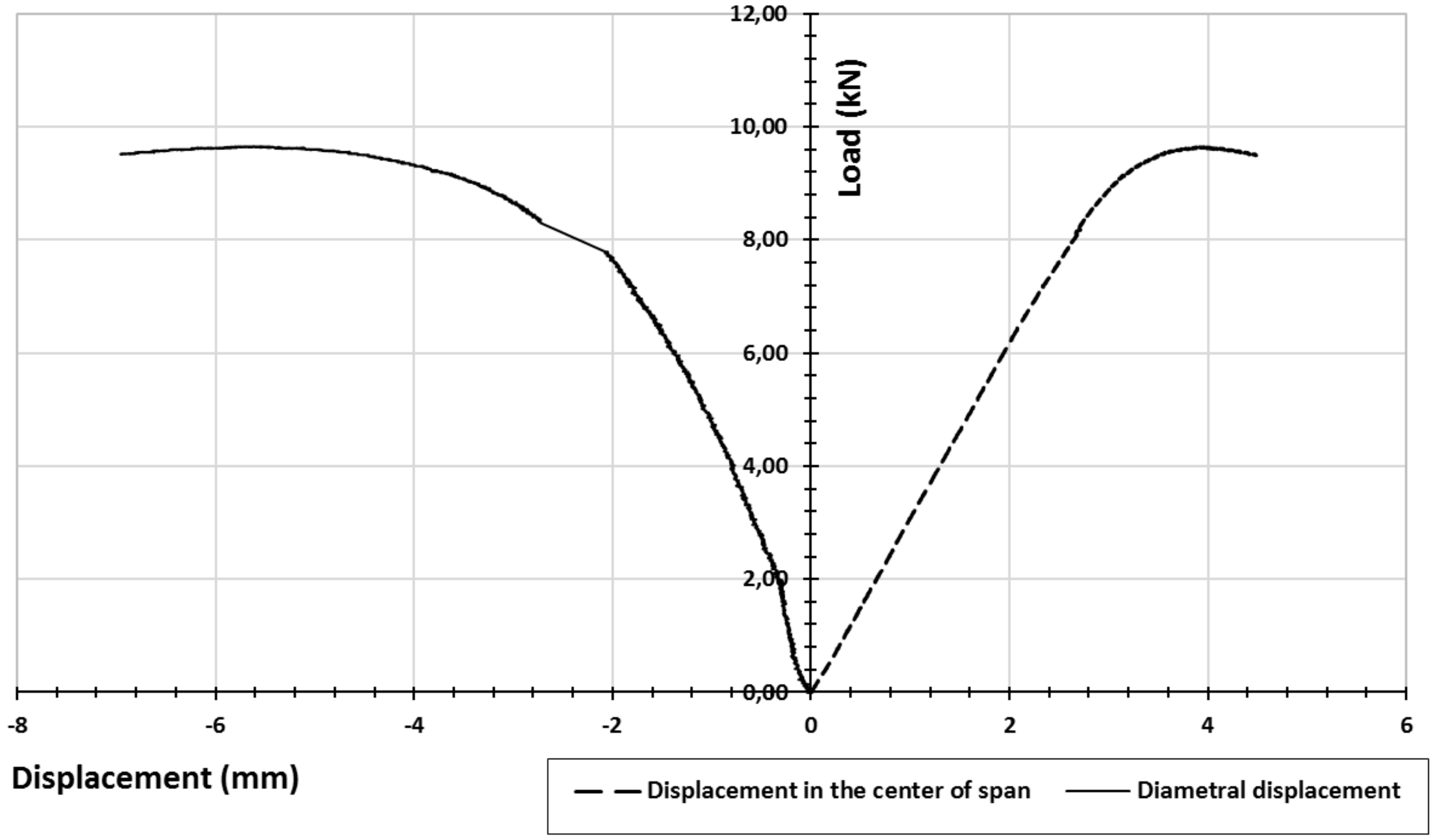
Pole Bamboo

Courtesy: Prof. Mario Seixas LILD|PUC|RIO

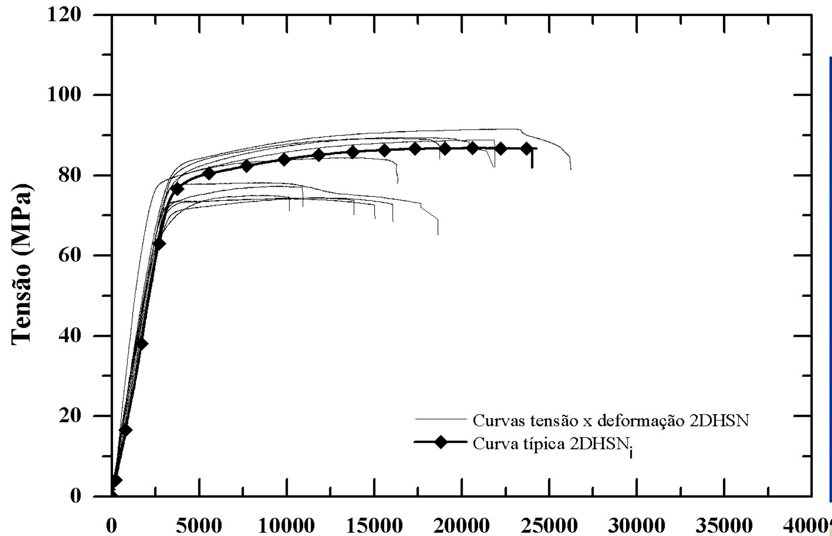
Bamboo Pole Mechanical Behaviour: Bending Behavior

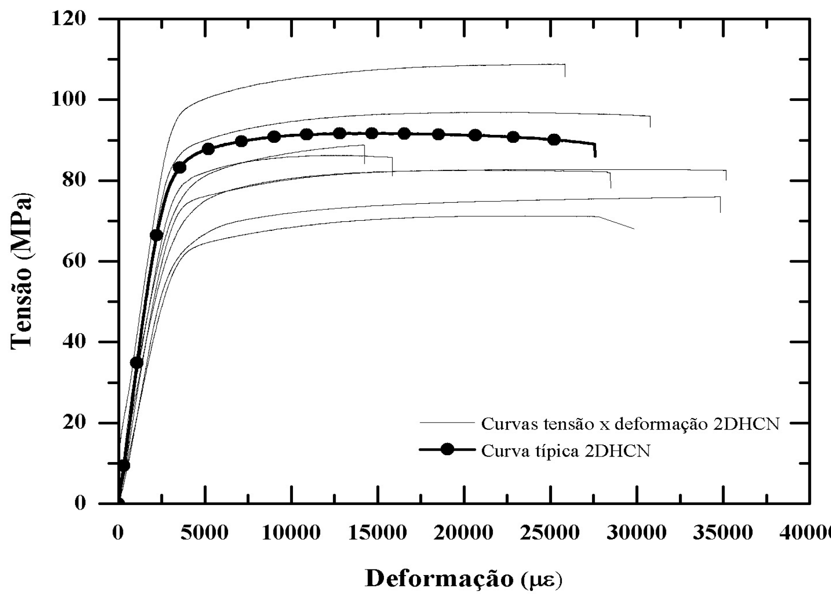


Bamboo Pole Mechanical Behaviour: Bending Behavior

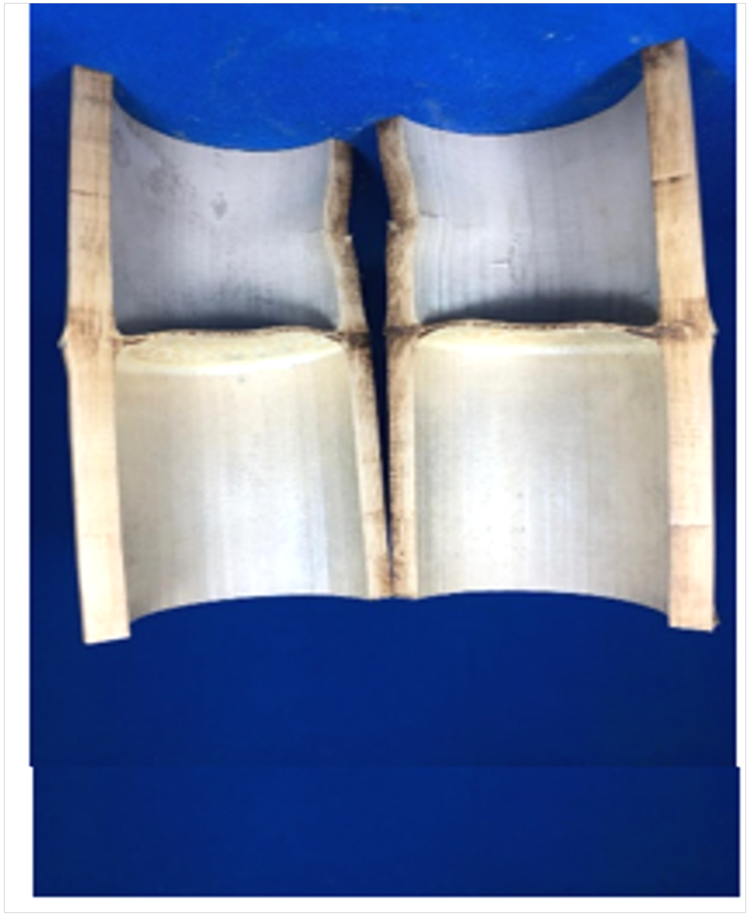


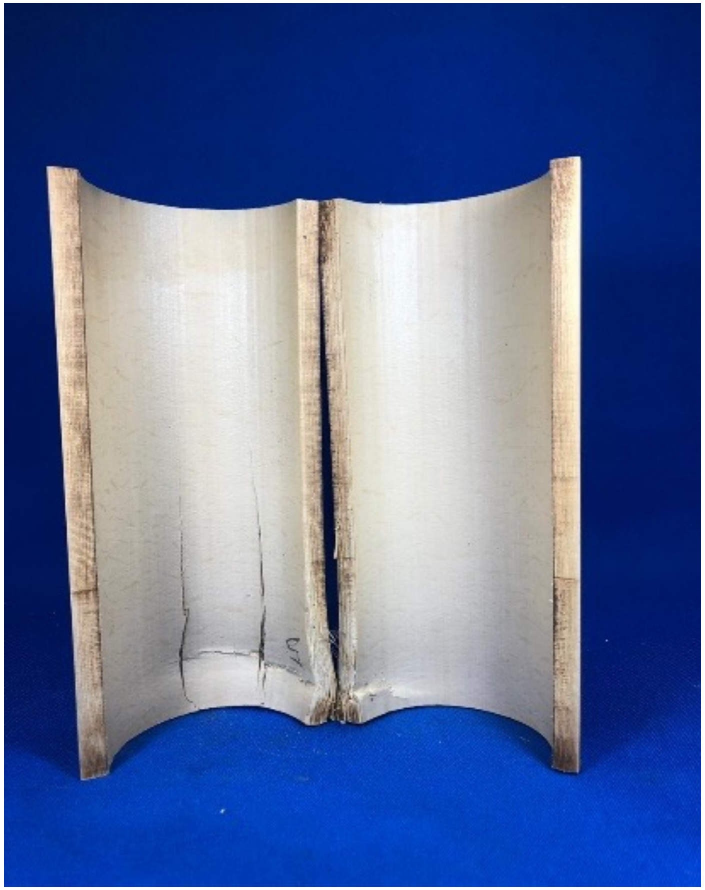
Bamboo Pole Mechanical Behaviour: Compression loads





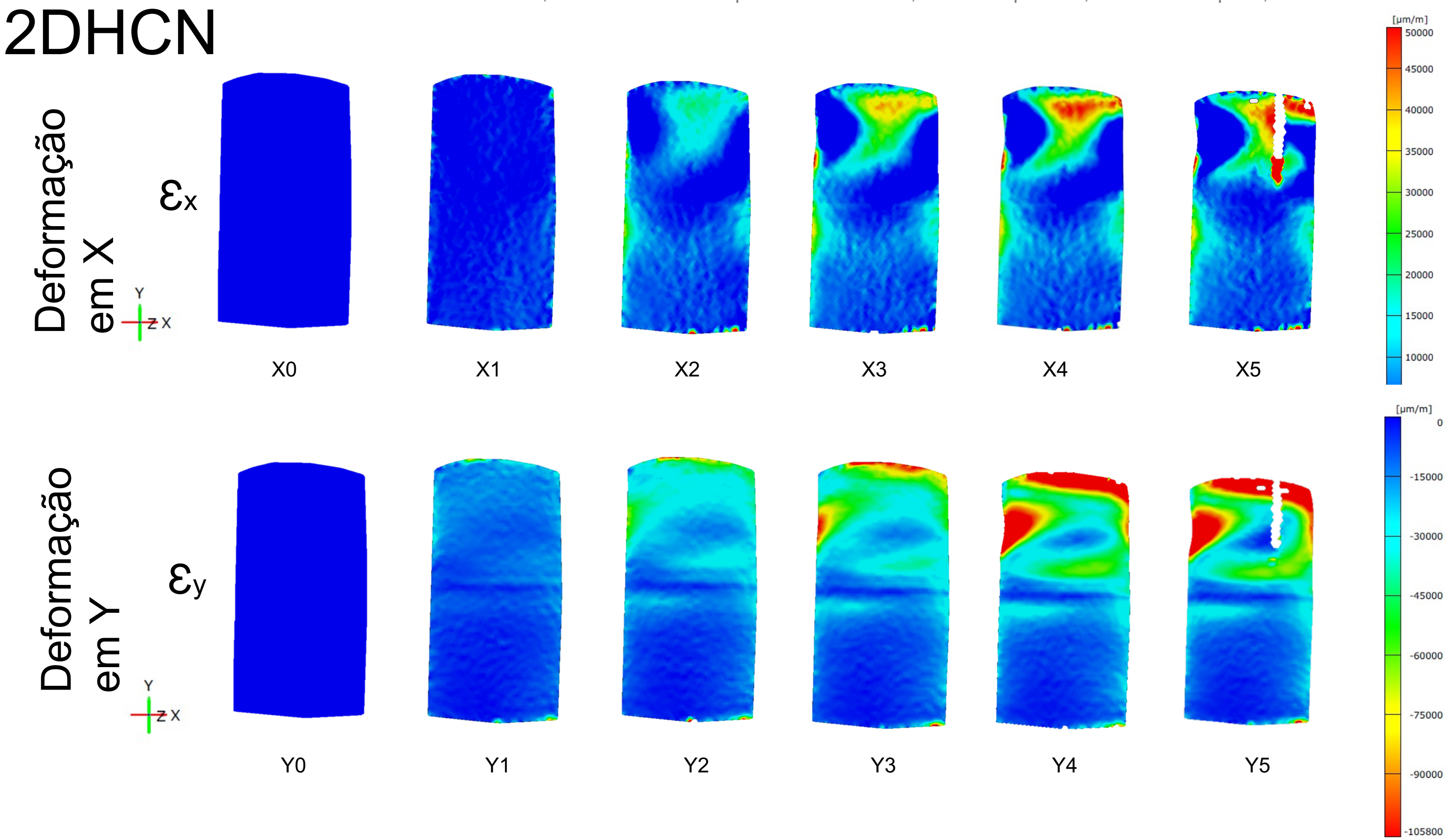
Failure mode





Failure mode - DIC

X0- Início do ensaio; X1- Final do trecho puramente elástico; X2- Zona plástica; X3- Início do platô; X4: Tensão máxima; X5: Ruptura.



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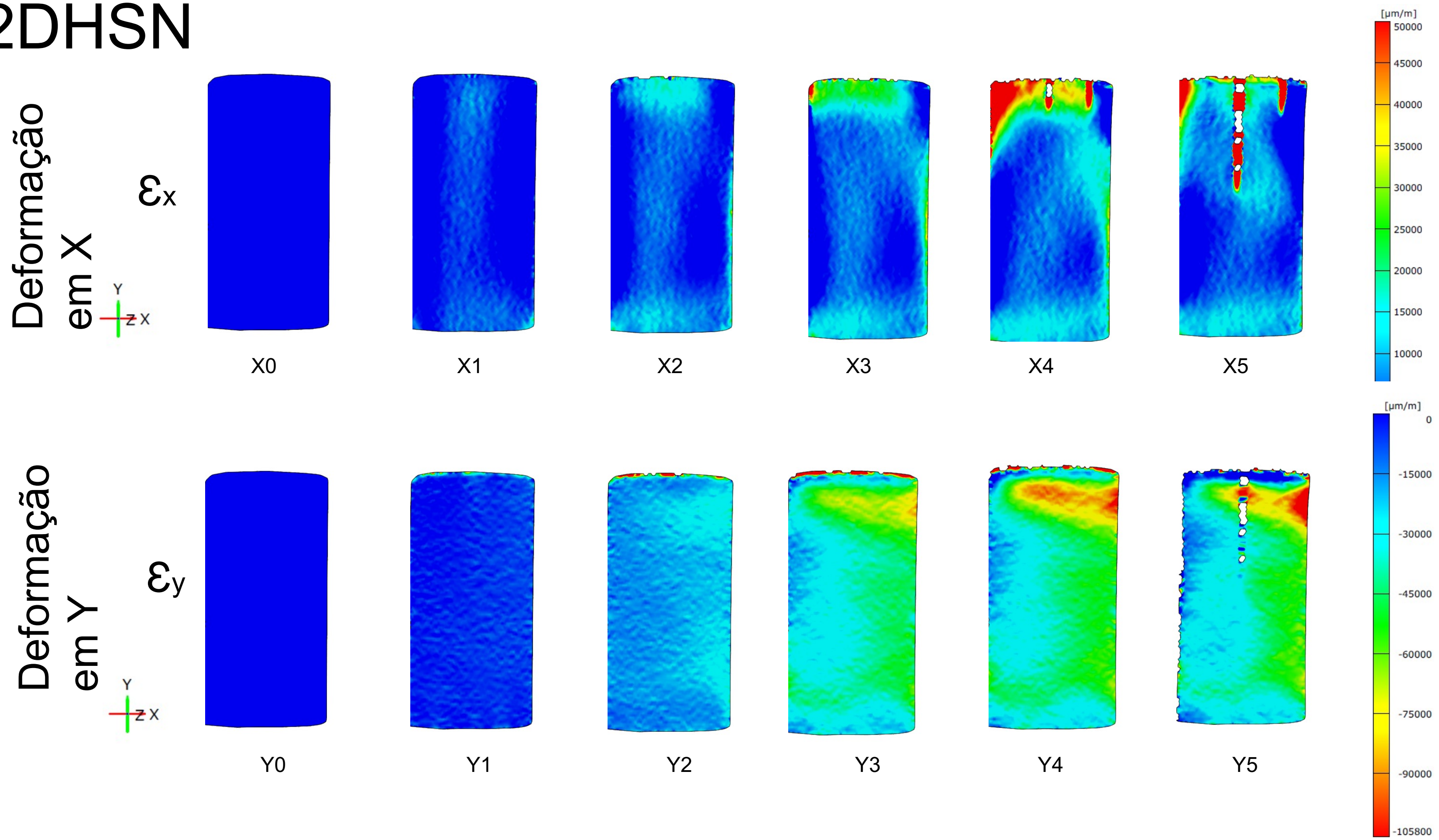
X0- Início do ensaio; X1- Final do trecho puramente elástico; X2- Zona plástica; X3- Início do platô; X4: Tensão máxima; X5: Ruptura.

2DHSN



Industrialized Bamboo

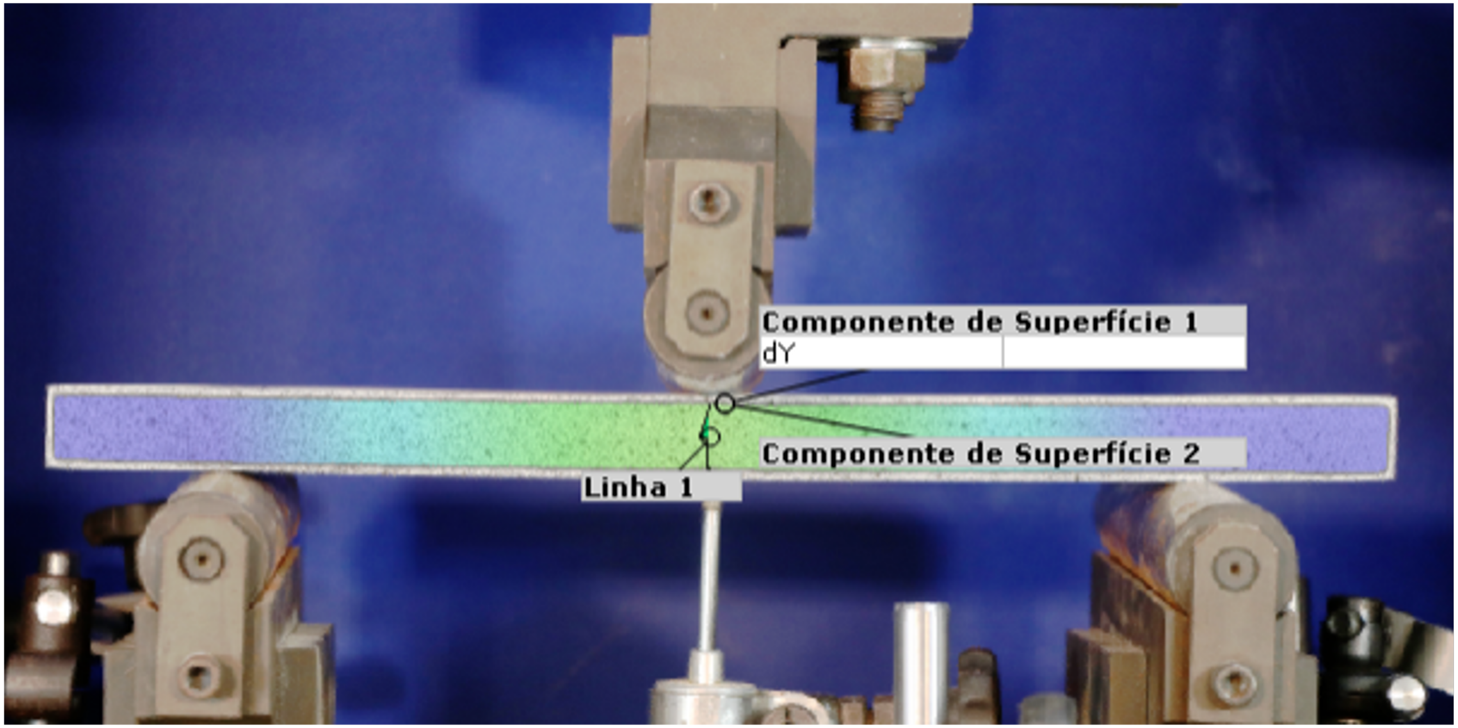
Madrid-Barajas Airport – Spain

https://www.archdaily.com.br/br/873425/terminal-do-aeroporto-de-madri-barajas-estudio-lamela-plus-richard-rogers-partnership

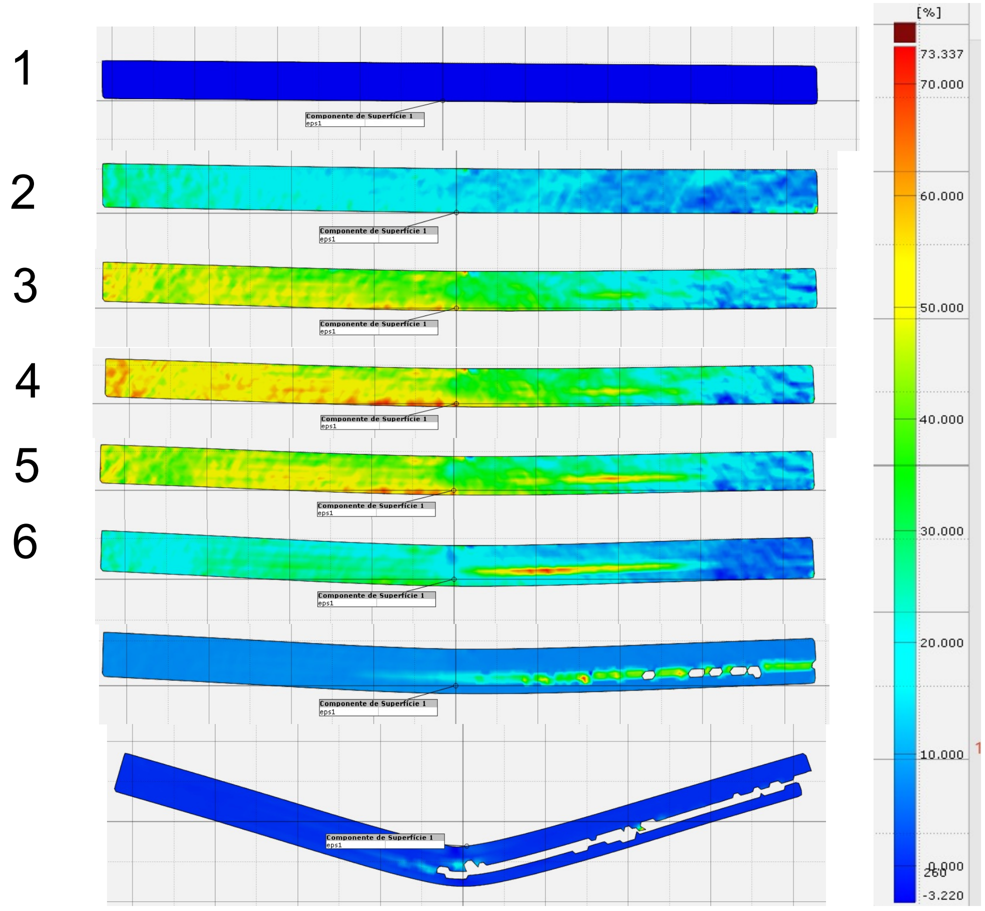
Industrialized bamboo – laminate production

Process Production

Bamboo laminate Mechanical Behaviour: ongoing

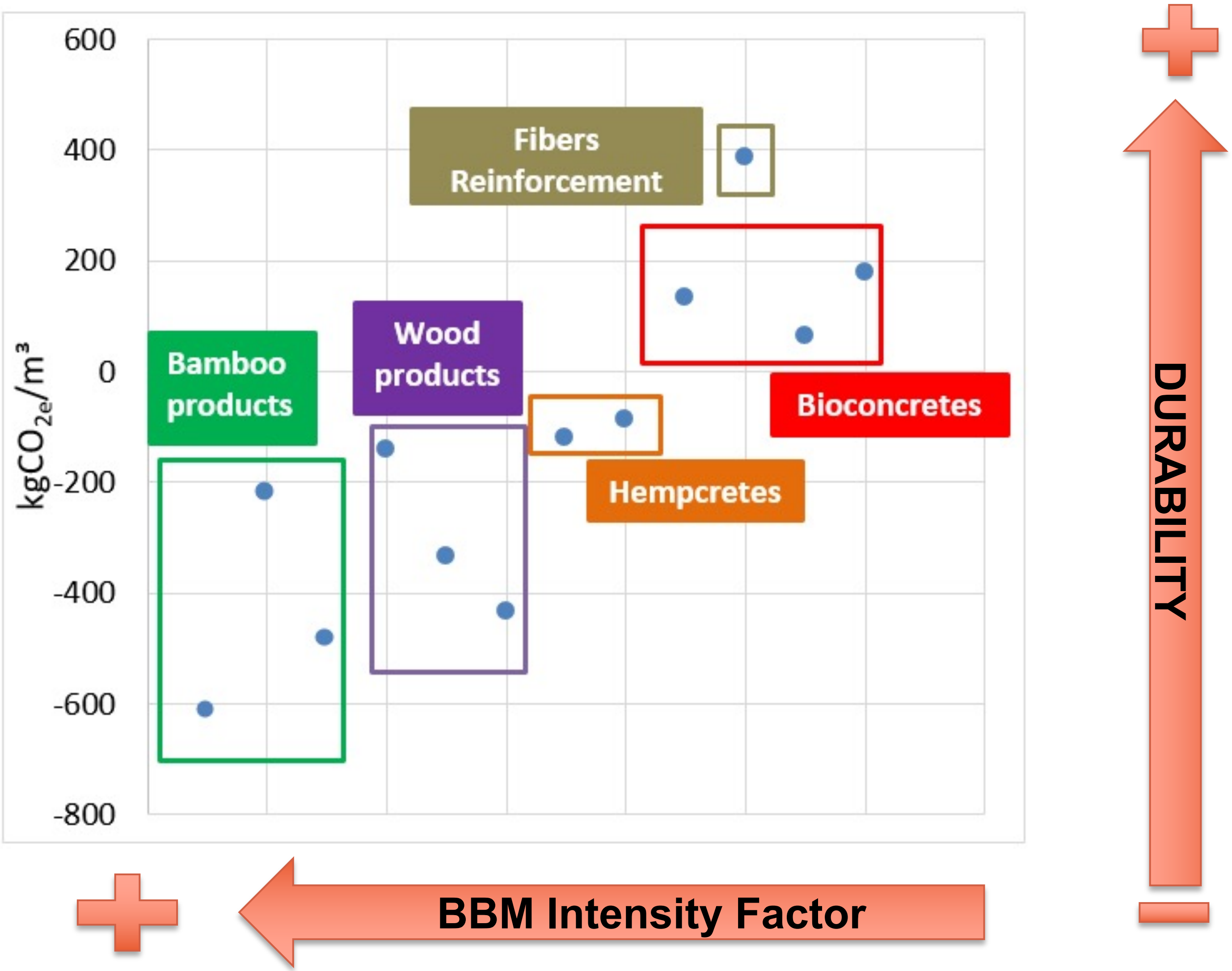


Bamboo Segments Mechanical Behaviour: ongoing



Life Cycle Assessment (LCA) of different BBMs

LCA must be adapted to the bio-based materials especially to properly considerate the biogenic carbon and its related aspects



Conclusions

- BBM can be avaliable as a **local and renewable source.**
- BBM can **absorb and storage CO_2** and therefore has high potential not only for mitigation but also for adaptation climate change given its better thermal performance which results in better thermal comfort and less energy consumption at the operational stage.
- **Lack of standardization (natural materials) and industrialization** may be barriers to entrance of these materials in the market.
- **Design Standards** are needed.
- **Durability driven design** – important and necessary.
- **Life Cycle Assessment** must be adapted to the bio-based materials especially to properly considerate the biogenic carbon and its related aspects

NUMATS Research Group: December 2018

Thank you!

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Laboratório de Estruturas e Materiais
Prof. Lobo Carneiro

COPPE
UFRJ