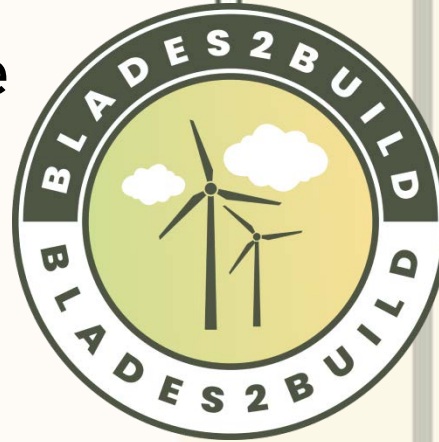


# BLADES2BUILD

Recycle, repurpose and reuse end-of-life wind blade composites – a coupled pre- and co-processing demonstration plant



## Welcome to the 2<sup>nd</sup> Blades2Build Summer School in Athens



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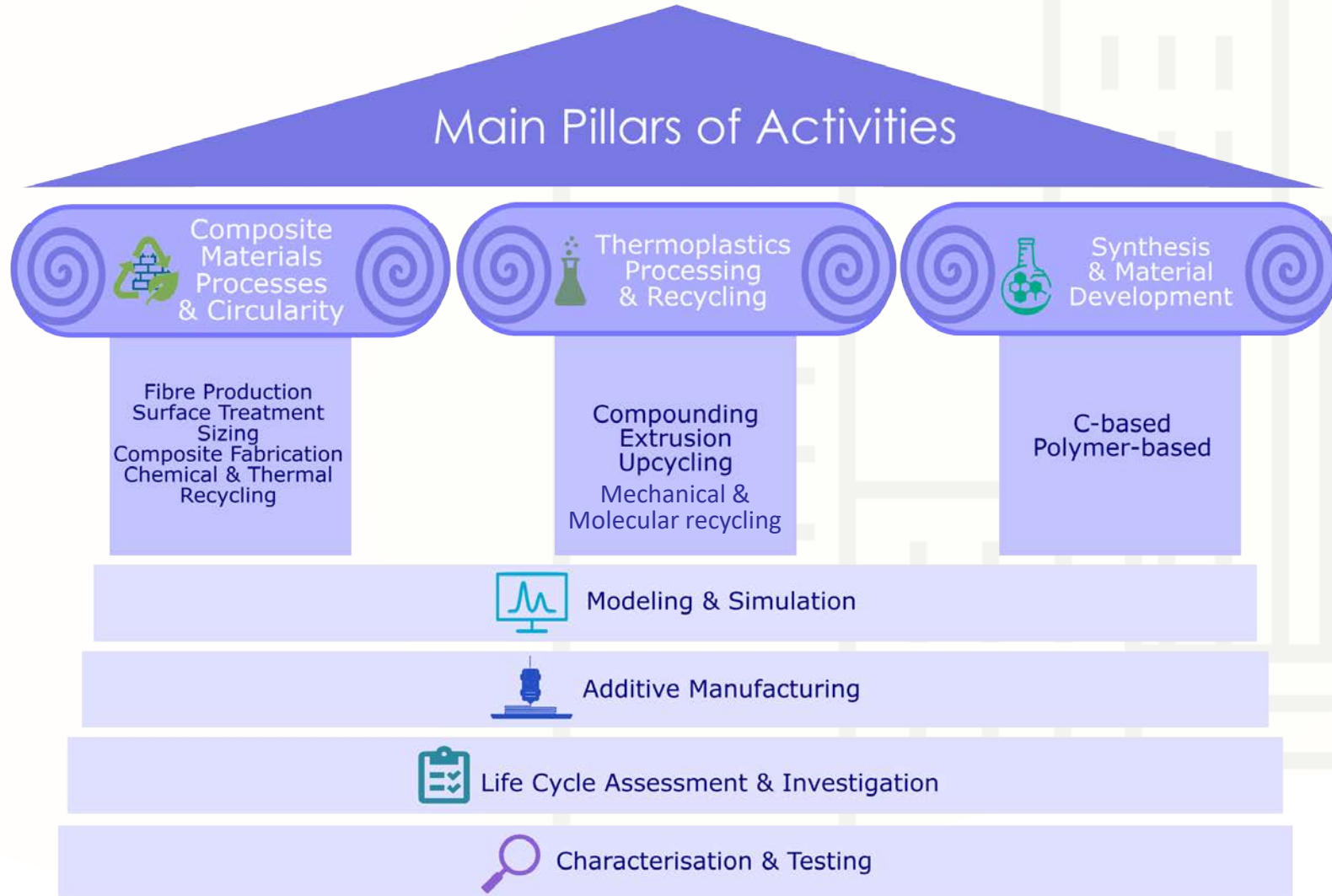
# Who are we?



The "Research Lab of Advanced, Composite, Nano Materials & Nanotechnology", R-NanoLab is established since 2006 and has extensive experience in Designing, Production and Characterization of Advanced-, Composite- and Nano- Materials.



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the European Union**

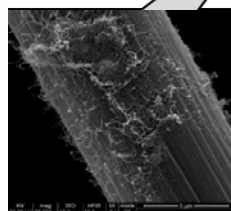




# Composites Group



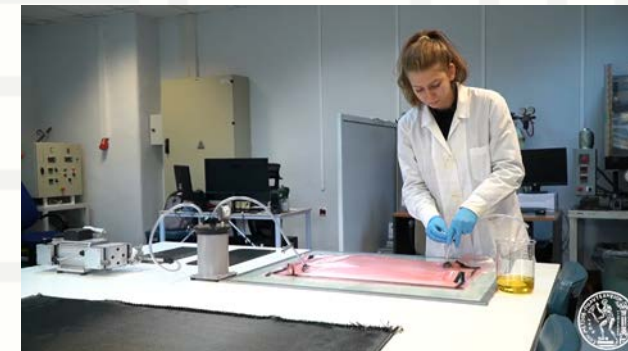
Continuous Carbonization  
plot line for CFs production



Continuous line for  
Surface Treatment



Composites  
Manufacturing



Composites Recycling

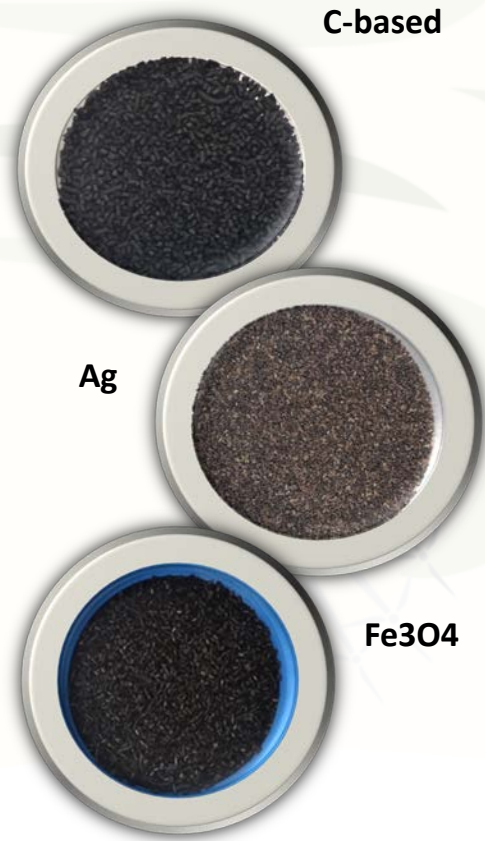


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# Polymers Group



## Processing & Recycling



## 3DP Filament Production



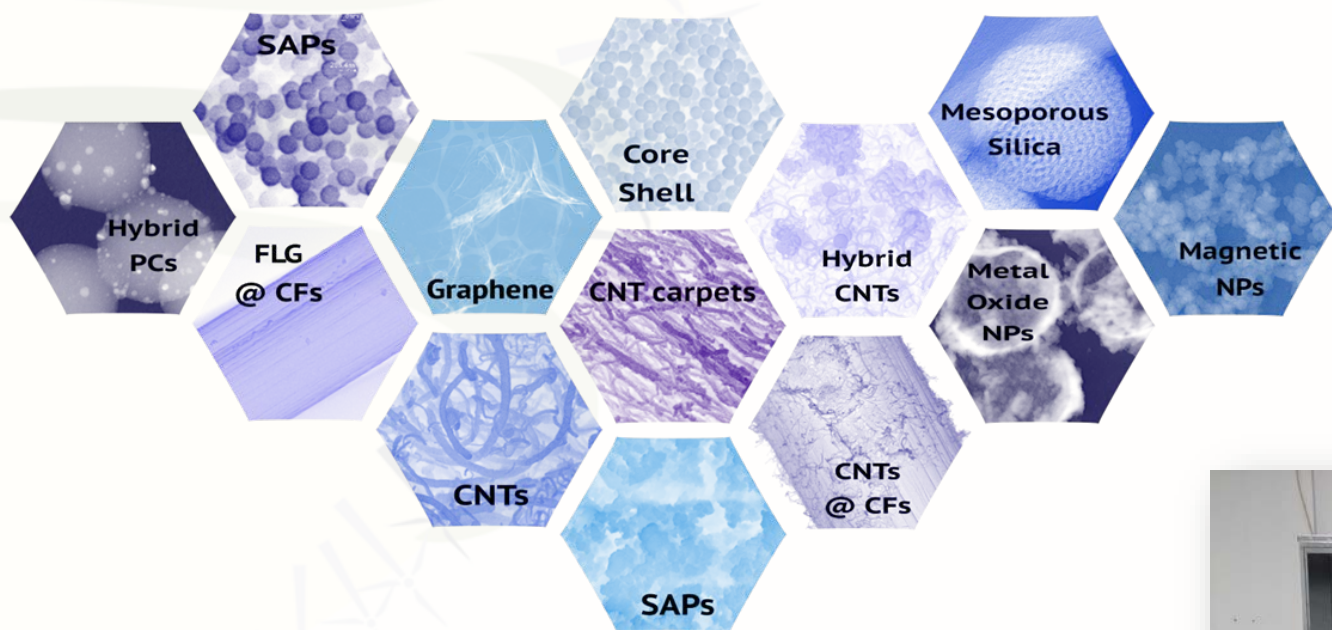
## 3D Printing





# Nanomaterials Group

## Synthesis



Applications:  
Construction  
Composites  
Coatings  
Energy



# Materials Characterizations

## Mechanical Testing



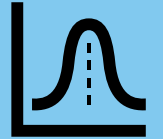
- ❖ Tensile, bend, shear & compression
- ❖ Nanoindentation/Nano scratch Testing/Fast mapping
- ❖ Adhesion testing

## Microscopies



- ❖ Metallography/Optical Microscopy
- ❖ Confocal Microscopy
- ❖ Scanning Electron Microscopy
- ❖ Atomic Force Microscopy/Scanning Probe Microscopy
- ❖ Particle shape & size analysis

## Chromatographies



- ❖ High-Pressure Liquid Chromatography (HPLC)
- ❖ Gel Permeation Chromatography (GPC)

## Structural/Surface Analysis



- ❖ Micro-computed tomography (m-CT)
- ❖ Rheology/Viscometry
- ❖ Wettability testing (surfaces, fibres)

## Electrochemical Analysis



- ❖ Cyclic Voltammetry
- ❖ Corrosion resistance
- ❖ Electrochemical Impedance Spectroscopy

## Conductivity Measurements



- ❖ Thermal conductivity
- ❖ Electrical conductivity/Surface resistance





# Target of the Summer School

The 2nd BLADES2BUILD Summer School focuses on end-of-life management and recycling of carbon fibre reinforced polymer (CFRP) blades, addressing key challenges related to circularity and sustainability in advanced composite materials, including:

- ◆ Carbon fibre production & surface treatments
- ◆ Prepreg and CFRP manufacturing
- ◆ Structure & properties of CFRPs
- ◆ Nanomaterials and advanced processing
- ◆ End-of-life management and recycling technologies
- ◆ Student presentations and networking opportunities



# Event Program

## Day 1

| Activity and timeslot | Content                                                                                         |
|-----------------------|-------------------------------------------------------------------------------------------------|
| 9:00-9:30             | Welcome and registration                                                                        |
| 9:30-9:45             | Introduction to the summer school / NTUA activities, facilities, etc.                           |
| 9:45-10:00            | BLADES2BUILD INTRODUCTION                                                                       |
| 10:00 - 10:45         | <i>Invited Lecture 1:</i><br>Rethinking Polymer Composites: Recycling and the Road Ahead        |
| 10:45 - 11:30         | <i>Invited Lecture 2:</i><br>Replacement and Reinforcement Concepts for Circular Design         |
| 11:30 - 12:00         | Coffee break                                                                                    |
| 12:00 - 12:45         | Composites Recycling through Solvolysis & Pyrolysis                                             |
| 12:45 - 13:15         | Presentations from the students (know each other)                                               |
| 13:15-14:00           | Interactive session for the recycling of wind turbine blades                                    |
| 14:00-15:00           | Lunch break                                                                                     |
| 15:00-16:00           | <i>Lab Activities:</i> Solvolysis of CFRPs, Thermal Recycling of CFRPs, Nanomaterials Synthesis |

## Day 2

| Activity and timeslot | Content                                                                                                            |
|-----------------------|--------------------------------------------------------------------------------------------------------------------|
| 9:15-9:30             | Welcome                                                                                                            |
| 9:30-10:15            | <i>Lecture 1:</i><br>Carbon Fibre Production & Surface Treatments                                                  |
| 10:15-11:00           | <i>Lecture 2:</i><br>Composites chemical recycling                                                                 |
| 11:00 - 11:30         | Coffee break                                                                                                       |
| 11:30-13:00           | <i>Lab activities 1:</i> Carbon Fibre Production & CF Surfactant Treatment & CFRP manufacturing/ Water Jet Cutting |
| 13:00-14:00           | Lunch break                                                                                                        |
| 14:00-15:30           | <i>Lab activities 2:</i> Prepreg production, Compounding-Extrusion of 3DP filaments, Mechanical Testing            |
| 15:30-16:00           | Interpreting lab results in the context of real applications<br>Closing of Training School                         |



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# Summer School Lecturers – R-NanoLab Team



Maria Modestou



Kate Trompeta



Dionisis Semitekolos



# Summer School Lecturers – Invited



Nataliya Lushnikova, TUE



Shashank Tumkur Karnick, TUE



Spyros Soulis, NTUA

# Thank you!



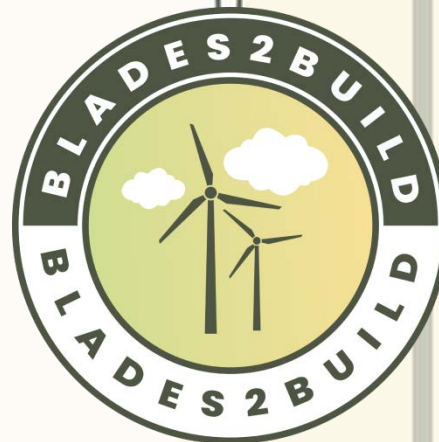
modestou@chemeng.ntua.gr



r-nano.gr



R Nano NTUA



[www.blades2build.com](http://www.blades2build.com)

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# Rethinking Polymer Composites: recycling and the road ahead

**2<sup>nd</sup> Blades2Build summer school 2026, NTUA, Greece**

Email: [s.tumkur.karnick@tue.nl](mailto:s.tumkur.karnick@tue.nl)

Department of Built Environment, Eindhoven University of Technology, Netherlands



Funded by European Union

**TU/e**



# Overview and objectives

- Polymer composites and their growing market
- Polymer composite waste in wind industry
- Mechanical recycling approach for wind blade waste
- Environmental and economic benefits
- Future directions for composites recycling

# About me



**Shashank Tumkur Karnick**

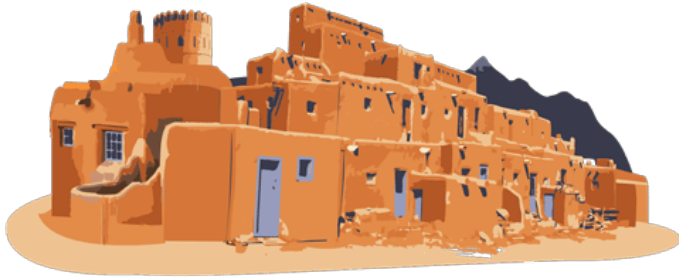
- **Doctoral researcher** at TU Eindhoven, The Netherlands
- Master's in Chemical and Energy Engineering, Otto von Guericke University, Germany
- Bachelor's in Mechanical Engineering, India

## Research expertise:

- Polymer composites
- Recycling of fibrous materials
- Material characterization
- Life cycle assessment
- Material informatics

# Polymer composites

## History of polymer composites



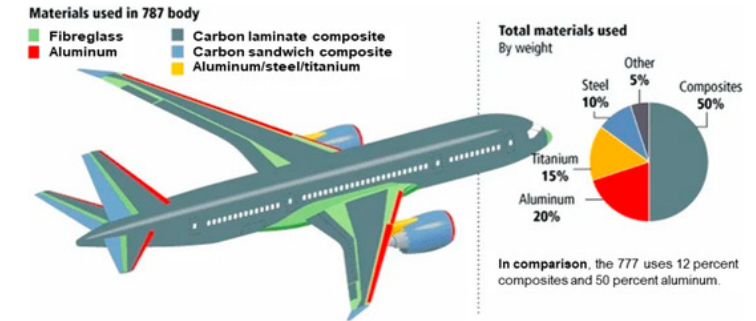
Plywood in 3400 B.C and bows in 12<sup>th</sup> century A.D

- Cartonnage from linen and plasters (2181 – 2055 BC)
- Mud bricks from clay reinforced straws (1500 BC)
- Mud walls reinforced with bamboo shoots (500 BC)



A rise in synthetic resins and invention of glass fibers (1900s)

- Bakelite gearshift knob (1917, Rolls Royce automobiles)
- Dinghy made from fiber glass and polyester resin (1942)
- Fiberglass pipe (1948)
- Advancements in composite manufacturing methods



Invention of carbon, aramid fibers and widespread use of FRPs (1960s - present)

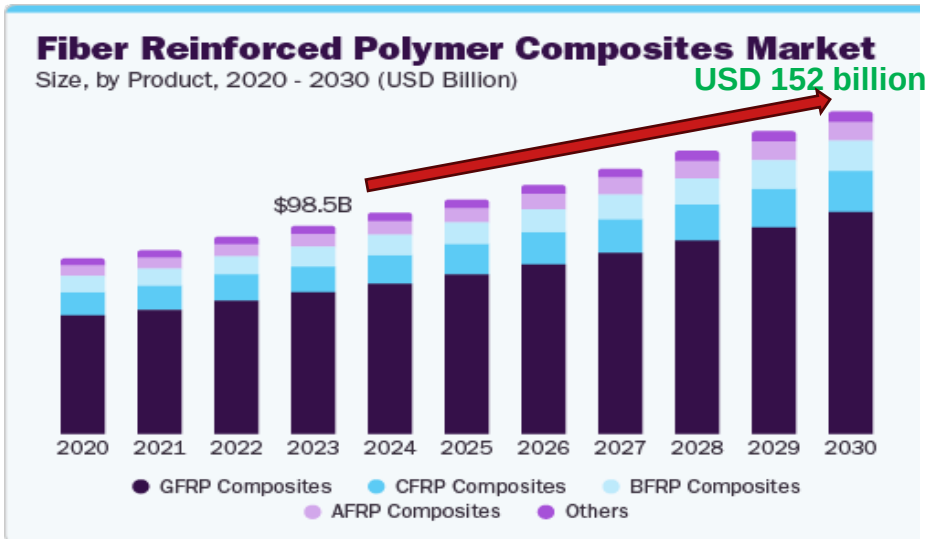
- Marine industry (since 1960s)
- Automobile (since 1970s)
- Development of 787 Boeing Dreamliner



# Polymer composites

## Market size and waste volumes

Applications of FRPs



## Market size

- Doubling of composite market between 2025 and 2035
- 67.7% - GFRP market
- USD 29.7 billion - CFRP market

## Expected waste generation by 2030

- CFRP waste: 34,000 tons/year
- GFRP waste: 112,000 tons/year

## The challenge: End-of-life management

- ⚠ Non-biodegradable waste
- ⚡ High manufacturing energy
- 📈 Industry growth surge
- 🔒 Thermoset limitation

# Wind industry



 Emissions - 55% by 2030

 Net zero by 2050

 100% renewable energy

0.4 %  
  
Geothermal

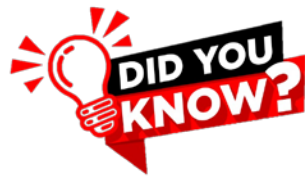
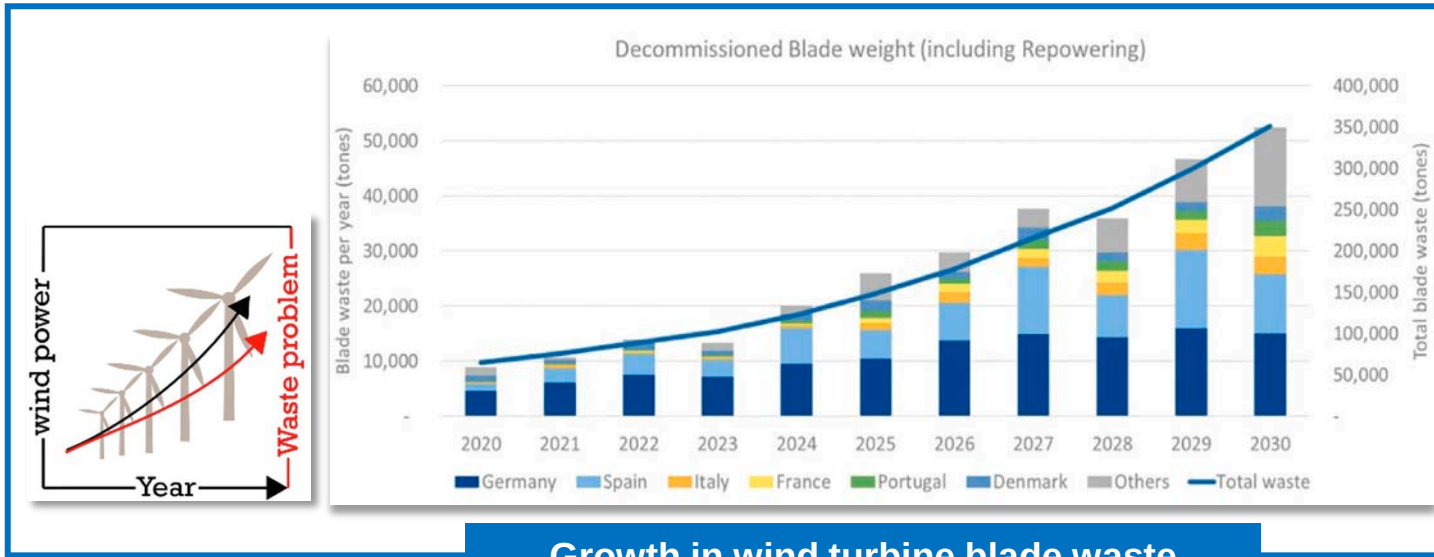
1.2 %  
  
Biomass

3.4 %  
  
Solar

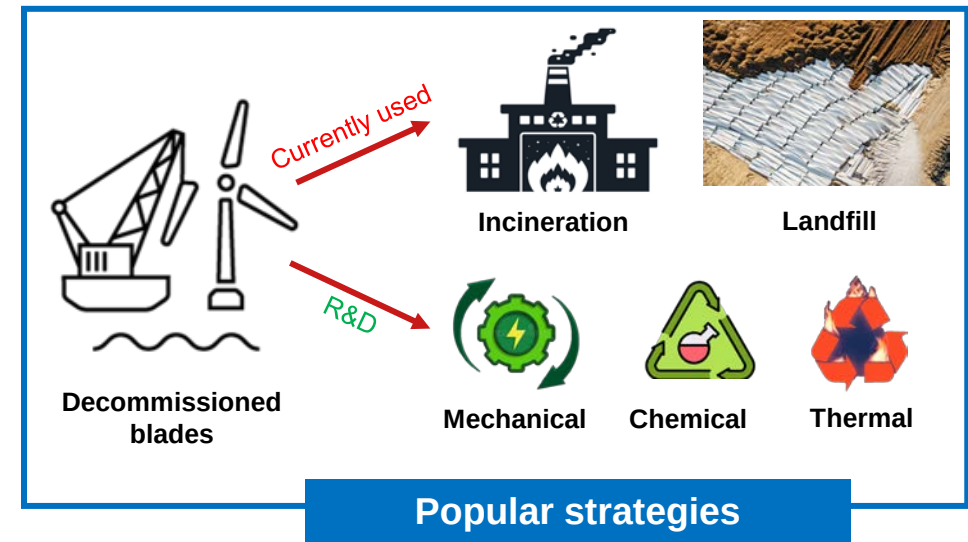
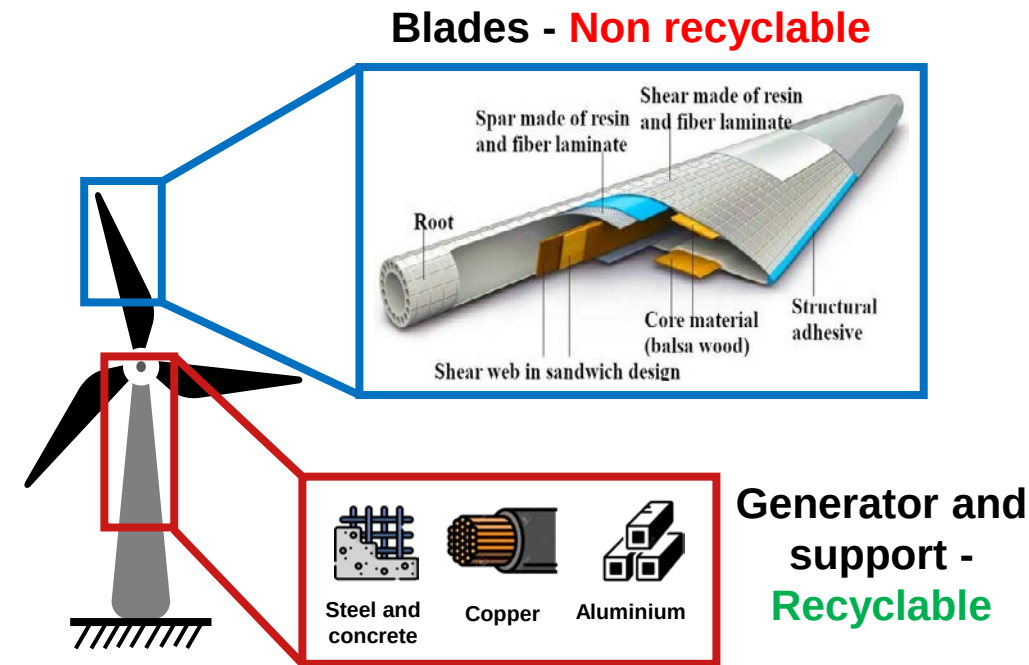
6 %  
  
Hydropower



# Problem

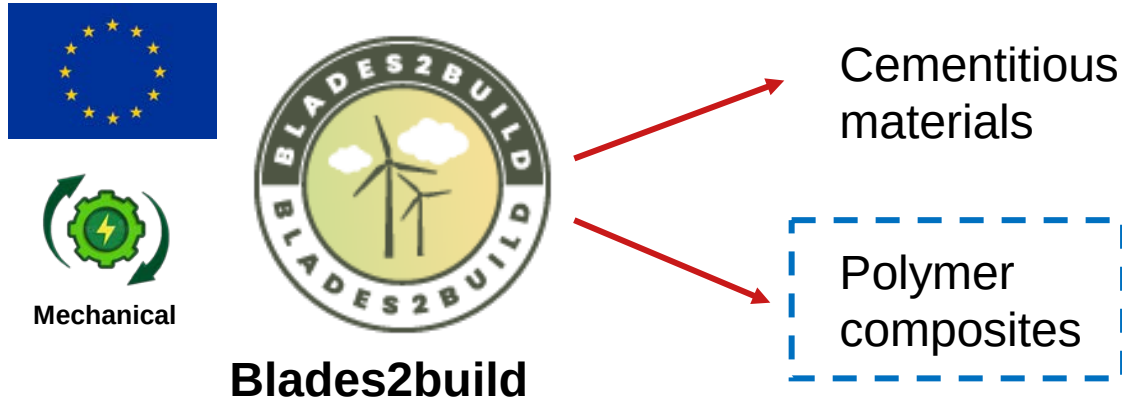


Between 2021 and 2025, approximately 8,000 blades are removed annually in the USA. 3800 blades are removed per year in Europe





# Current scenario



## How to make it circular?

**Answer: Reprocessing of secondary composites**

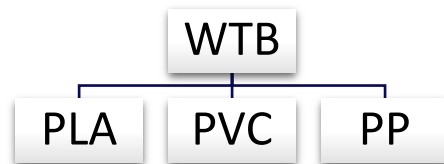
**AIM:** Develop circular construction materials with materials produced from recycling & repurposing routes

### Recent studies



❖ Reprocessing of virgin GFRPs

❖ Recycling of wind turbine blade waste into polymer composites

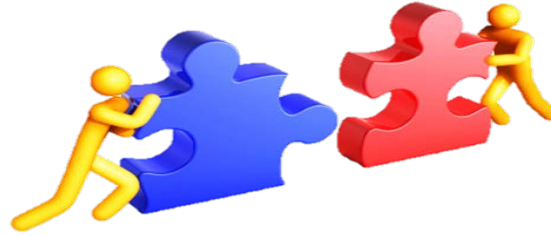


### Why reprocessing?

- ❖ Embodied energy of manufacturing for **virgin glass fiber** (13–32 MJ/kg)
- ❖ The energy consumption of mechanical recycling is **0.1–4.8 MJ/kg**

# Challenges and objectives

## Challenges

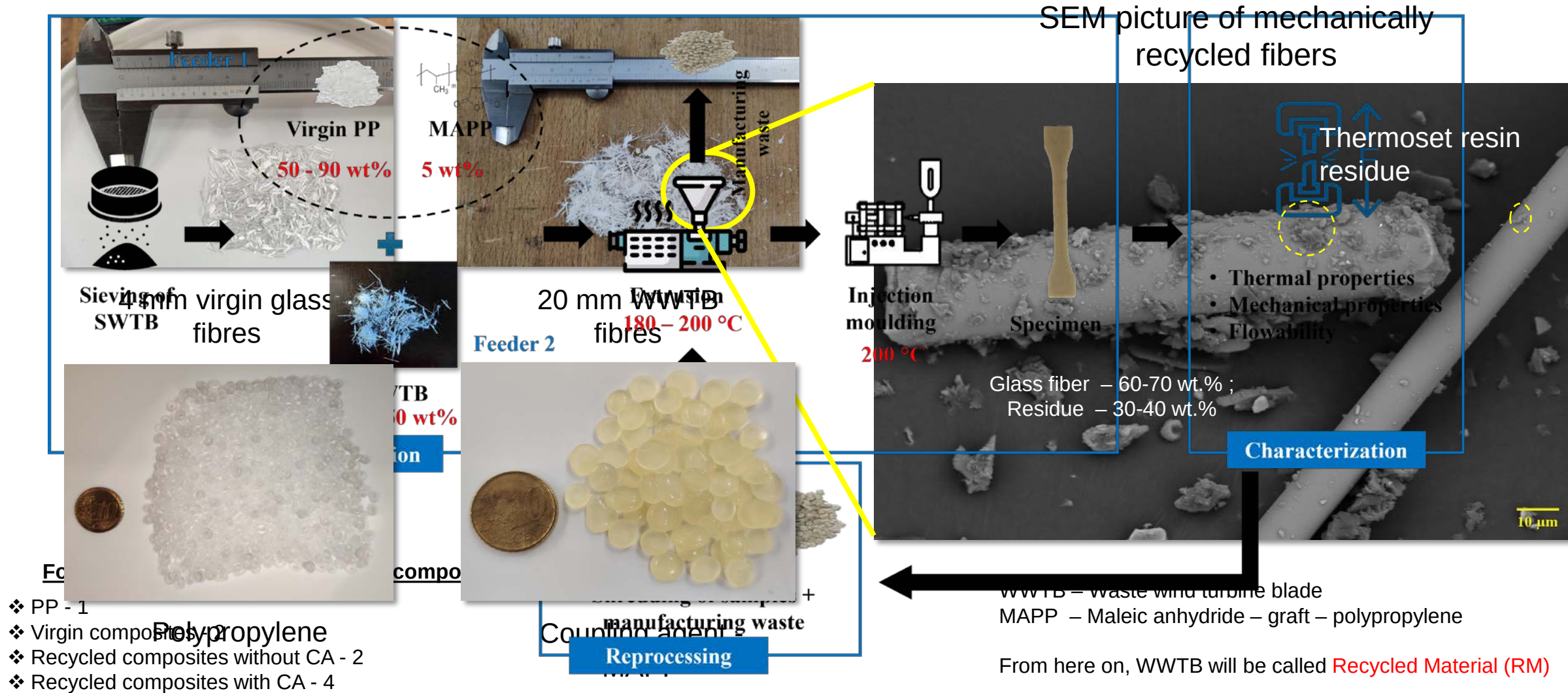


## Research objectives

- ❖ **Recycled material:** Glass fiber with thermoset residue on it and fiber agglomeration
- ❖ **Interfacial strength:** Issues with adhesion between matrix and recycled fiber
- ❖ **Performance comparison:** Virgin VS recycled composites
- ❖ **Multiple cycles:** Ability of performing better even after multiple reprocessing cycles

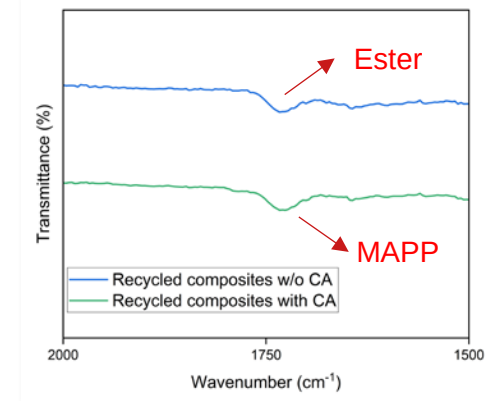
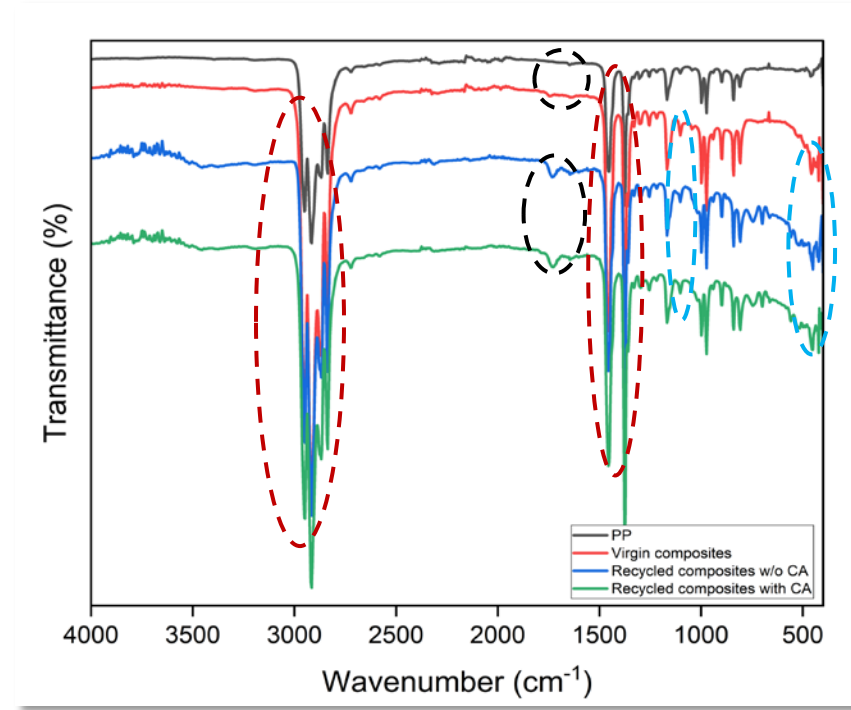
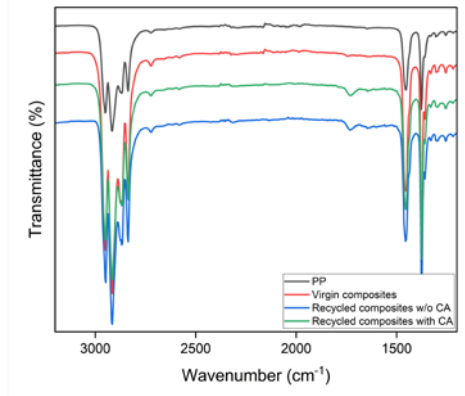
- ❖ **Aim:** To produce recycled composites suitable for multiple reprocessing cycles
- ❖ **Approach:** By assessing the impact on structural, mechanical, thermal, and rheological properties of reprocessed composites
- ❖ **Expected outcomes:** higher mechanical and thermal properties, and reprocessing effects, structural changes, reduction in molecular weight

# Materials | Methodology





# Structural properties

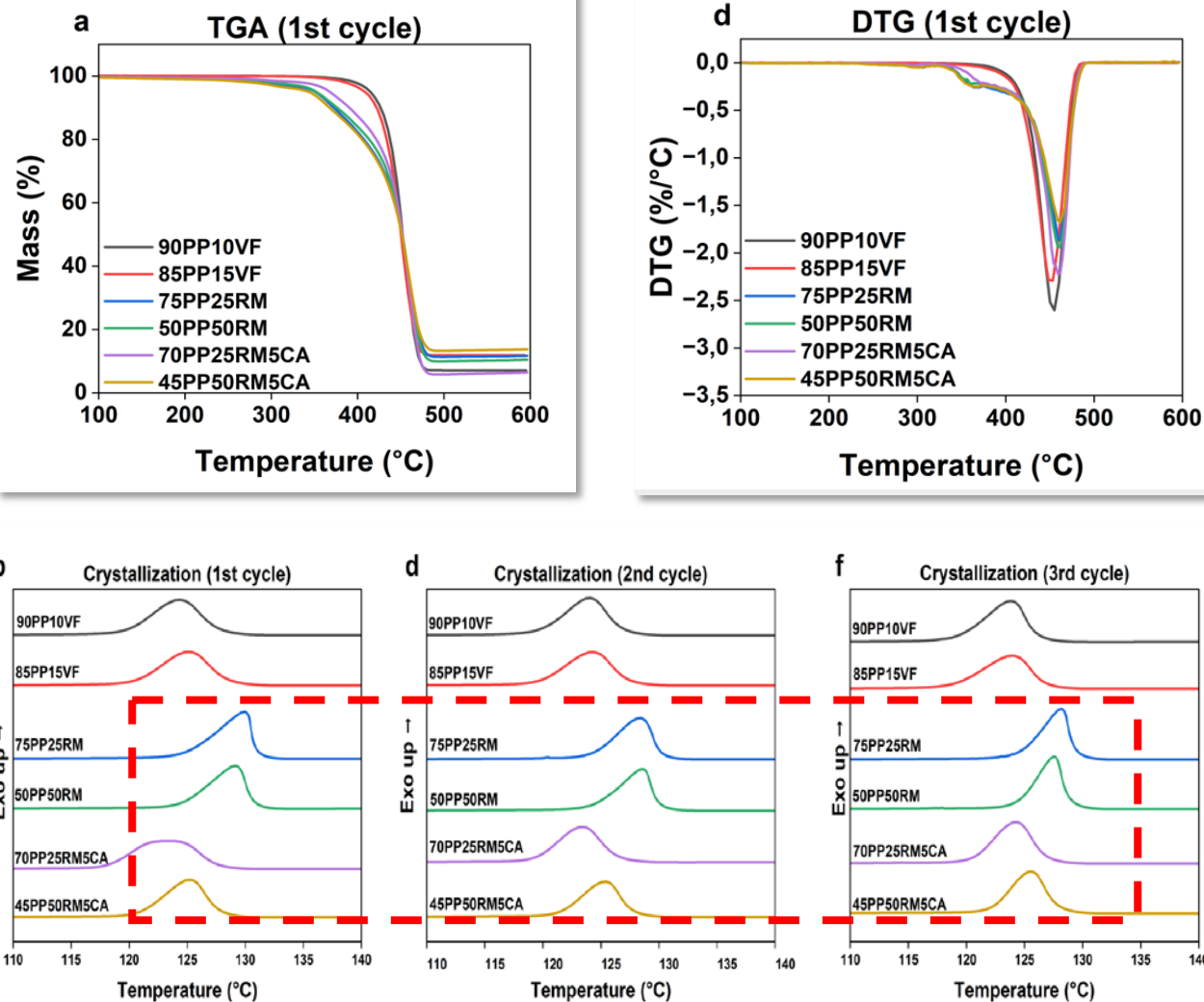


FTIR spectra of all the composites at different reprocessing cycles

## Key results

- ❖ **Polypropylene**,  $\text{CH}_3$  (asymmetrical bending) at  $1457 \text{ cm}^{-1}$ , and  $\text{CH}_3$  bond (asymmetrical stretching) at  $2950 \text{ cm}^{-1}$
- ❖ **MAPP compatibiliser/ester**,  $\text{C}=\text{O}$  bond was observed at  $1720 \text{ cm}^{-1}$
- ❖ **Glass fibers**,  $\text{Si}-\text{O}$  bonds at  $1100 \text{ cm}^{-1}$  and  $\text{Si}-\text{O}-\text{Si}$  bond at  $455 \text{ cm}^{-1}$
- ❖ No significant structural change
- ❖ Not thermo-oxidative degradation but thermo-mechanical

# Thermal properties



## Key results

- ❖ 5-12°C higher degradation temperature in recycled composites
- ❖ Stable  $T_m$  and significant improvement in  $T_c$
- ❖ Lower  $T_c$  of pure PP and virgin composites
- ❖ Significant improvement in CI due to nucleation-inducing effect of recycled material

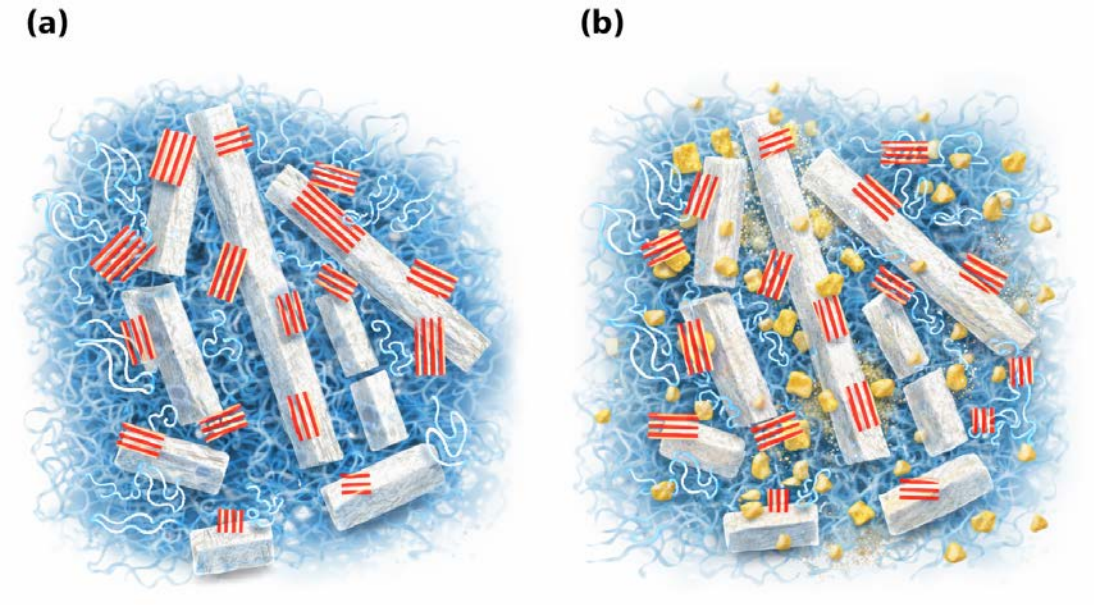
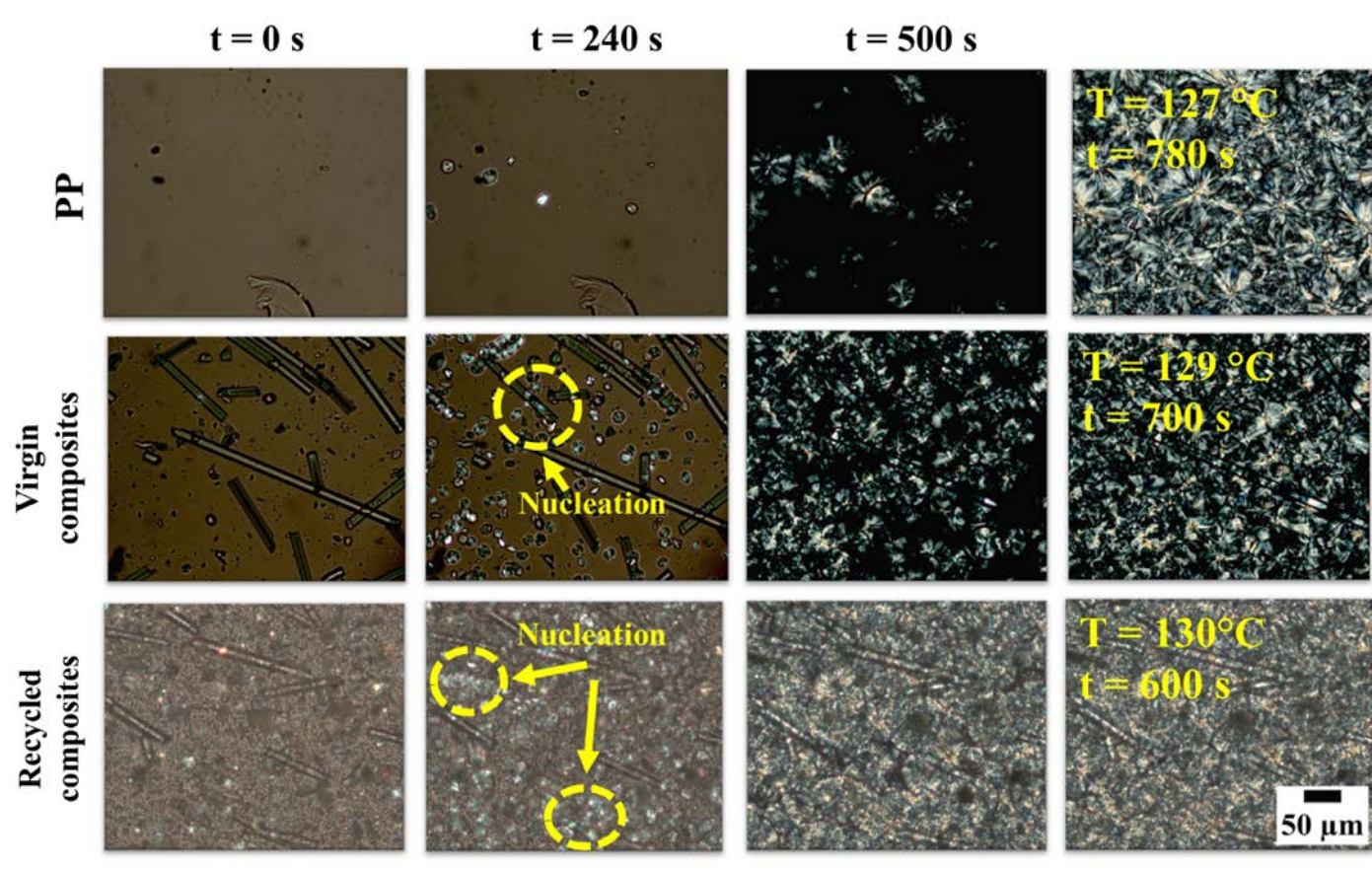
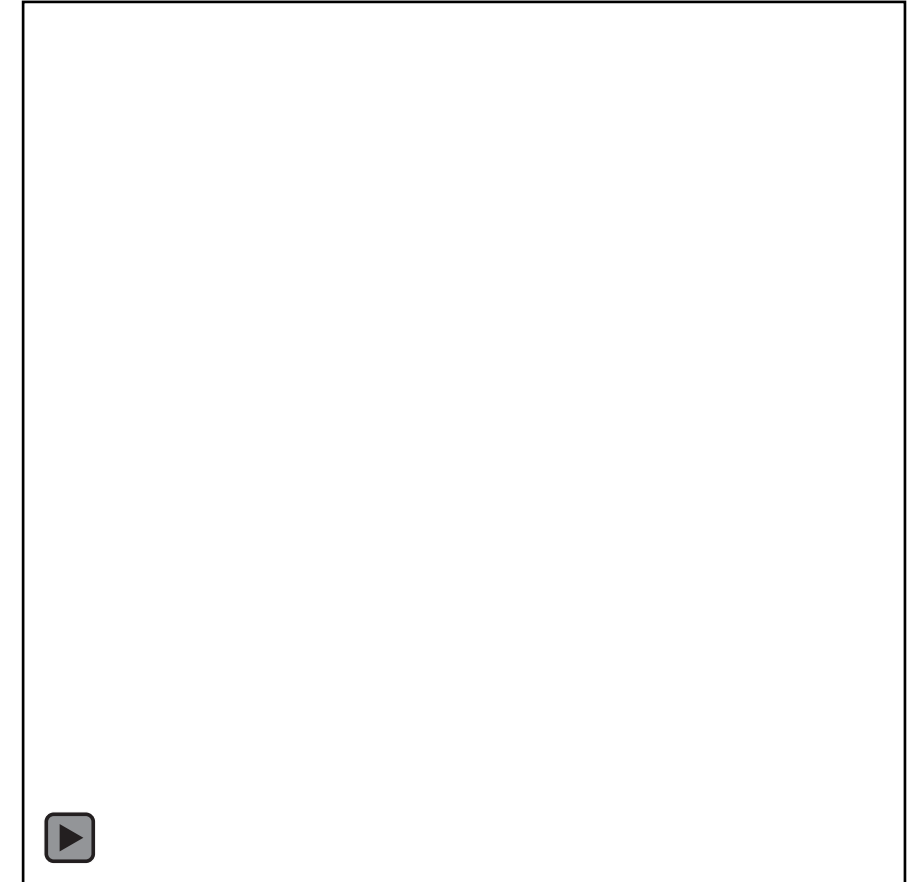


Illustration of nucleation effect

# Nucleation



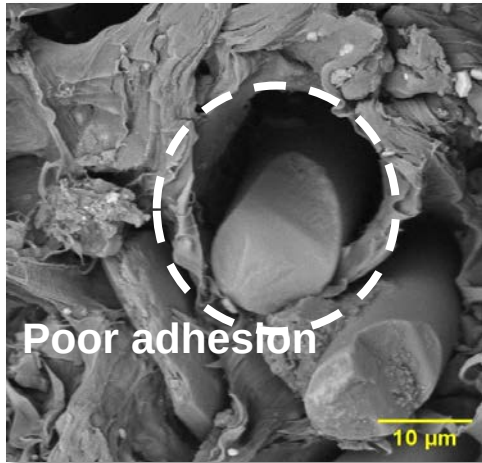
Rate of crystallization affected by nucleating agents



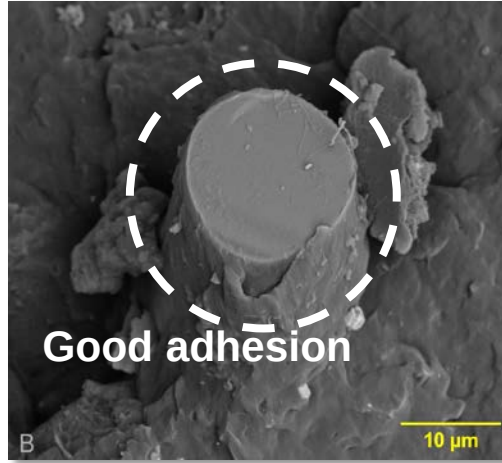
Heterogeneous nucleation in recycled composites



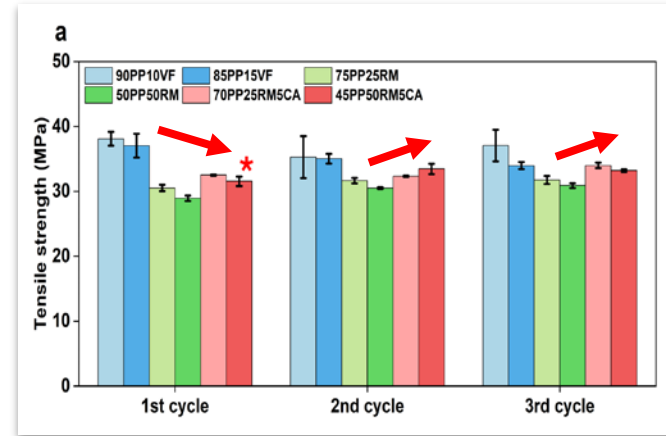
# Mechanical properties



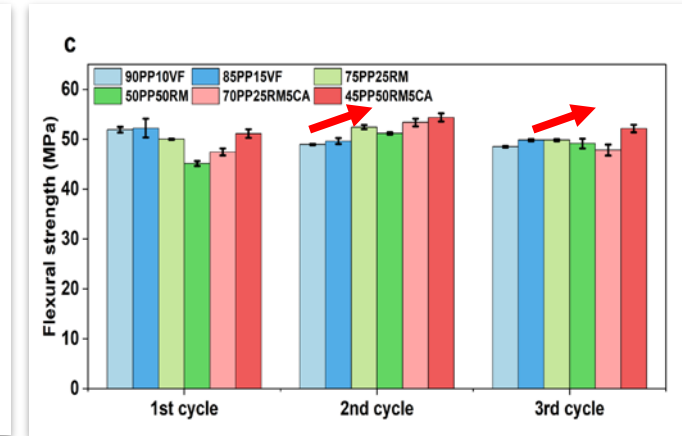
Without CA



With CA



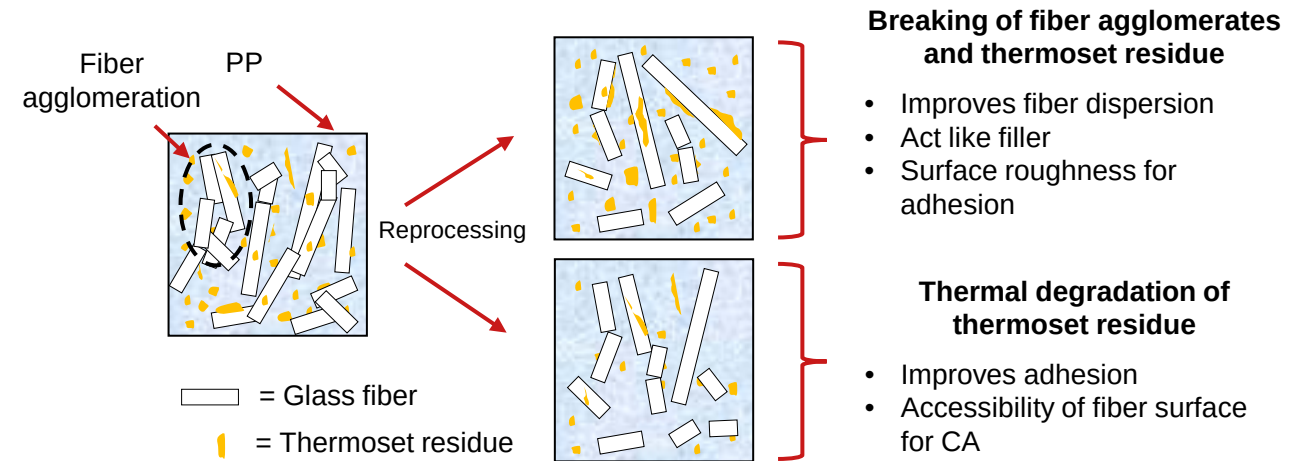
Tensile strength



Flexural strength

## Key results

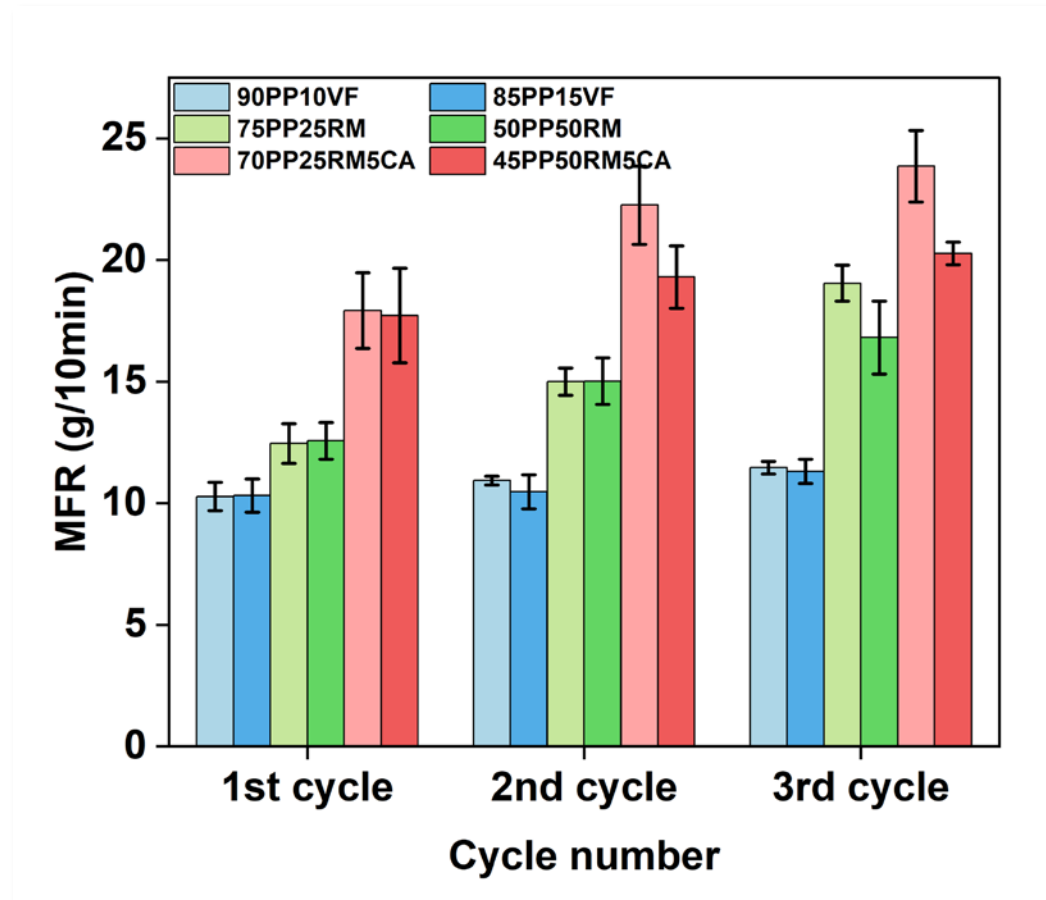
- ❖ Positive influence of coupling agent (CA)
- ❖ Low tensile and flexural strengths for 1<sup>st</sup> cycle recycled composites
- ❖ Strength reduction in virgin composites after 2<sup>nd</sup> and 3<sup>rd</sup> cycles
- ❖ Increasing trend in the recycled composites after 2<sup>nd</sup> and 3<sup>rd</sup> cycle
- ❖ Retention of 98% tensile strength after 3 cycles
- ❖ Lower screw speed and lower melt temperature



Reasons for better mechanical performance of recycled composites



# Rheological properties



MFR of different secondary composites

## Key results

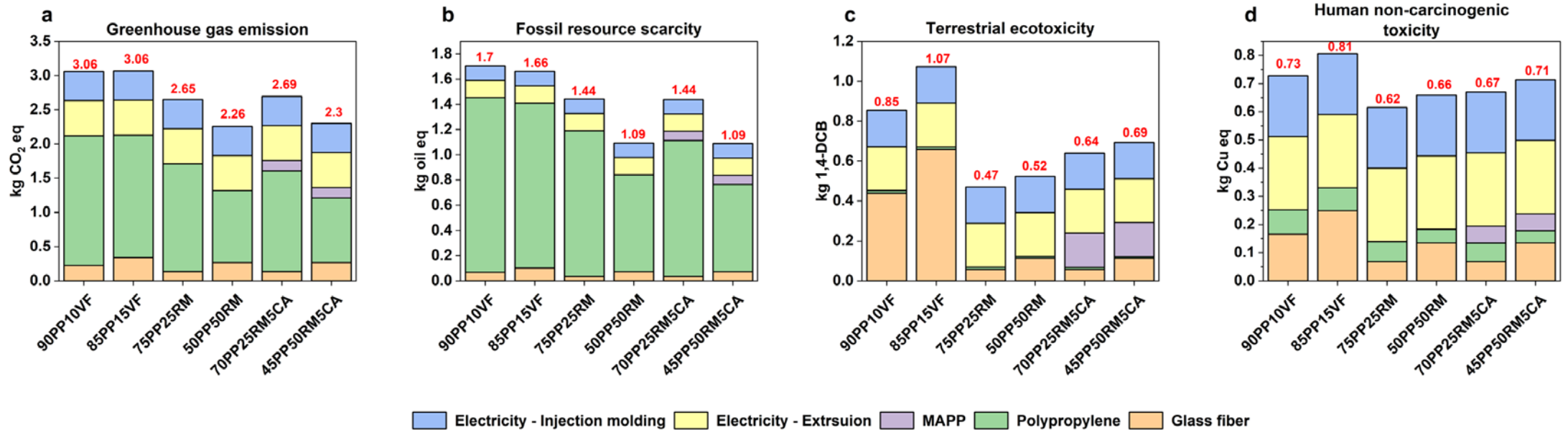
- ❖ MFR increases progressively for recycled composites
- ❖ Lower MFR for virgin composites and PP
- ❖ Increasing trend with higher dosage of CA

## Reasons for higher MFR

- ❖ A decrease in the molecular weight of PP
- ❖  $\beta$ -scission reactions
- ❖ Plasticizing effect

**Favourable for injection moulding**

# LCA



## Key results

- ❖ High CO<sub>2</sub> emissions in virgin composites
- ❖ **12-25% reduced CO<sub>2</sub> emissions** in recycled composites
- ❖ **35-41% reduction** in **fossil resource scarcity**
- ❖ **25-51% higher ecotoxicity** in virgin composites
- ❖ Further reduction in emissions due to reprocessing

# Environmental and economic benefits



## Environmental benefits

- ✓ Preferred over landfill and incineration
- ✓ Reduces non-biodegradable waste
- ✓ Prevents environmental contamination
- ✓ Reduces virgin material extraction

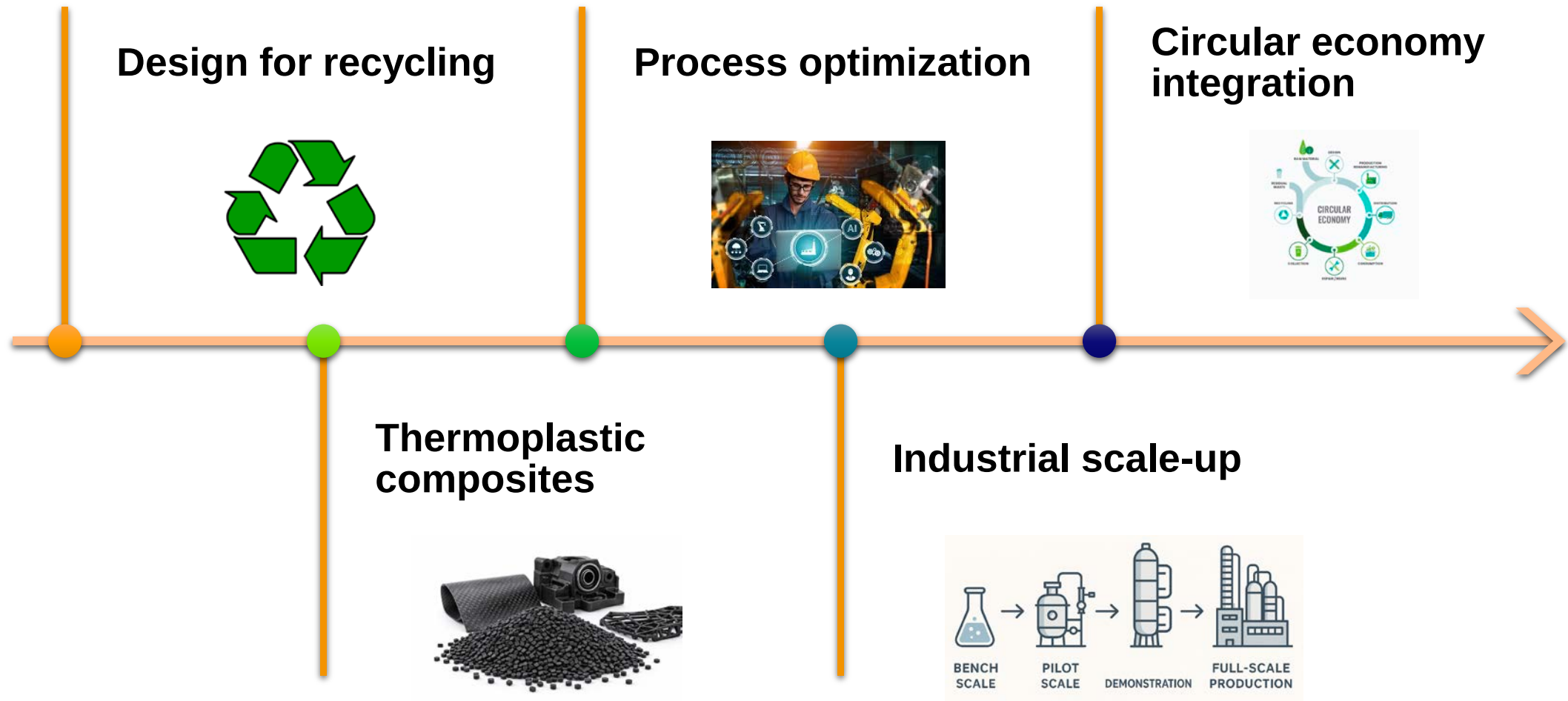


## Economical benefits

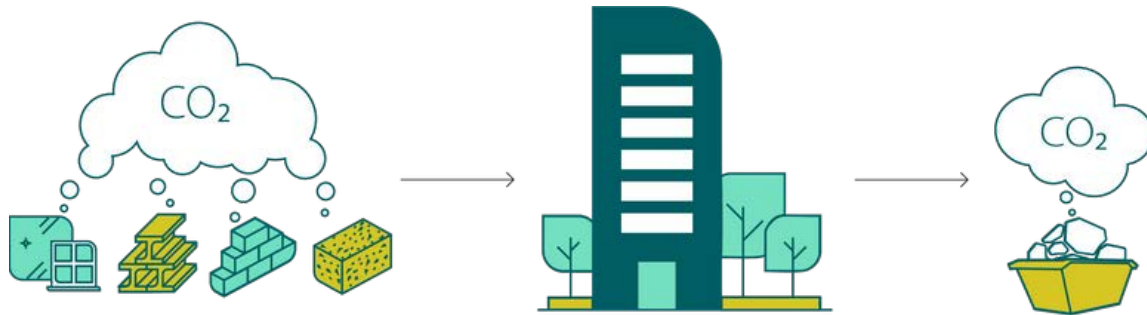
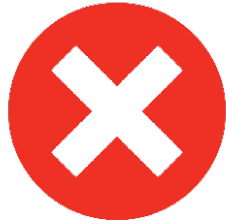
- ✓ 70% cost reduction with rCF
- ✓ 98% reduction in energy costs
- ✓ Growing market for recycled composites: \$234 M to \$701 M (by 2033)
- ✓ Job creation in recycling sector
- ✓ Reduced production costs for OEMs



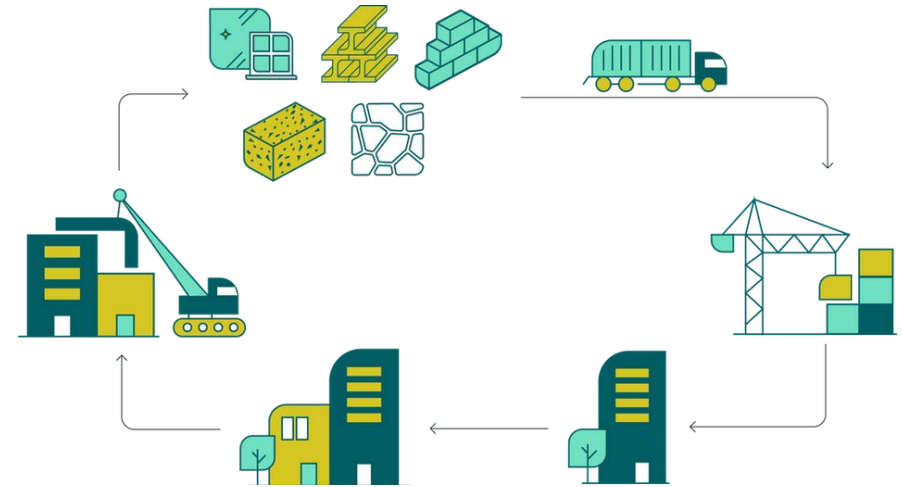
# Future directions & road ahead



# Think circular!



Linear



Circular

# Thanks for your attention

**Shashank Tumkur Karnick**

[s.tumkur.karnick@tue.nl](mailto:s.tumkur.karnick@tue.nl)

Doctoral candidate  
Building materials group  
TU Eindhoven, Netherlands



Find out more  
about  
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here



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2nd BLADES2BUILD Summer School  
End-of-life Management and Recycling of  
Wind Turbine Blades

# BLADES2BUILD

Recycle, repurpose and reuse end-of-life  
wind blade composites – a coupled pre-  
and co-processing demonstration plant



Wind Turbine Blade Waste in Concrete:  
Replacement and Reinforcement Concepts  
for Circular Design

Ceren Duyal Kulak, PhD Candidate  
Nataliya Lushnikova, Postdoctoral researcher



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# Content



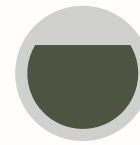
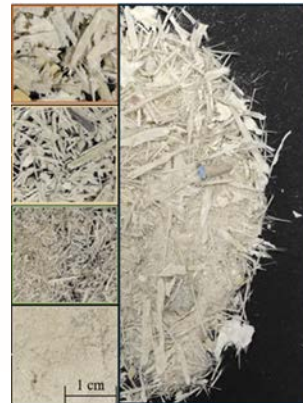
## Properties of wind turbine blades (WTB) waste

Physical characterization  
Chemical characterization  
Morphology



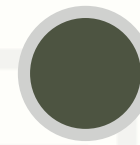
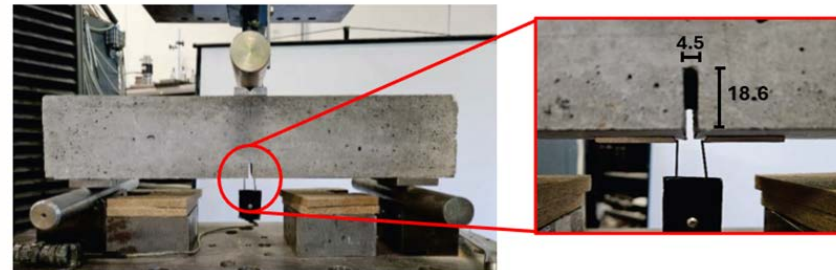
## Function of WTB waste in composite materials

Replacement  
Reinforcement  
Hybrid



## Normal-weight concrete with WTB waste

Optimization of concrete mix design  
Particle packing approach  
Properties of fresh concrete  
Properties of hardened concrete



## Light-weight aggregate with WTB waste

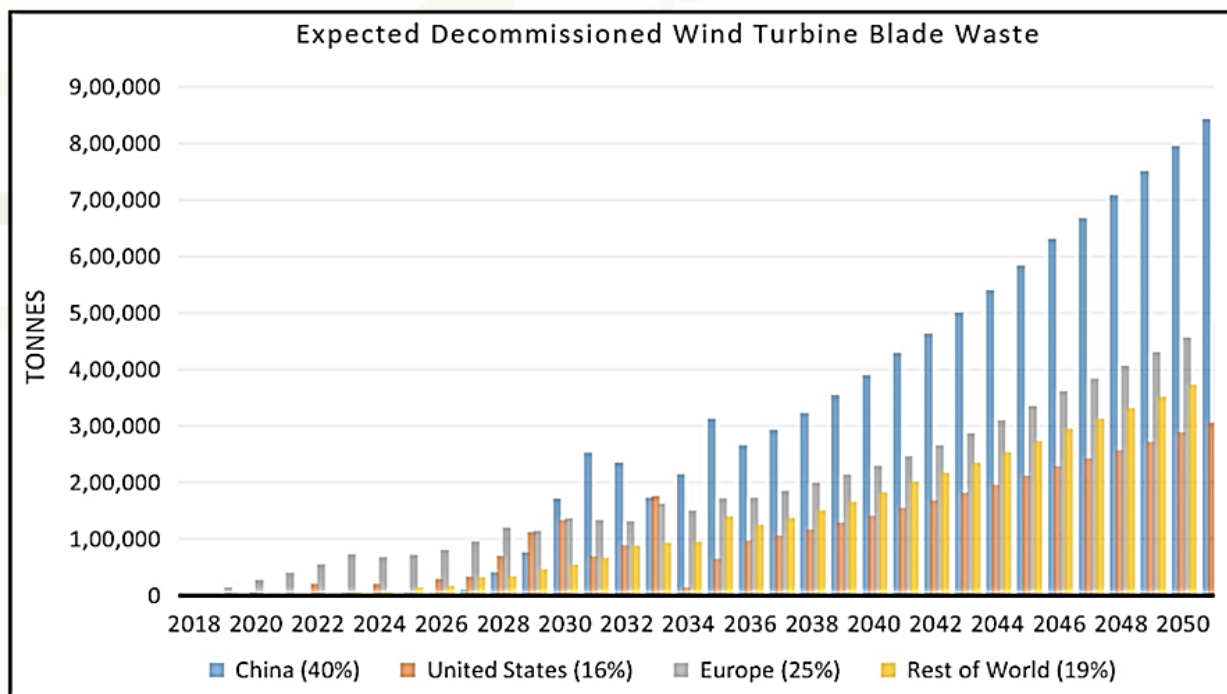
Components  
Manufacturing  
Properties of the aggregate



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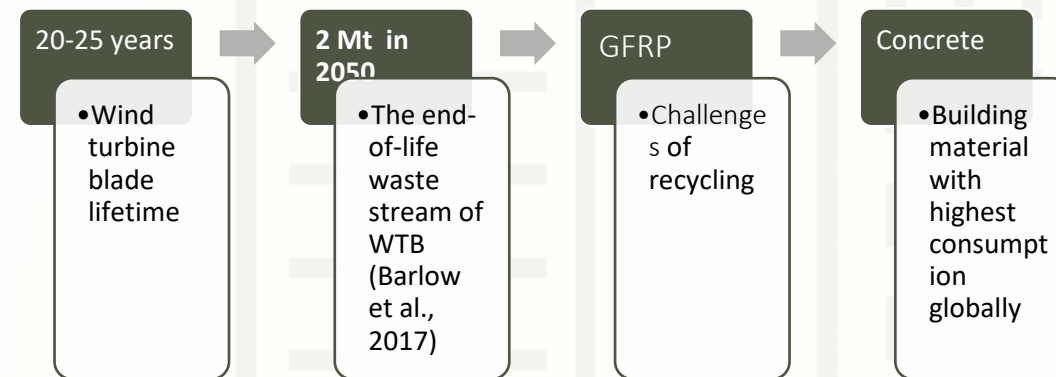
TU/e

# Why WTB waste? Motivation & key concept

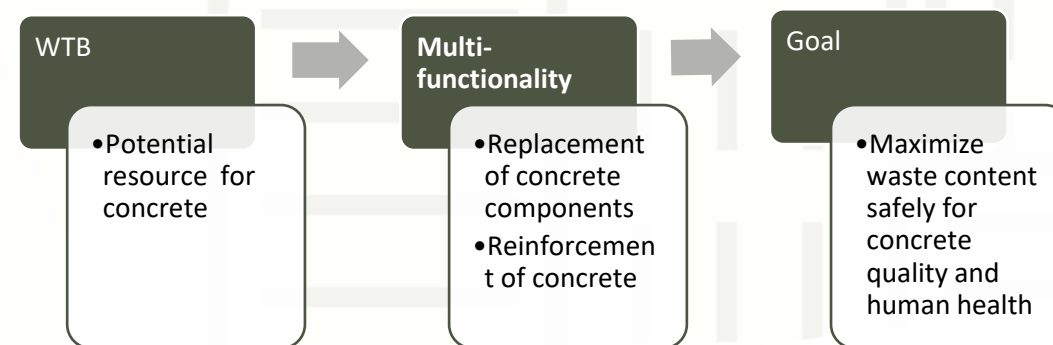


P. Liu, C.Y. Barlow, Wind turbine blade waste in 2050, Waste Management 62, 229–240 (2017)

## Motivation



## Key concept



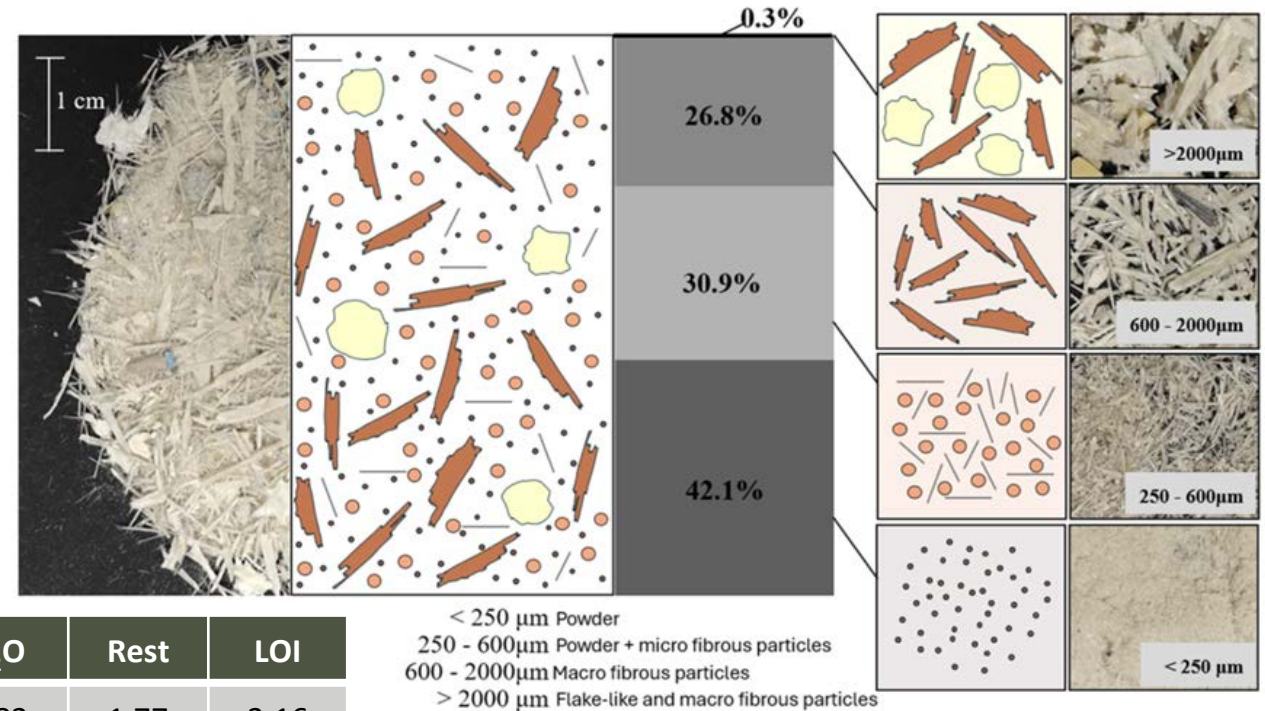
# Properties of shredded wind turbine blades

## o Non-selective mechanical treatment of WTB

Shredding of WTB after cutting



## Particle size distribution and shape shredded WTB



## Chemical composition of WTB comparing to OPC

| Component    | CaO   | SiO <sub>2</sub> | Al <sub>2</sub> O <sub>3</sub> | Fe <sub>2</sub> O <sub>3</sub> | MgO  | SO <sub>3</sub> | K <sub>2</sub> O | Rest | LOI   |
|--------------|-------|------------------|--------------------------------|--------------------------------|------|-----------------|------------------|------|-------|
| CEM I 42,5 N | 67.86 | 14.75            | 3.60                           | 3.13                           | 1.38 | 4.46            | 0.82             | 1.77 | 2.16  |
| SWTB         | 16.85 | 38.33            | 11.12                          | 1.16                           | -    | -               | -                | 0.82 | 31.70 |

Density: 1.79g/cm<sup>3</sup> Water Absorption: 22.97% Composition: Epoxy (32%), Inorganic components (68%)



# Properties of shredded wind turbine blades: microstructure



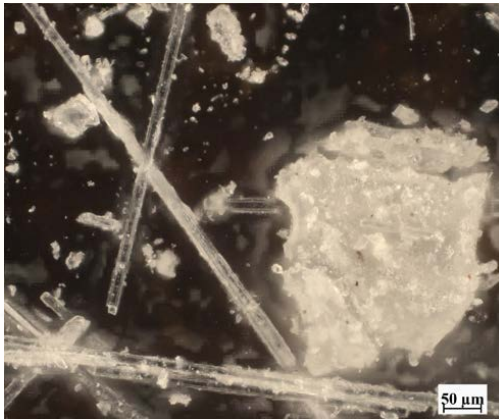
Optical microscopy image of shredded WTB



SWTB powder grain



Fibrous SWTB



Micro-fibers and SWTB powder



Flaws and irregularities on fiber cross-sections



# Function of WTB waste in composite materials: Reinforcement vs. replacement



Visualization of the concrete design approach

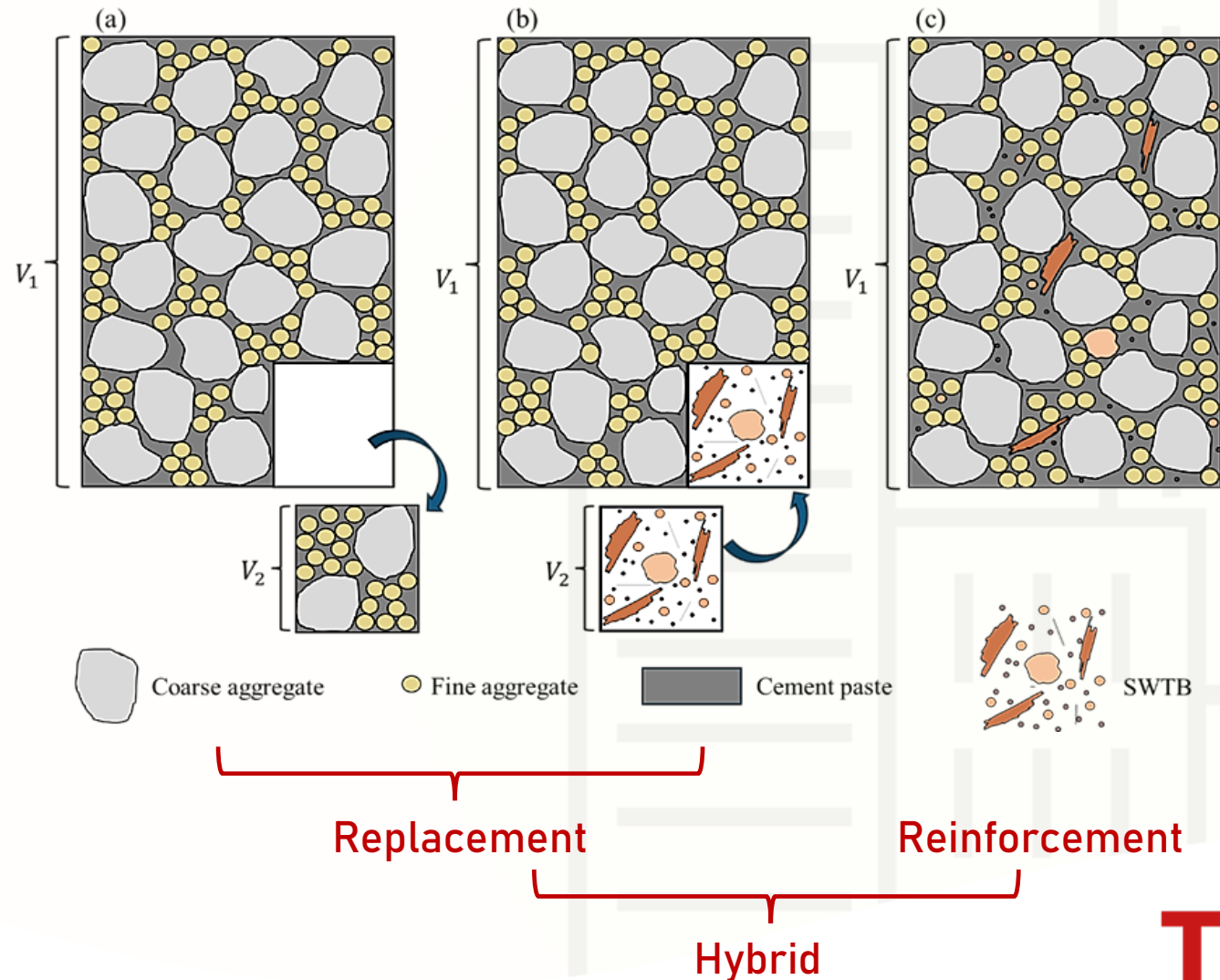
$V_1$  - the total concrete volume,

$V_2$  - the portion selected for replacement

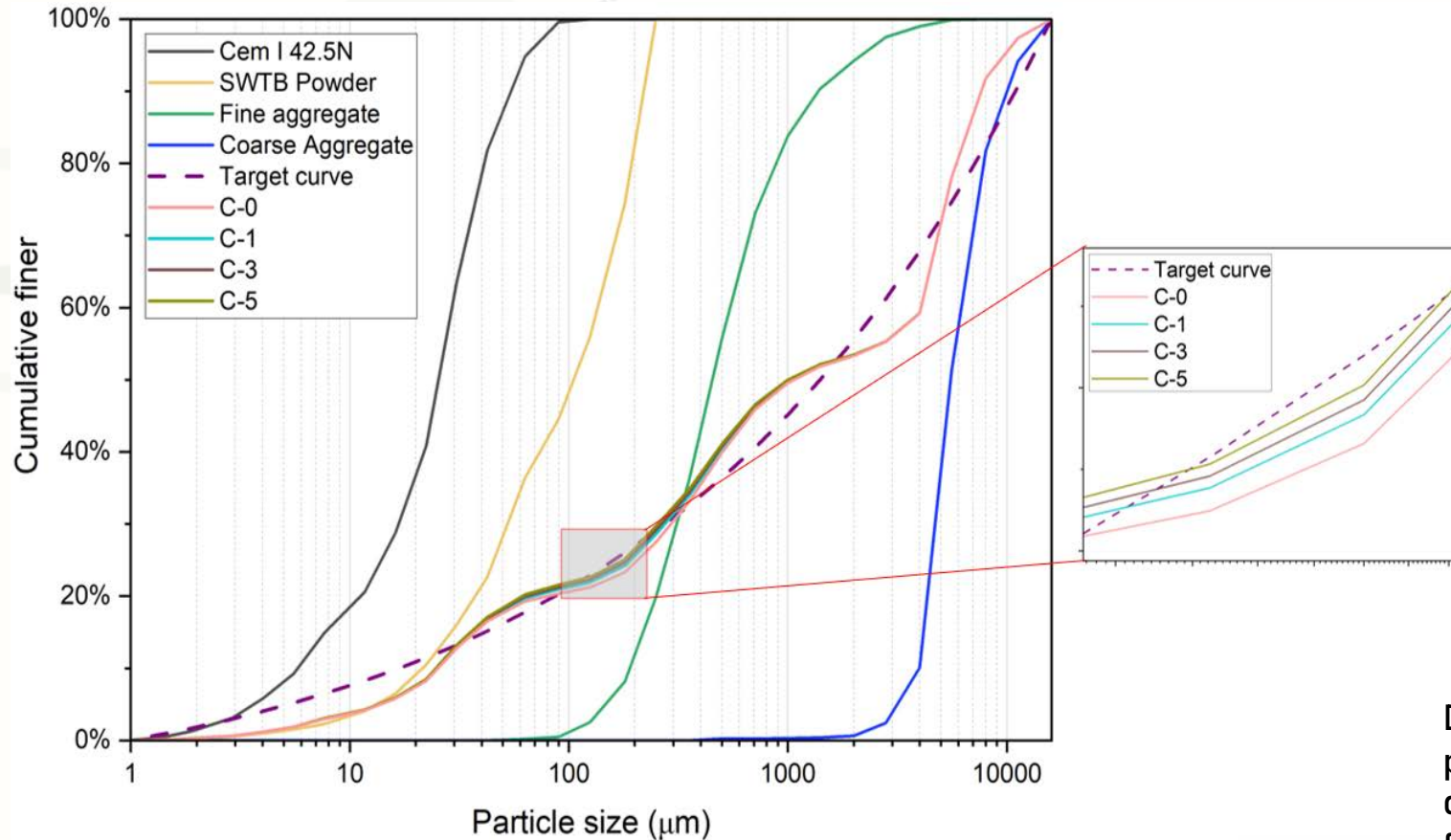
(a) Reference concrete with the predefined replacement volume ( $V_2$ ) indicated,

(b) Shredded WTB fractions occupying the replacement volume,

(c) Concrete incorporating shredded WTB



# Normal-weight concrete with WTB waste: particle packing approach



The concrete was designed to match the target curve of the Modified Andreasen and Andersen (MAA) model

$$P_{target}(D_i^{i+1}) = \frac{(D_i^{i+1})^q - D_{min}^q}{D_{max}^q - D_{min}^q}$$

$D_{min}$  and  $D_{max}$  – the minimum and maximum particle size  
 $q$  is the particle size distribution modulus;  $q=0.25$  for workability class S3

Target curve, granular components, and resulting mix curves for the initial stage of the concrete design



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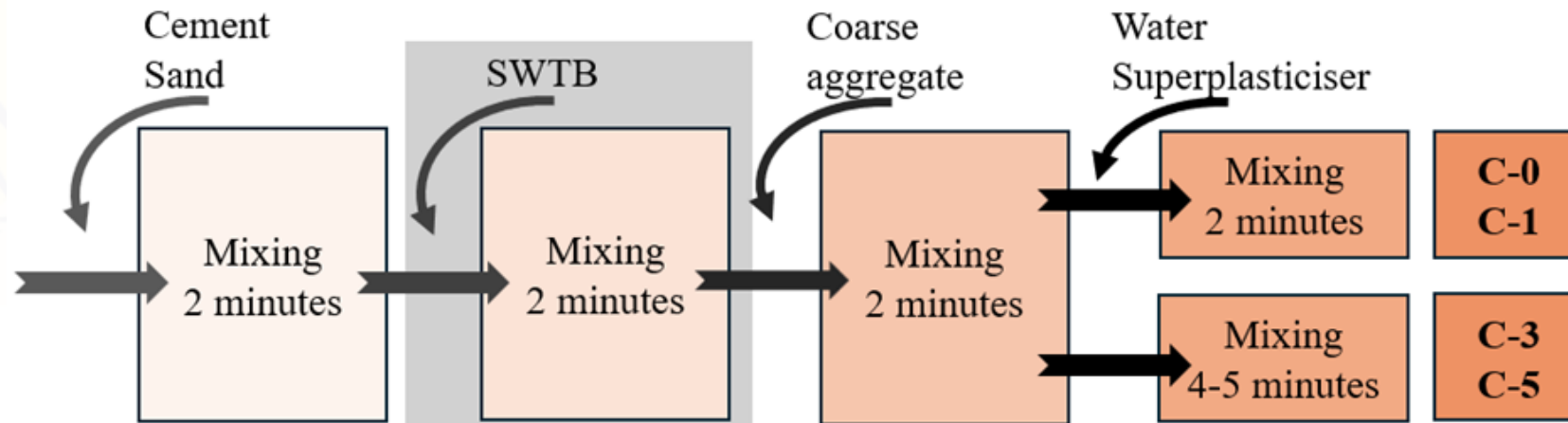
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# Normal-weight concrete with WTB waste: role of waste and mixing process



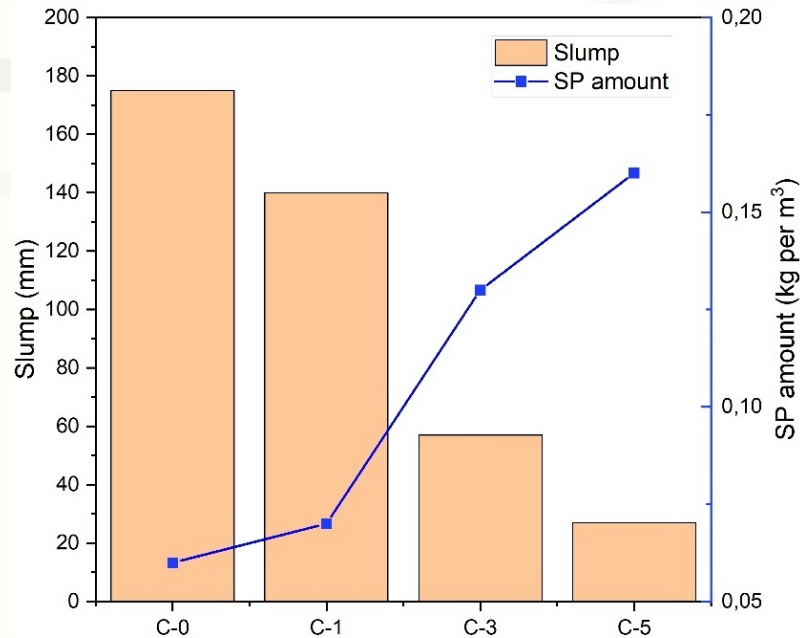
Total incorporation of SWTB in concrete and its distribution according to functional roles

| Sample ID | Amount in total concrete |                   |                             | Amount per component          |                            |
|-----------|--------------------------|-------------------|-----------------------------|-------------------------------|----------------------------|
|           | Used SWTB (mass %)       | Used SWTB (vol.%) | Fiber reinforcement (vol.%) | Aggregate replacement (vol.%) | Cement replacement (vol.%) |
| C-0       | 0.0                      | 0.0               | 0.0                         | 0.0                           | 0.0                        |
| C-1       | 1.0                      | 1.0               | 0.5                         | 2.1                           | 0.9                        |
| C-3       | 3.0                      | 4.0               | 1.6                         | 6.2                           | 2.6                        |
| C-5       | 5.0                      | 7.0               | 2.6                         | 10.2                          | 4.4                        |



# Properties of fresh concrete: workability and air content

## Effect of SWTB content on slump and superplasticizer (SP) demand

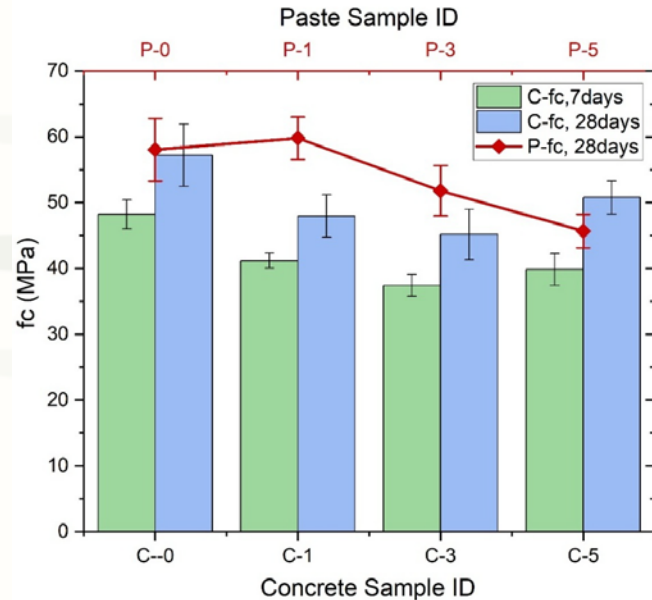


## Properties of fresh concrete

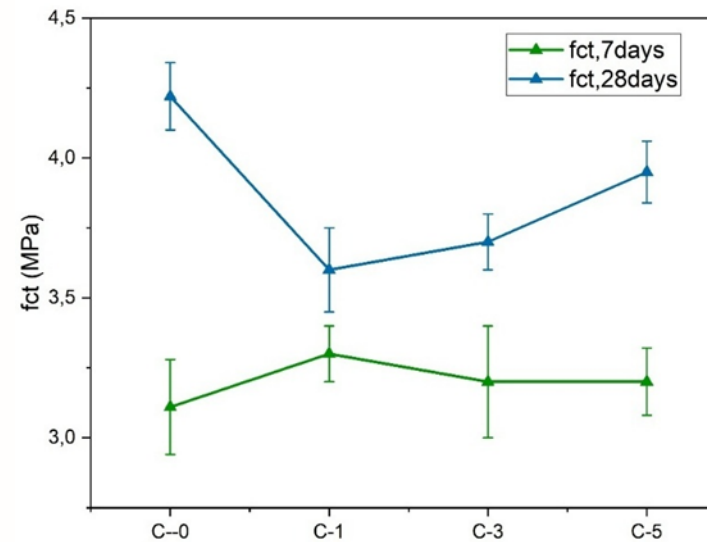
| Sample | Slump (mm) | Fresh Density (kg/dm <sup>3</sup> ) | Air content (%vol.) |
|--------|------------|-------------------------------------|---------------------|
| C-0    | 175 ± 5    | 2.34 ± 0.02                         | 3 ± 0.01            |
| C-1    | 140 ± 3    | 2.33 ± 0.01                         | 2.5 ± 0.01          |
| C-3    | 57 ± 2     | 2.32 ± 0.02                         | 1.6 ± 0.02          |
| C-5    | 27 ± 2     | 2.28 ± 0.02                         | 1.7 ± 0.01          |



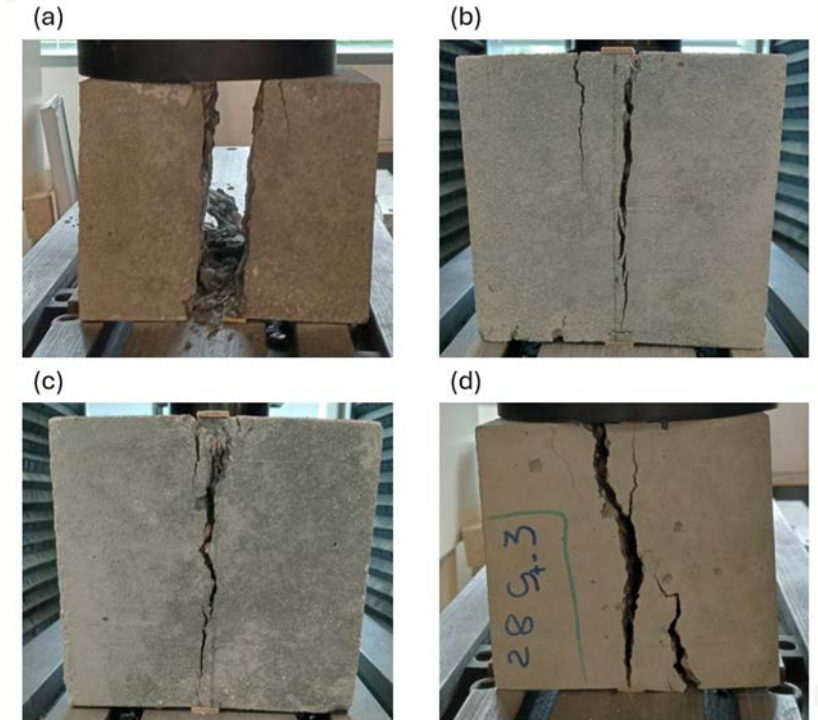
# Properties of concrete with shredded WTB waste: compressive and splitting tensile strength



Compressive strength of concrete samples at 7 and 28 days and correlation with cement paste values at 28 days

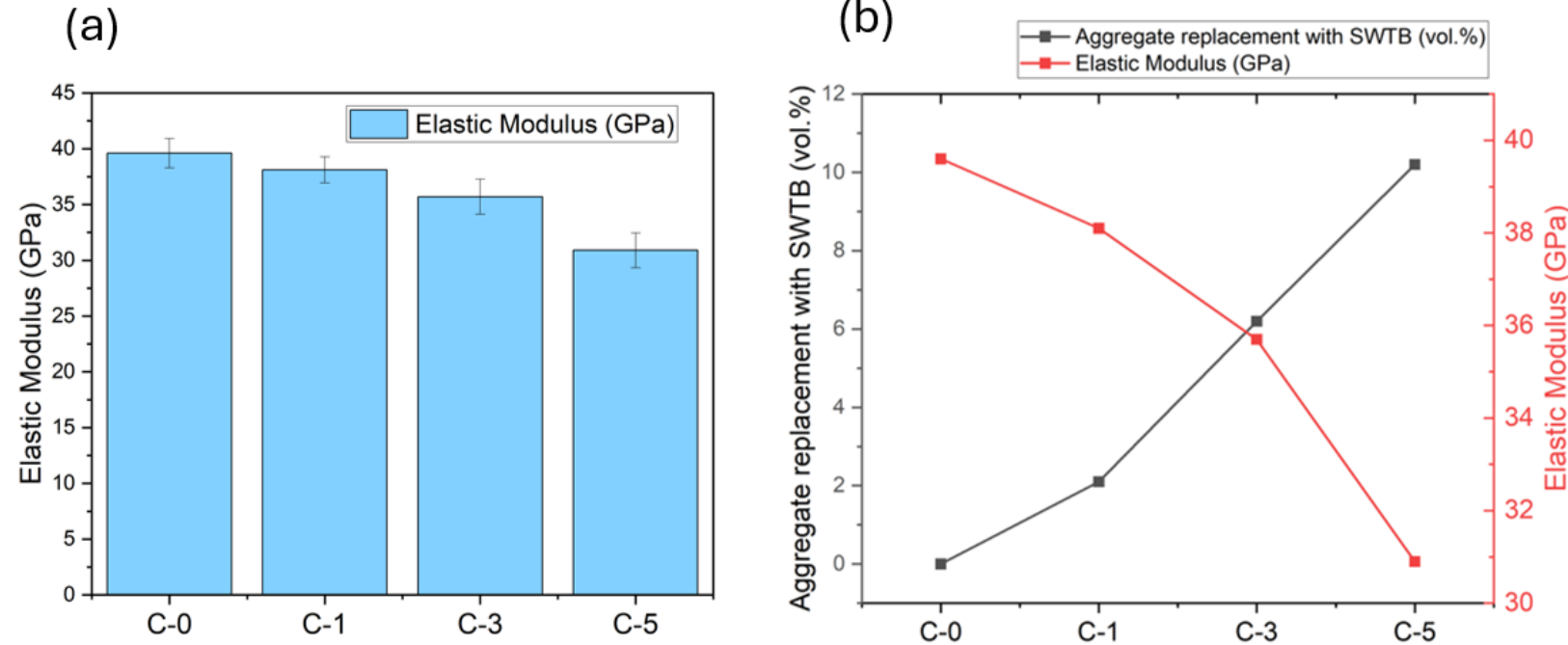


Split tensile strength of concrete samples at 7 and 28 days



Fracture of concrete samples at the 28-day split tensile test: (a) C-0, (b) C-1, (c) C-3, and (d) C-5

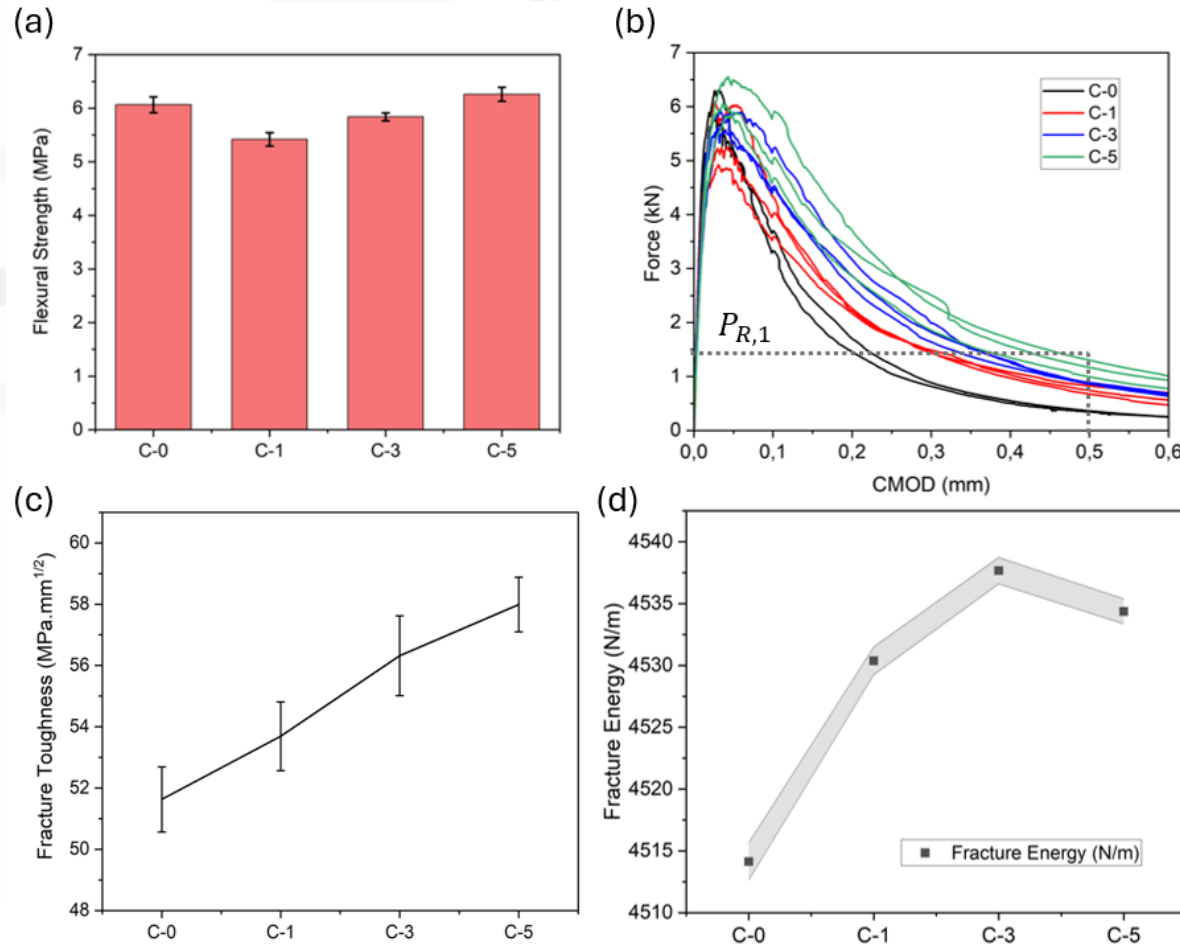
# Properties of concrete with shredded WTB waste: elastic modulus



Elastic modulus results of concrete specimens:

- (a) measured elastic modulus values for C-0, C-1, C-3, and C-5 mixtures;
- (b) relationship between SWTB aggregate replacement level (vol.%) and elastic modulus

# Properties of concrete with shredded WTB waste: fracture behaviour



Fracture properties of the concrete specimens:

- (a) Flexural strength;
- (b) Load-CMOD curves of concrete beams;
- (c) Fracture toughness ( $K_{IC}$ );
- (d) Fracture energy ( $G_f$ )

# Properties of concrete with shredded WTB waste: CMOD and $E_{mod}$ testing setups

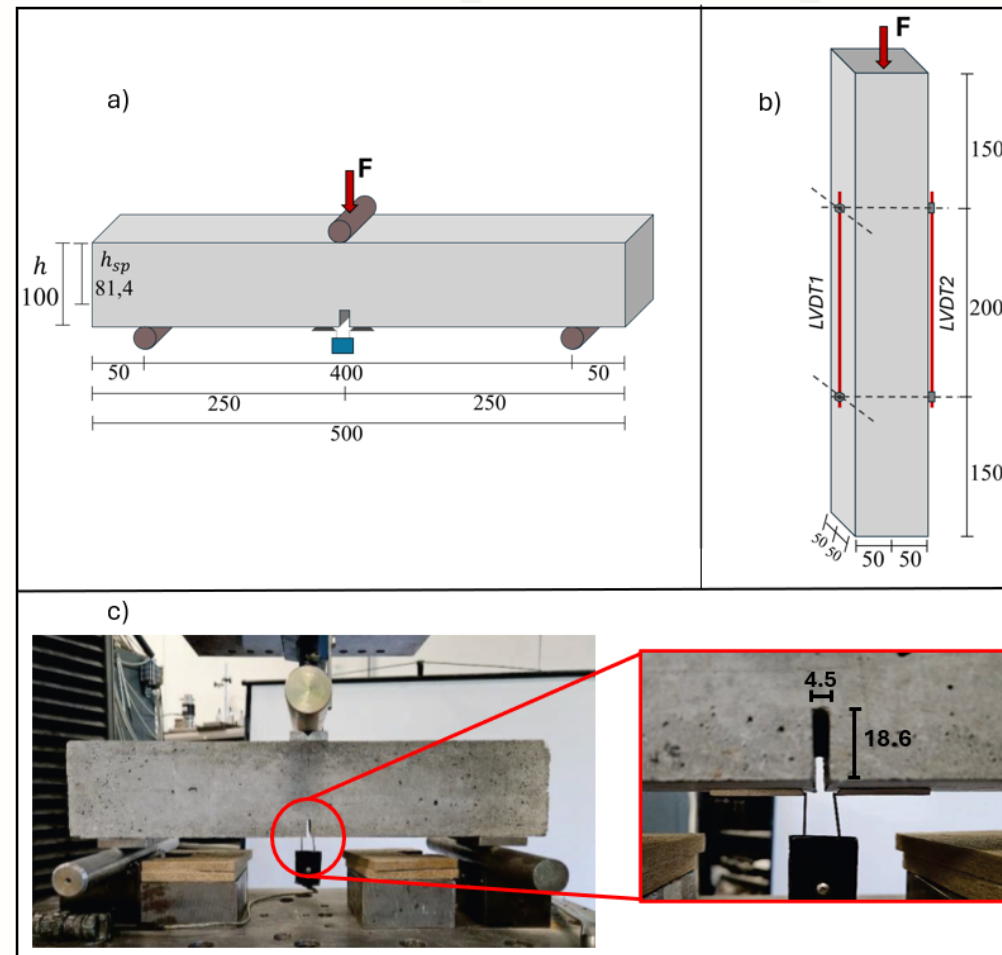


Experimental setups (dimensions in mm):

(a) CMOD test setup,

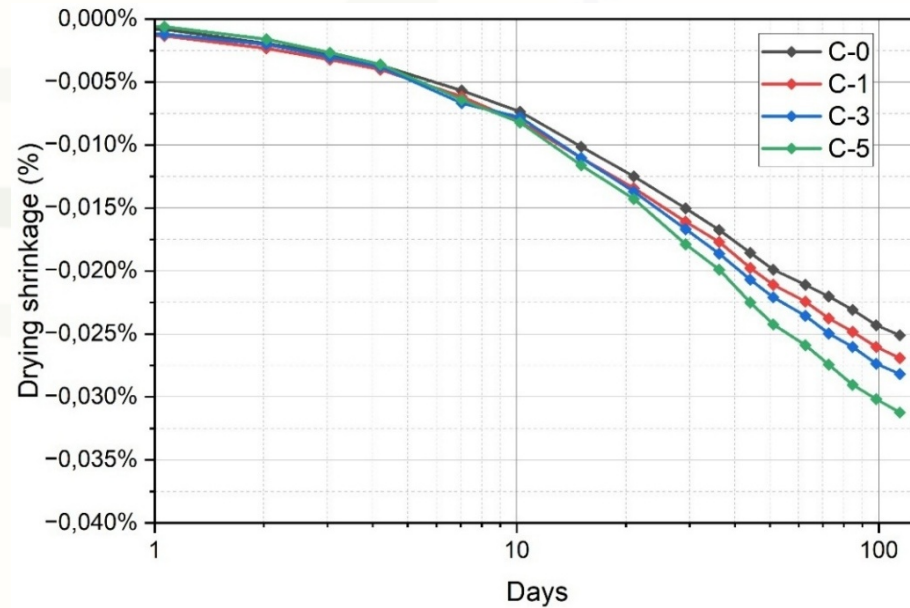
(b)  $E_{Mod}$  test setup,

(c) concrete specimen with a preformed notch and clip gauge for the CMOD test

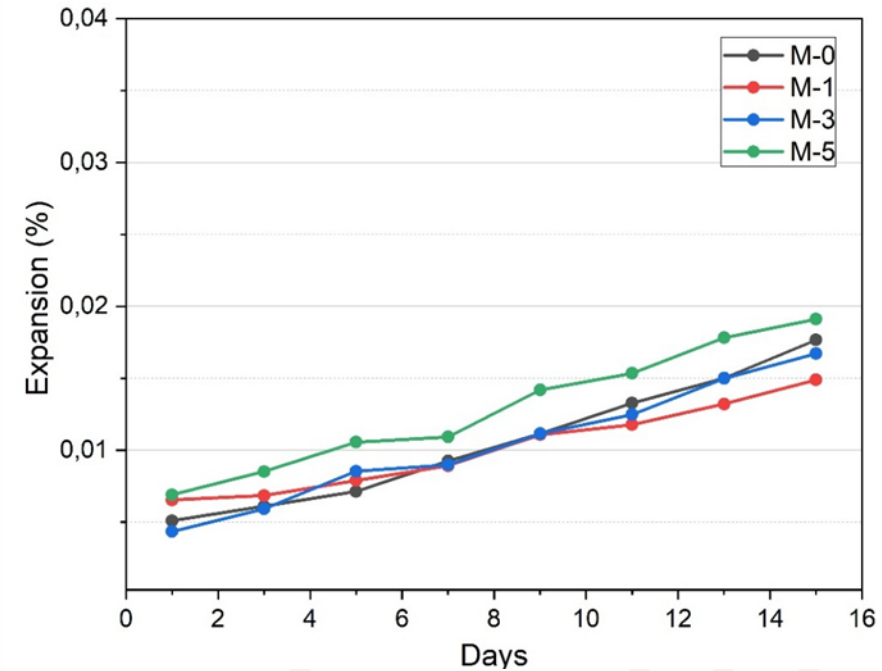




# Properties of concrete with shredded WTB waste: drying shrinkage and ASR



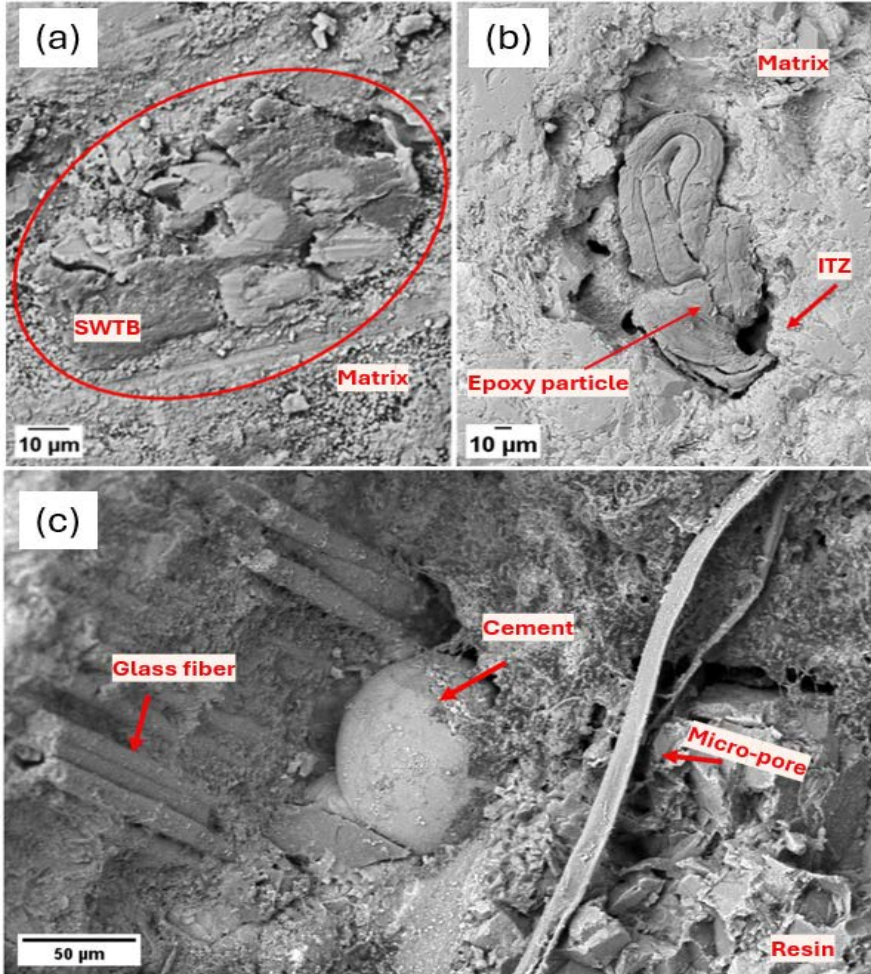
Drying shrinkage kinetics of concrete prisms depending on SWTB dosage



Expansions during accelerated mortar bar test  
Expansion limit 0.1%



# Microstructure of concrete with SWTB



SEM images of the C-5 concrete specimen showing SWTB particles at different size ranges:

(a) cement replacement-sized SWTB with glass fiber residues,

(b) cement replacement-sized SWTB without glass fiber residues,

(c) inside of a large SWTB particle used as aggregate replacement in concrete

# Summary of concrete properties with shredded WTB waste



## Concept

- Hybrid function: replacement of cement and + aggregates + reinforcement
- Wide particle size range(0.06–80 mm)
- Optimized mix design with particle packing

## Mechanical performance

- Compressive strength >45 MPa
- Slight reduction of stiffness
- Improved ductility and toughness
- Significant increasing of residual flexural ↑ up to 250%

## Durability

- No ASR risk observed
- Low shrinkage
- Enables 10% aggregate + 4% cement replacement

More information  
in our paper



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# What is next?



From replacement and reinforcement

## 💡 Challenge with direct SWTB use

- 👉 Heterogeneous mix (powder + fibers + flakes) → poor dispersion [
- 👉 High water demand & workability loss
- 👉 Reduced stiffness and strength
- 👉 Risk of clustering & weak ITZ
- 👉 Limits **high-volume application**

## 💡 Concept shift

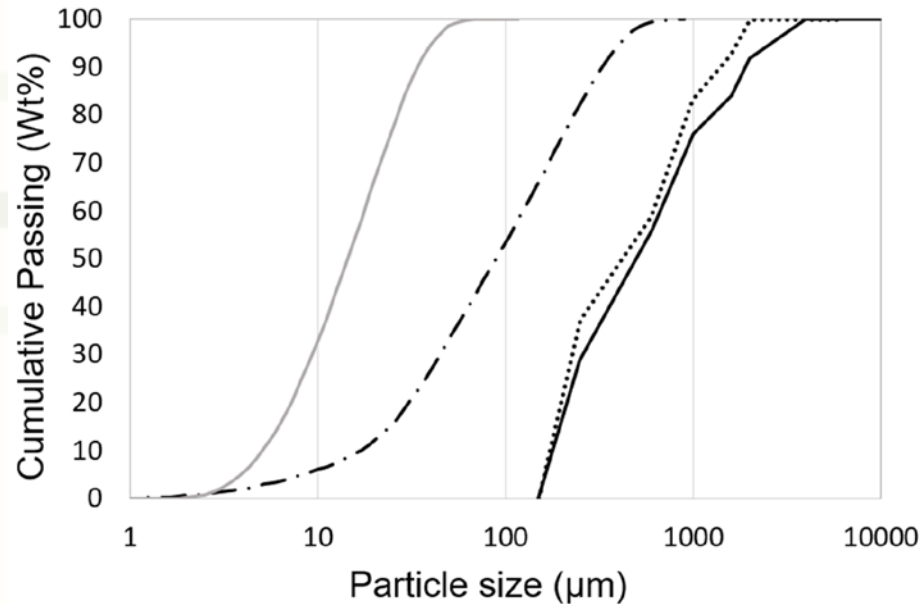
- 👉 Instead of mixing waste → redesign the material
- 👉 Convert SWTB into engineered pellets (LWA)
- 👉 Controlled size & shape
- 👉 Core-shell structure (SWTB + cement) [
- 👉 Uniform, stable aggregate behavior



To light-weight aggregate



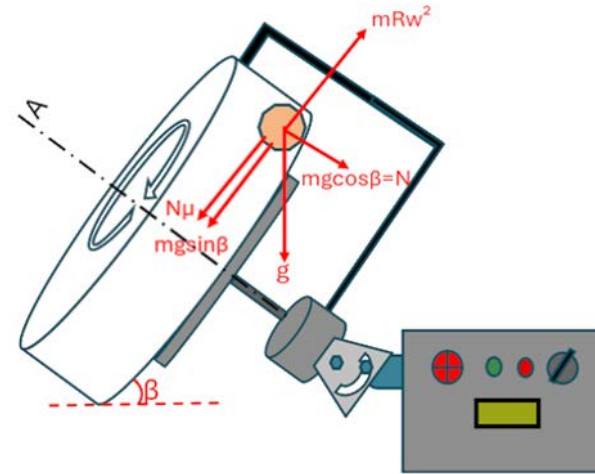
# Light-weight aggregate with WTB waste



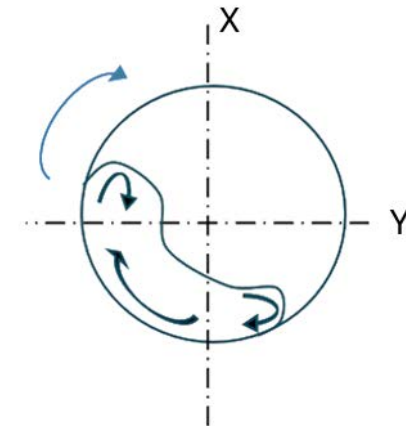
— STBW 0-180 μm ..... STBW 0-2mm — SWTB 0-4mm — CEM I 52,5R

Particle size distributions of the raw materials used for aggregate production

(a)

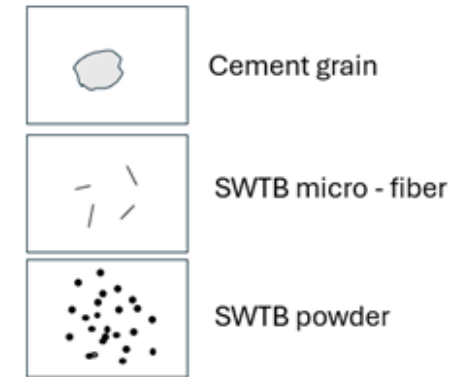
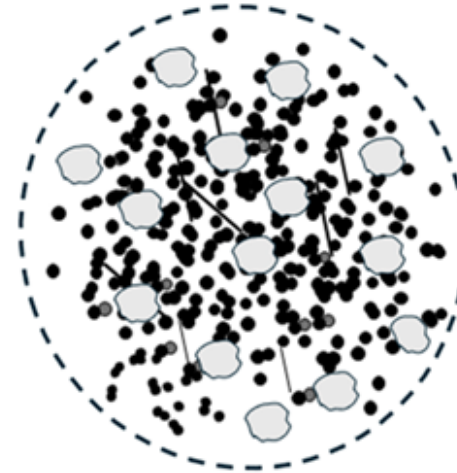
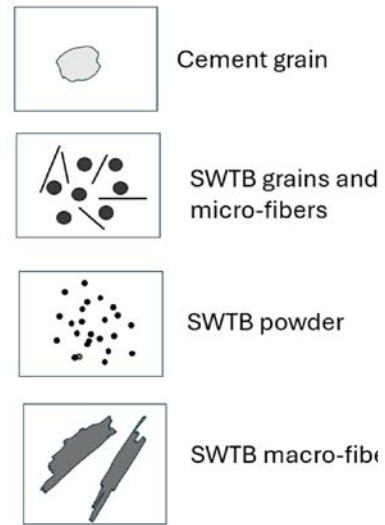
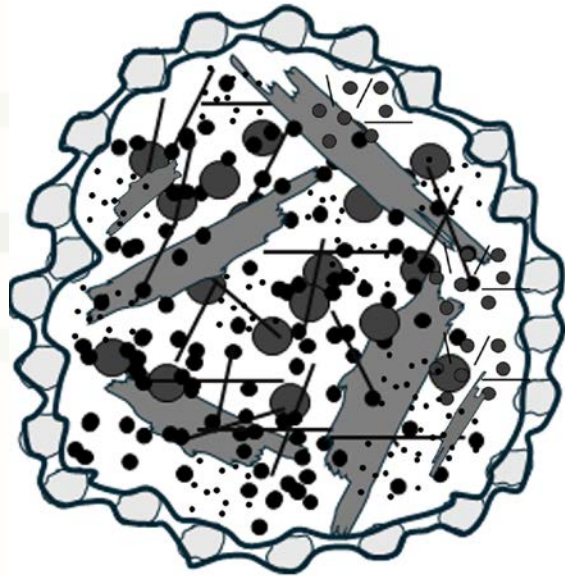


(b)



- o Disc type pelletizer (a) and the forces acting on an individual pellet (b) motion of the material in the disc type pelletizer

# Pellets produced with cement and particles of WTB with different shape and size



Schematic illustration of a pellet produced with cement and micro-sized SWTB particles

Schematic illustration of a pellet produced with cement and micro-sized SWTB particles

# Pellets produced with cement and particles of WTB with different shape and size



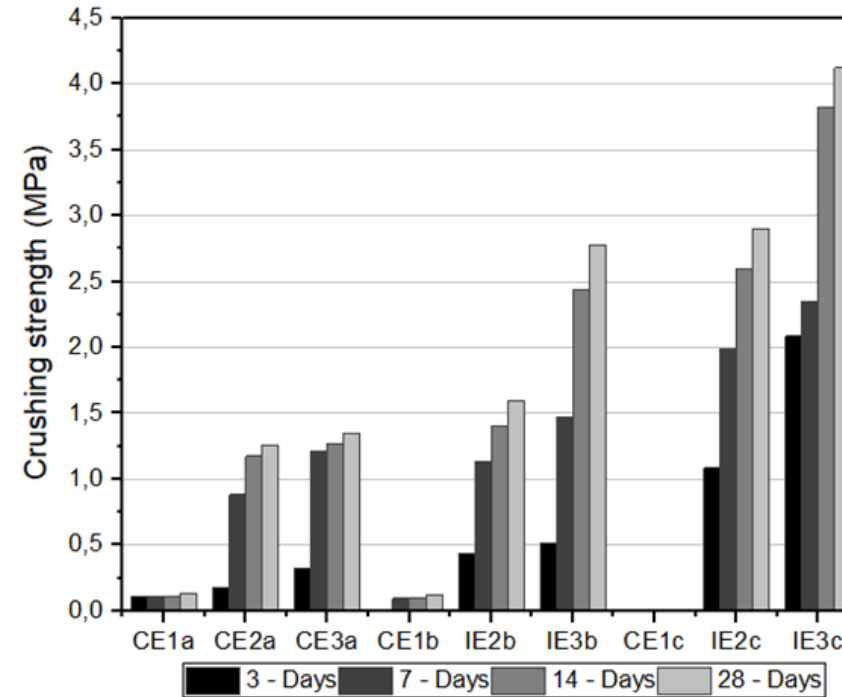
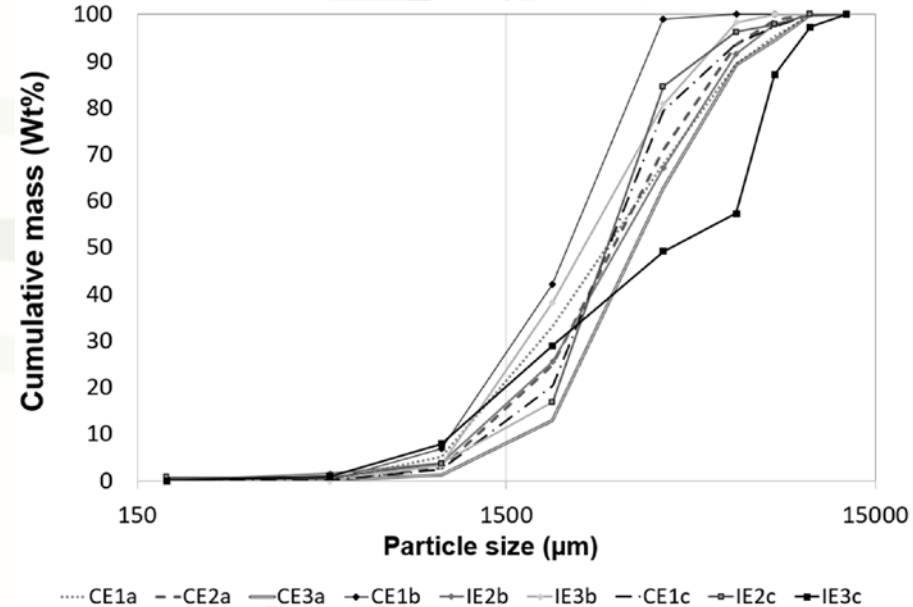
Pellets produced with cement and fibrous-granular SWTB waste



Pellets produced with cement and micro-sized SWTB particles

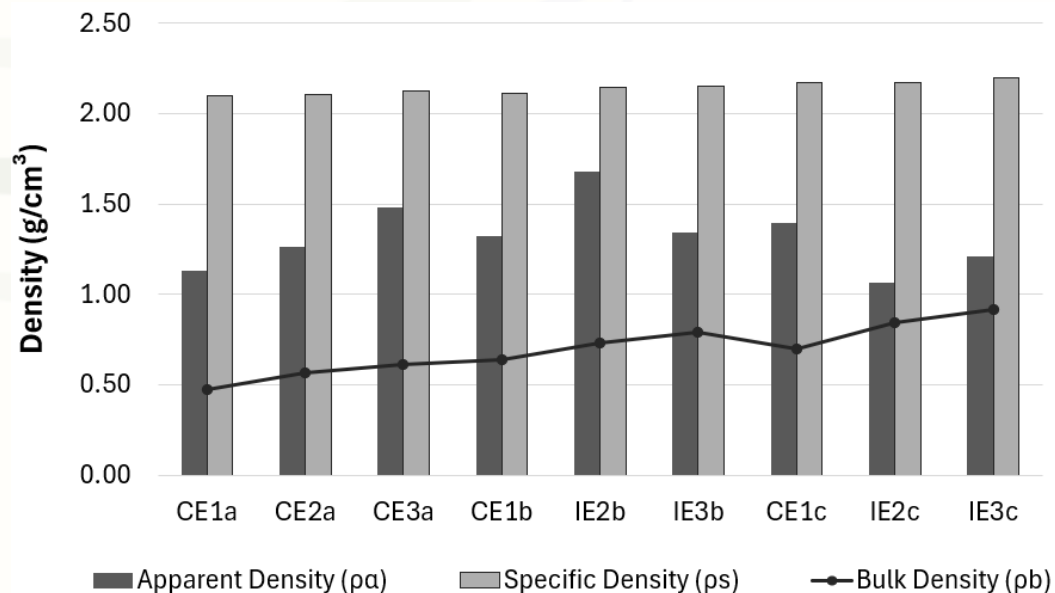


# Properties of pellets: particle size and crushing strength

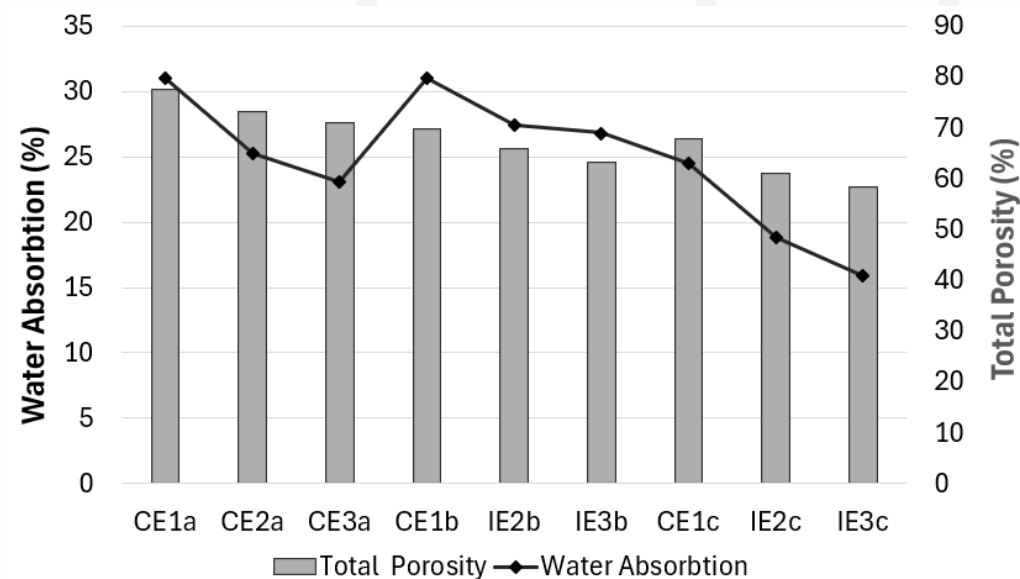




# Properties of pellets: density and water absorption

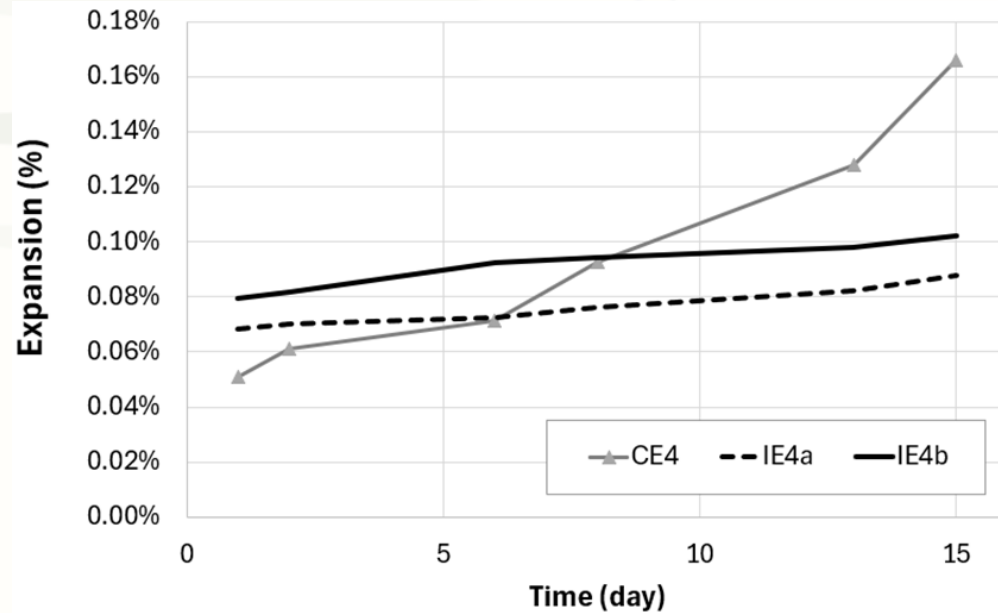


Density of pellets, g/cm<sup>3</sup>

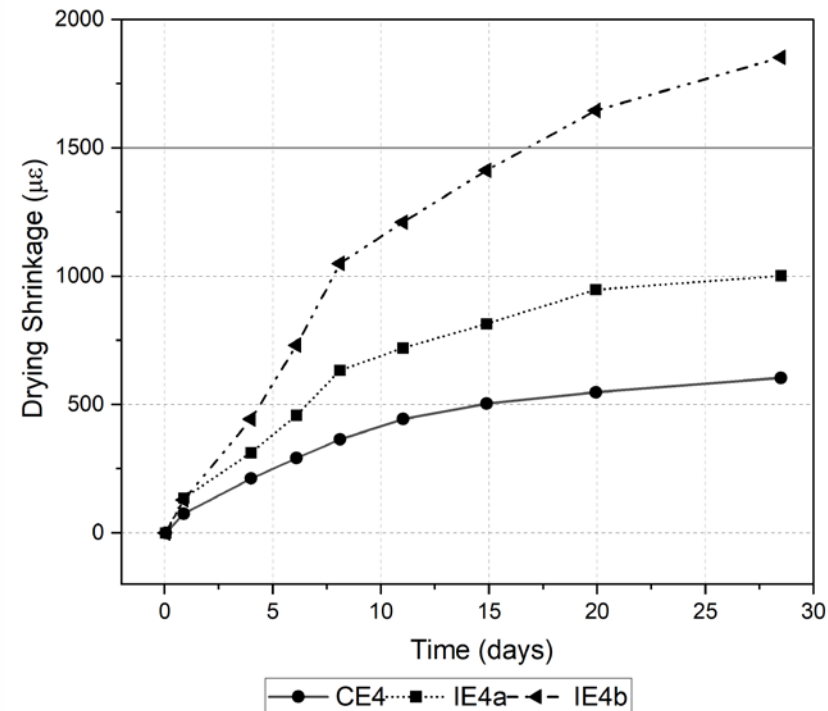


Water absorption & total porosity of pellets

# Properties of pellets



ASR expansion of mortar samples



Drying shrinkage of mortar samples

# Summary of light-weight aggregate properties and potential for application



| Concept                                                                                                                                                                                                                                    | Physical properties                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | Mechanical properties                                                                                                                                                                                                                                                                                                   | Durability                                                                                                                                                                                                                                                                                                         | Key advantages                                                                                                                                                                                                                      |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"><li>• Core-shell structure: SWTB core (fibers + powder) + cement shell [</li><li>• Cold-bonded pelletization (disc pelletizer)</li><li>• Conversion of heterogeneous waste to uniform granules</li></ul> | <ul style="list-style-type: none"><li>• Lightweight:<ul style="list-style-type: none"><li>• particle density <math>\leq 2000 \text{ kg/m}^3</math> bulk density <math>\leq 1200 \text{ kg/m}^3</math></li></ul></li><li>• Porosity: <math>\sim 50\text{--}85\%</math> (high internal voids)</li><li>• Water absorption: typically, <math>20\text{--}40\%</math>, reduced by outer shell</li><li>• Controlled size (<math>\sim 1.5\text{--}10 \text{ mm}</math> <math>\rightarrow</math> usable as standard aggregate)</li></ul> | <ul style="list-style-type: none"><li>• Crushing strength: <math>\geq 1\text{--}3 \text{ MPa}</math> (up to <math>\sim 4 \text{ MPa}</math> after curing)</li><li>• Strength increases with curing (<math>3 \rightarrow 28</math> days) [</li><li>• Lower stiffness than natural aggregates (due to porosity)</li></ul> | <ul style="list-style-type: none"><li>• ASR risk mitigated via cement encapsulation</li><li>• Shrinkage: higher than natural aggregates (typical for LWA)</li><li>• Thermal conductivity <math>\downarrow</math> significantly (good insulation)</li><li>• Stable microstructure due to protective shell</li></ul> | <ul style="list-style-type: none"><li>• Converts difficult composite waste into usable material Enables high-volume recycling of WTB</li><li>• Reduces density of concrete/mortar Improves thermal insulation performance</li></ul> |

# Conclusions

## WTB waste as a multifunctional resource

- Shredded WTB can act simultaneously as:  
**cement replacement + aggregate + reinforcement**  
Enables **structural-grade concrete (>45 MPa)** even at elevated waste content

## Performance vs. trade-offs

- Improved **ductility, toughness, and post-cracking behavior**
- No ASR risk and acceptable durability
- ⚠ Reduced **workability and stiffness** due to heterogeneity
- Optimization (particle packing) is essential

## From limitation to solution

- Direct incorporation → **limited by dispersion & heterogeneity**
- Pelletization → **engineered lightweight aggregates**
- Controlled size & structure

## Maximizing waste utilization

- Combination of two complementary pathways:  
**Direct use in concrete** → functionality  
**Pellets (LWA)** → volume and scalability

## Impact for circular construction

- Reduces:  
natural aggregate consumption  
cement demand
- Provides a **practical route for WTB recycling at scale**



# Thank you!



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[Building Materials](#)



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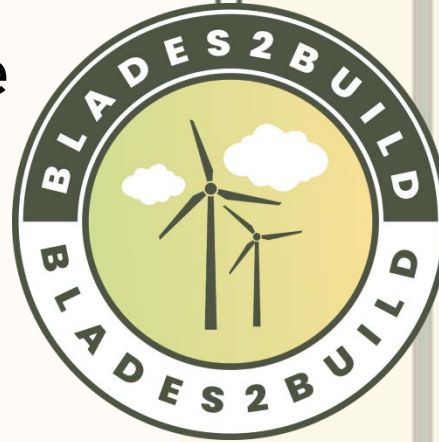
Funded by the European Union under the Grant Agreement no. 101096437. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.



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# BLADES2BUILD

Recycle, repurpose and reuse end-of-life wind blade composites – a coupled pre- and co-processing demonstration plant



**Composites Recycling through Pyrolysis**  
Dr. Kate Trompeta, NTUA/R-NanoLab



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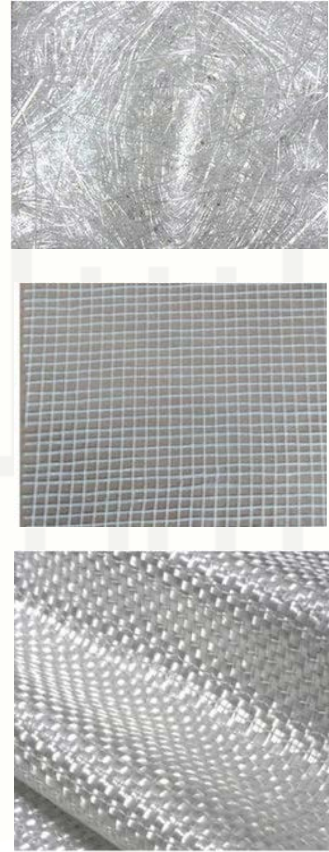
Funded by the European Union under the Grant Agreement no. 101096437. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.



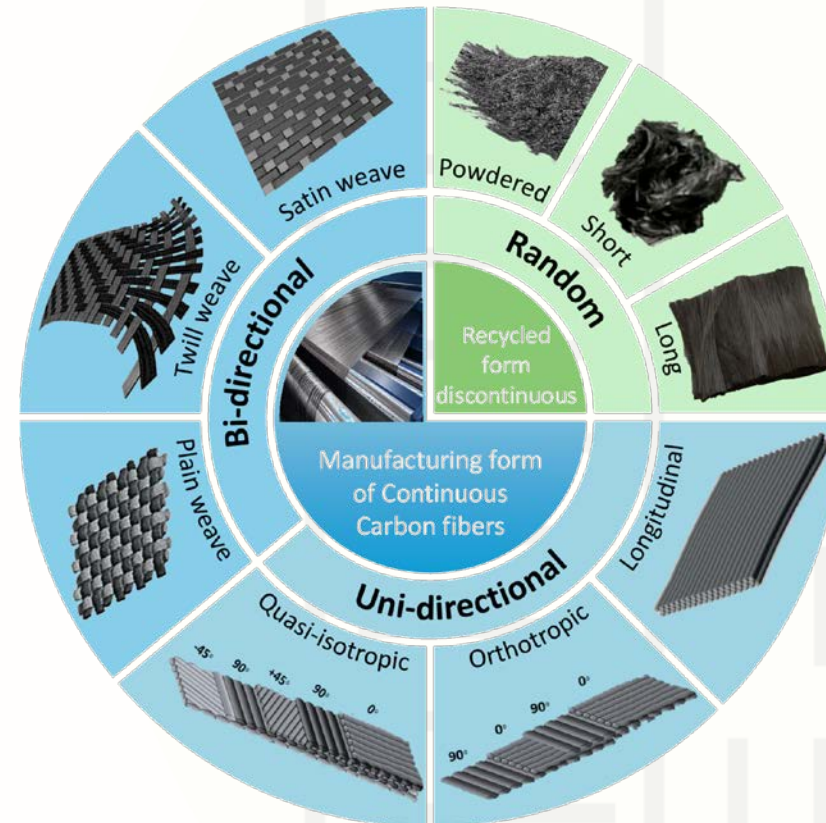
# Composite= Resin + Reinforcement



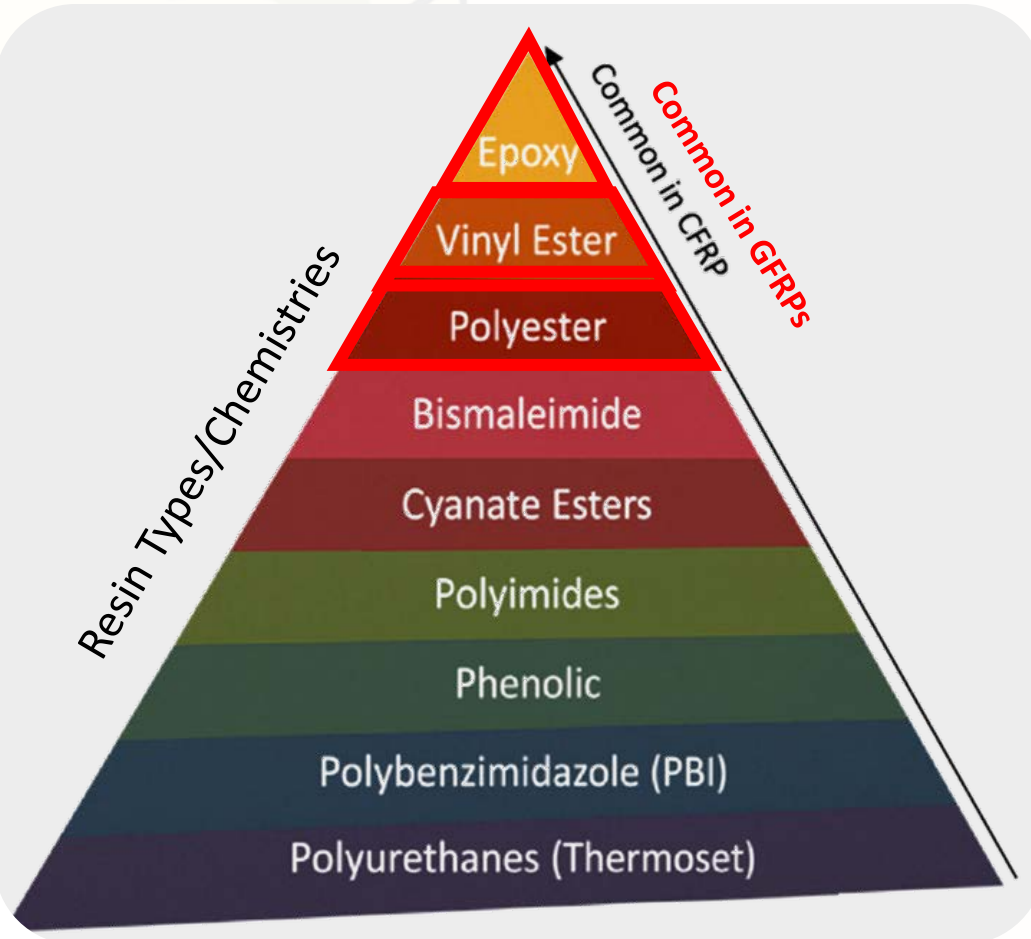
## Glass Fibres



## Carbon Fibres



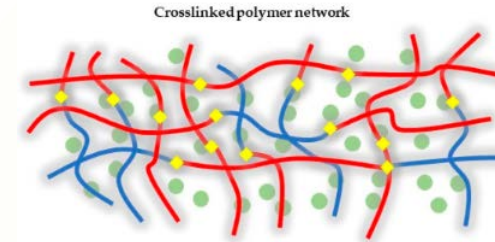
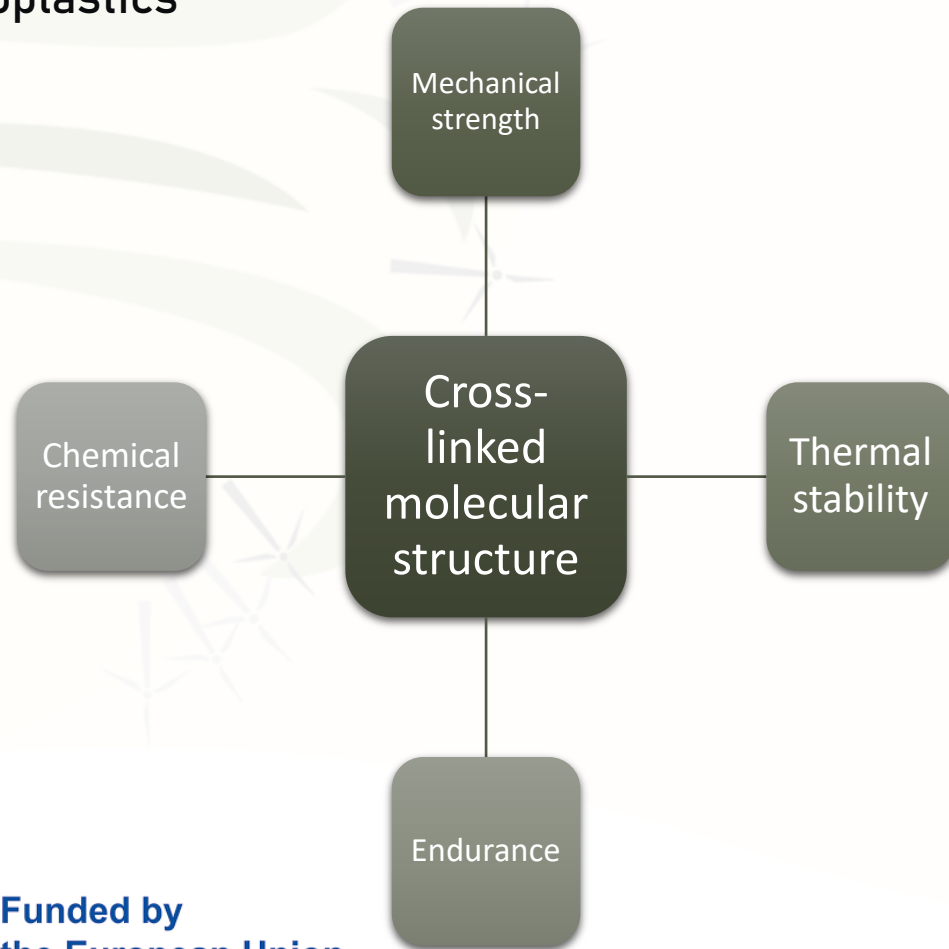
## Reinforcement Types





# Introduction to Composite Materials Recycling

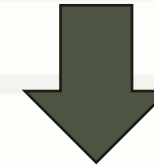
Thermosets are polymers with high molecular weight, offering alternative properties and applications compared to thermoplastics



However, their crosslinked nature is what makes their recycling challenging:



The 3D network prevents the material from melting, reforming, or dissolving under heat.

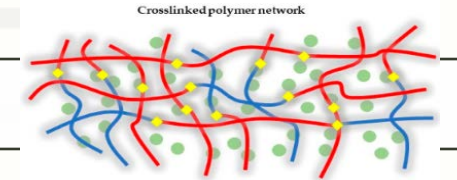


Consequently, processing them causes severe fiber degradation and limits the economic viability of recovering high-value reinforcements



# Primary Technical and Economic Barriers

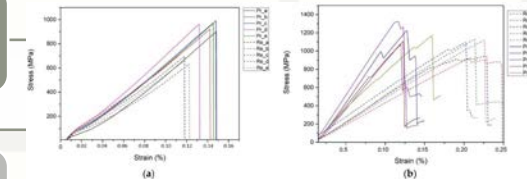
Irreversible Cross-Linking



Energy-Intensive Degradation



Fiber Damage and Reduced Strength



Contamination and Sorting Issues



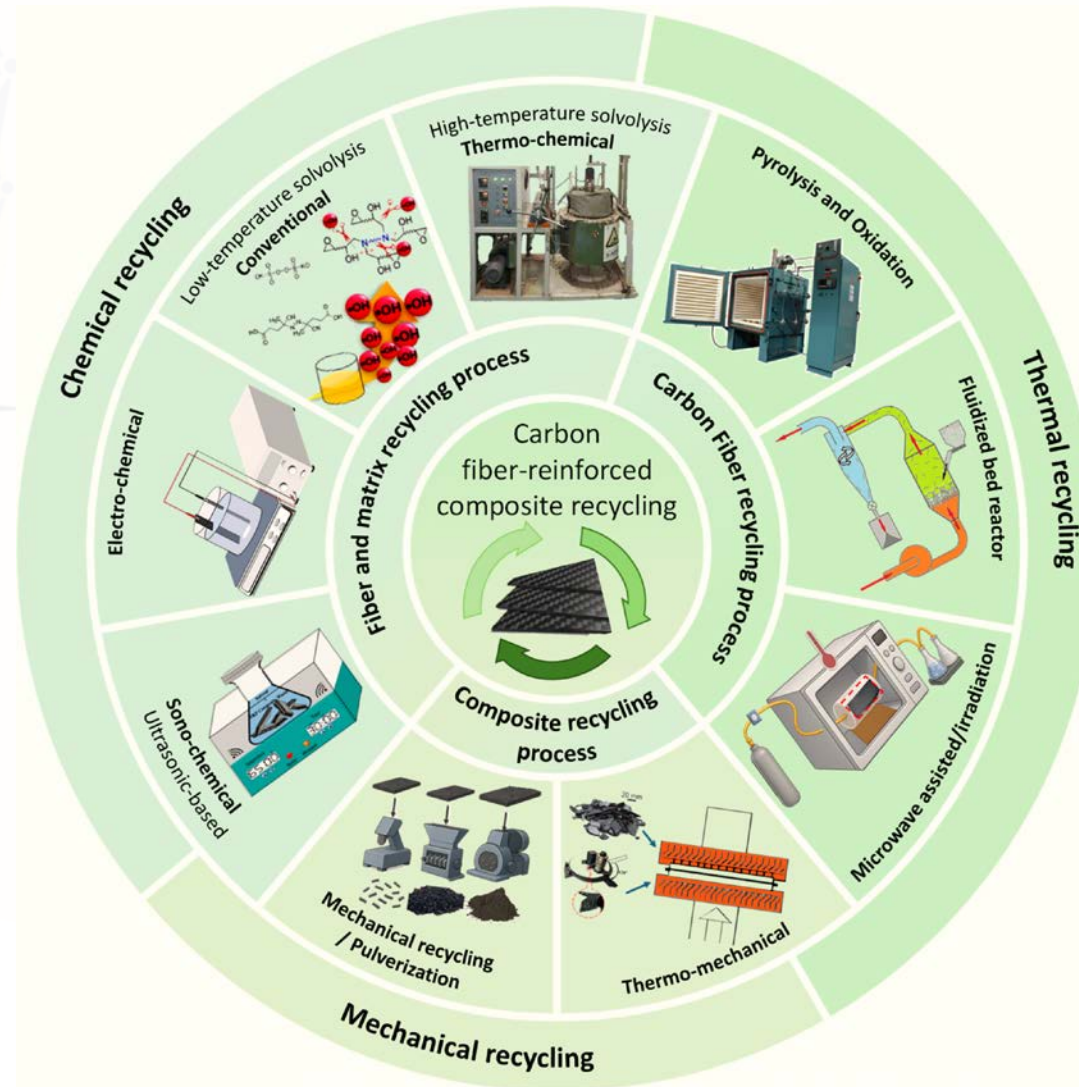
Low Economic Viability



Chemical Degradation Byproducts



# Classification of recovery and recycling technologies for thermosetting polymer composites



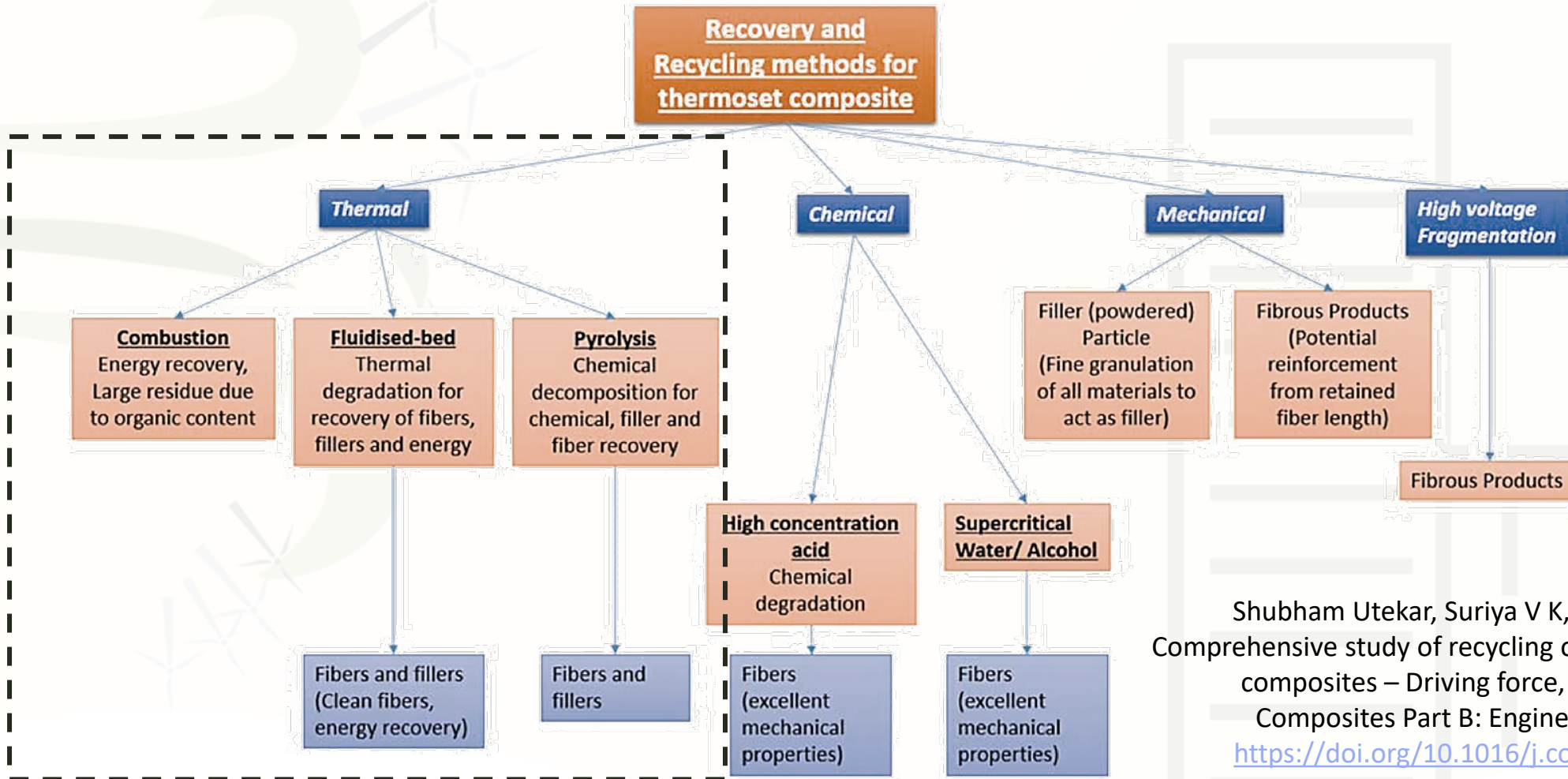
B. S.Chohan, Z.Yuan, A.Riaz, and K.Cheng, "Carbon Fiber-Reinforced Polymer Sustainability—A New Outlook on Recycling Methods and Strategic Decision-Making for the Recovery of Fiber, Matrix, and Composite," *Polymer Composites* 47, no. 6 (2026): 4869–4899, <https://doi.org/10.1002/pc.70470>.



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# Classification of recovery and recycling technologies for thermosetting polymer composites



Shubham Utekar, Suriya V K, Neha More, Adarsh Rao,  
Comprehensive study of recycling of thermosetting polymer  
composites – Driving force, challenges and methods,  
Composites Part B: Engineering, Volume 207, 2021,  
<https://doi.org/10.1016/j.compositesb.2020.108596>.

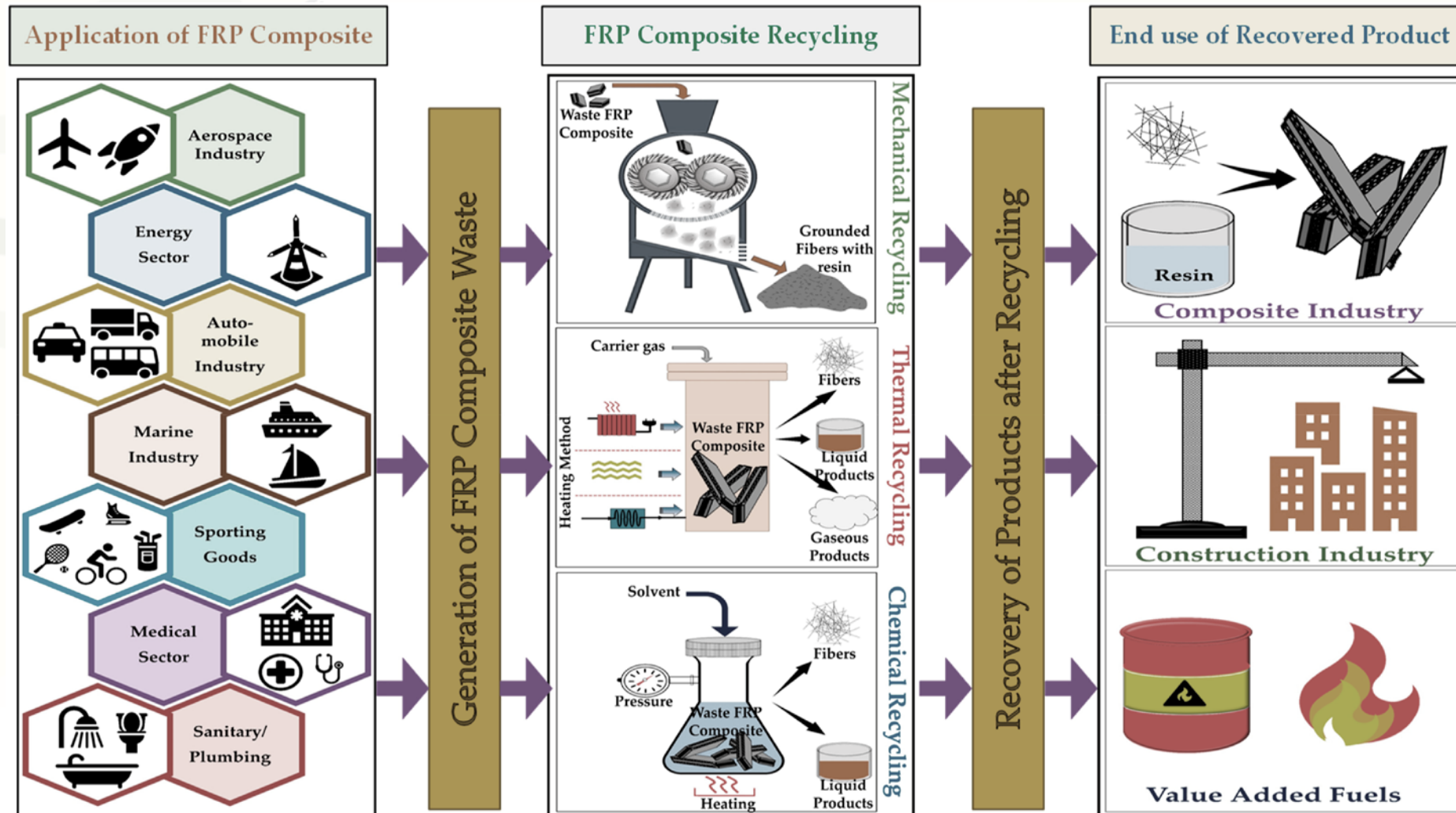


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# Composites Recycling Methods (also Hybrid)

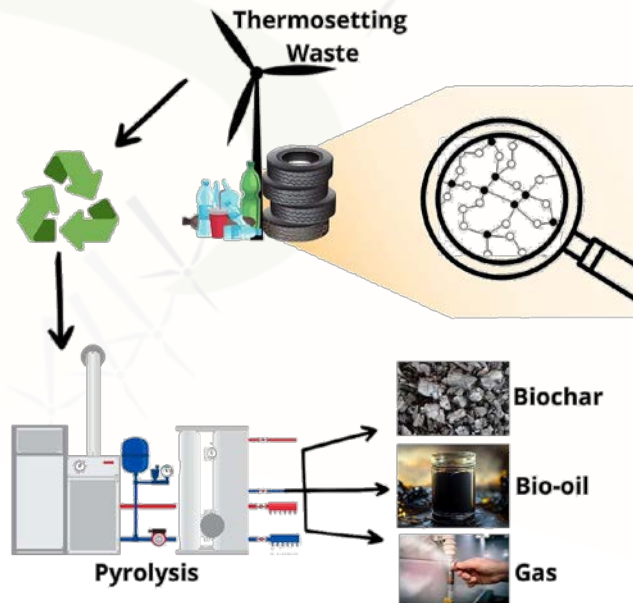




# Comparison of main Thermal Processes

## Pyrolysis

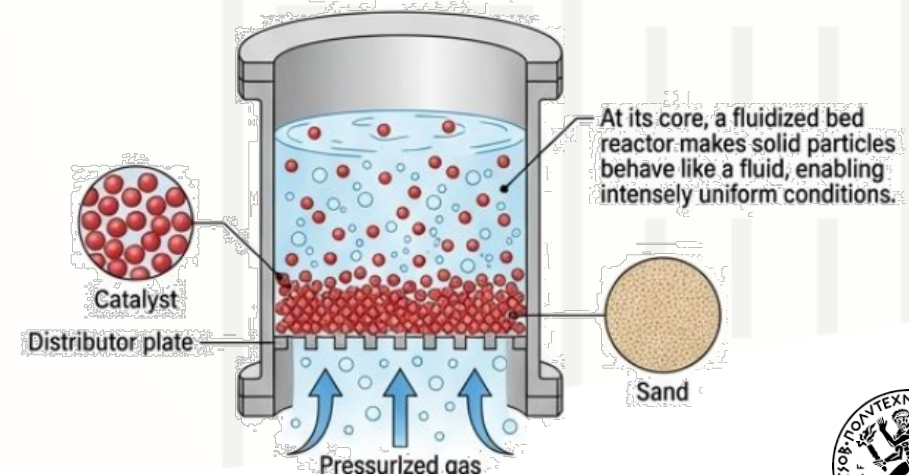
- Main principle: Thermal degradation of the cross-linked polymer matrix in an oxygen-free (inert) atmosphere.



## Fluidised bed

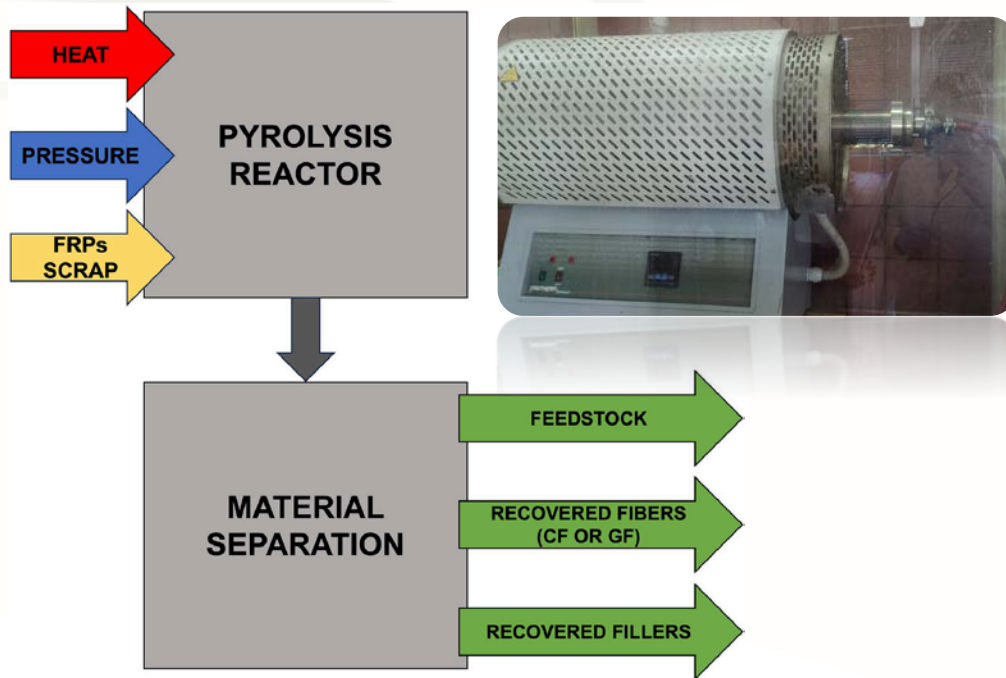
- Main principle: Rapid, high-temperature stream of hot air to vaporise the polymer resin matrix of a composite material, liberating and recovering the underlying reinforcing fibres (such as carbon or glass) for reuse

Transforming Solid Particles into a Fluid-Like State for Efficient Mixing and Heat Transfer

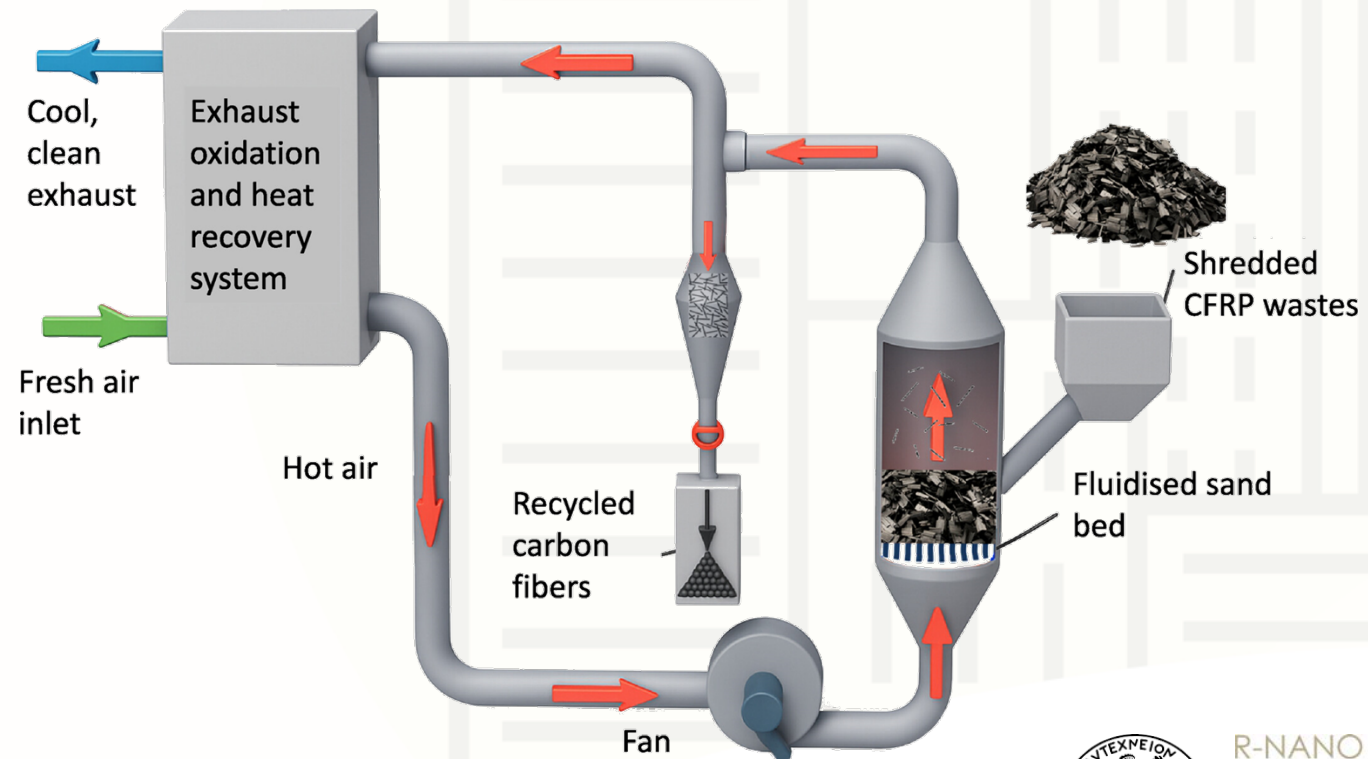


# Comparison of Thermal Processes

## Pyrolysis Reactor



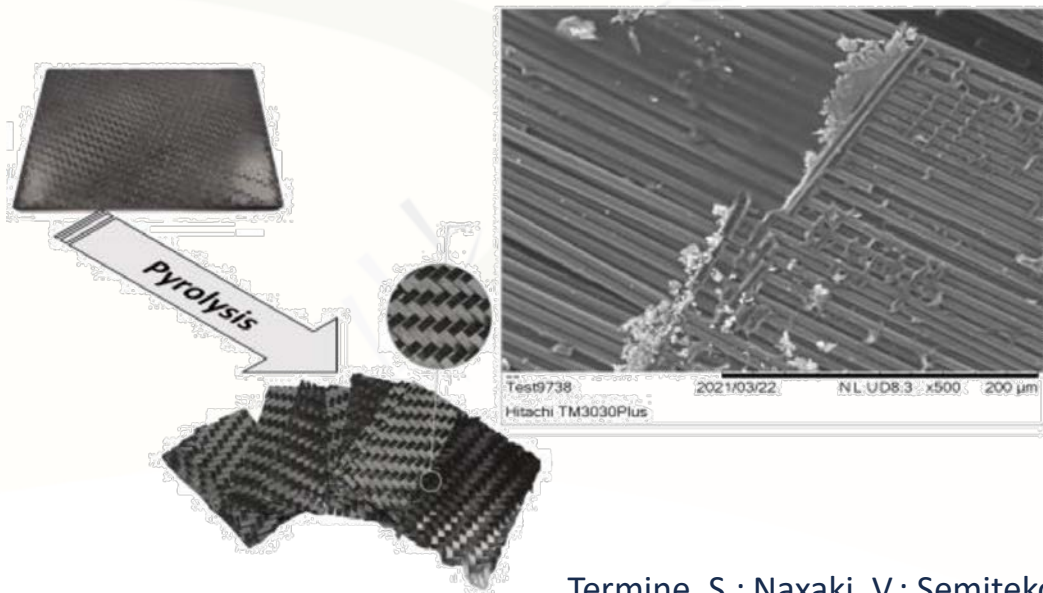
## Fluidised Bed Reactor



# Comparison of Thermal Processes

## Pyrolysis

- Advantages:
  - Unique ability to transform organic waste into valuable products like bio-oil, biochar, and syngas
  - Reclamation of whole patches



## Fluidised bed

- Advantages:
  - High-Quality Fiber Recovery
  - Contaminant Tolerant
  - Energy Recovery
  - Continuous Operation
  - Economic Viability
  - Low Carbon Footprint
- Disadvantages:
  - significant mechanical property degradation of the recovered fibres
  - high operational energy costs
  - short and "fluffy" fibre lengths,
  - high greenhouse gas emissions

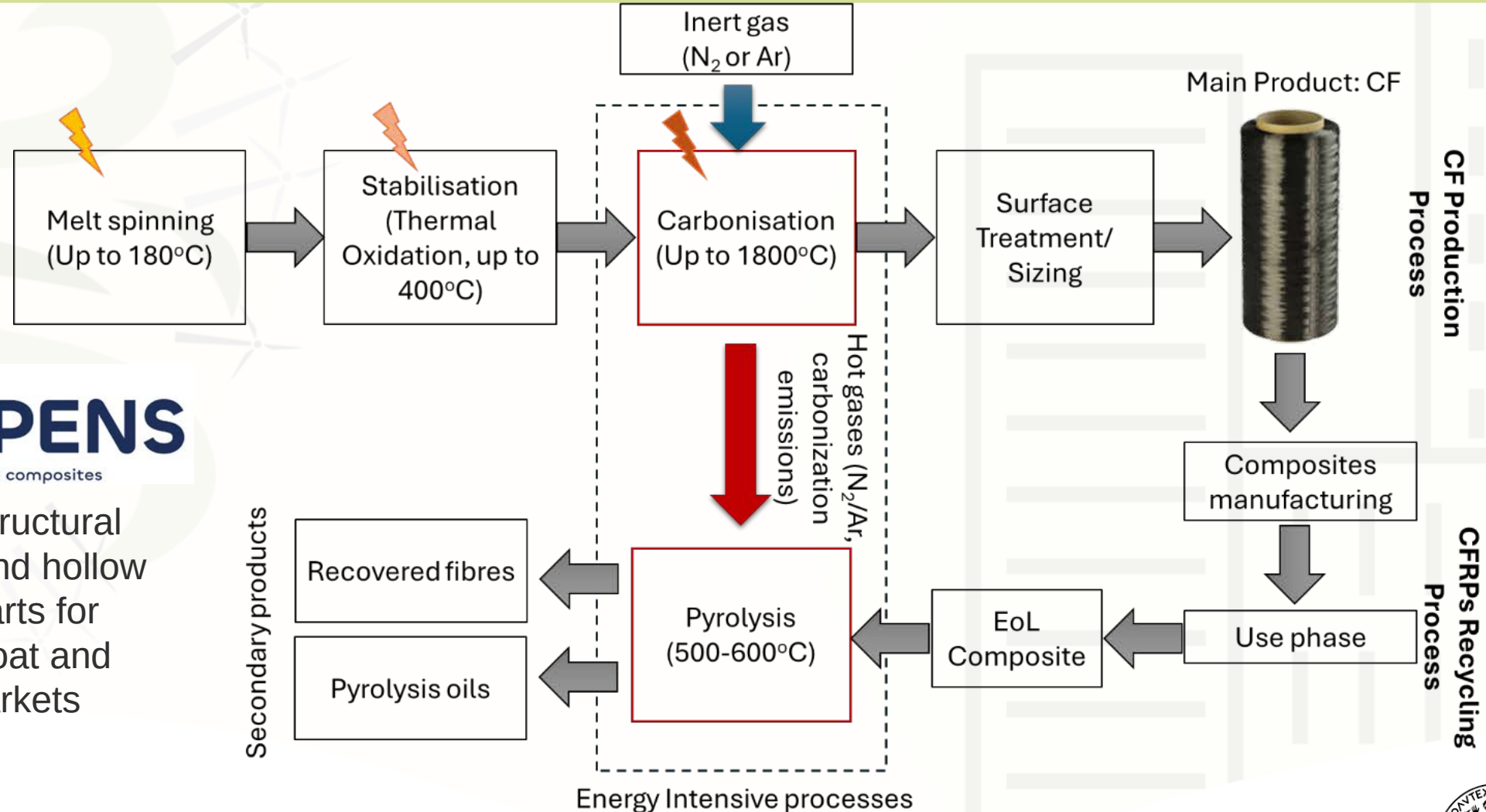
Termine, S.; Naxaki, V.; Semitekolos, D.; Trompeta, A.-F.; Rovere, M.; Tagliaferro, A.; Charitidis, C. Investigation of Carbon Fibres Reclamation by Pyrolysis Process for Their Reuse Potential. *Polymers* **2023**, *15*, 768 <https://doi.org/10.3390/polym15030768>

# Composites Pyrolysis Drawbacks:

- Pyrolysis plants require significant upfront capital investment. The high-temperature, oxygen-free reactor and sophisticated control systems are expensive to build and install.
- Operating costs are also substantial. The process is energy-intensive, requiring a constant supply of heat to maintain high temperatures, and ongoing maintenance is critical for safety and efficiency.
- While syngas can offset some energy needs, the process often requires a net energy input, especially during startup. Achieving and maintaining precise temperature control is a constant technical challenge.
- Crucially, the raw bio-oil is not a drop-in fuel. It is acidic, unstable, and contains high levels of oxygen and water. It requires significant and costly secondary refining (upgrading) before it can be used as a transportation fuel or chemical feedstock.



# Sustainable pyrolysis conceptualisation



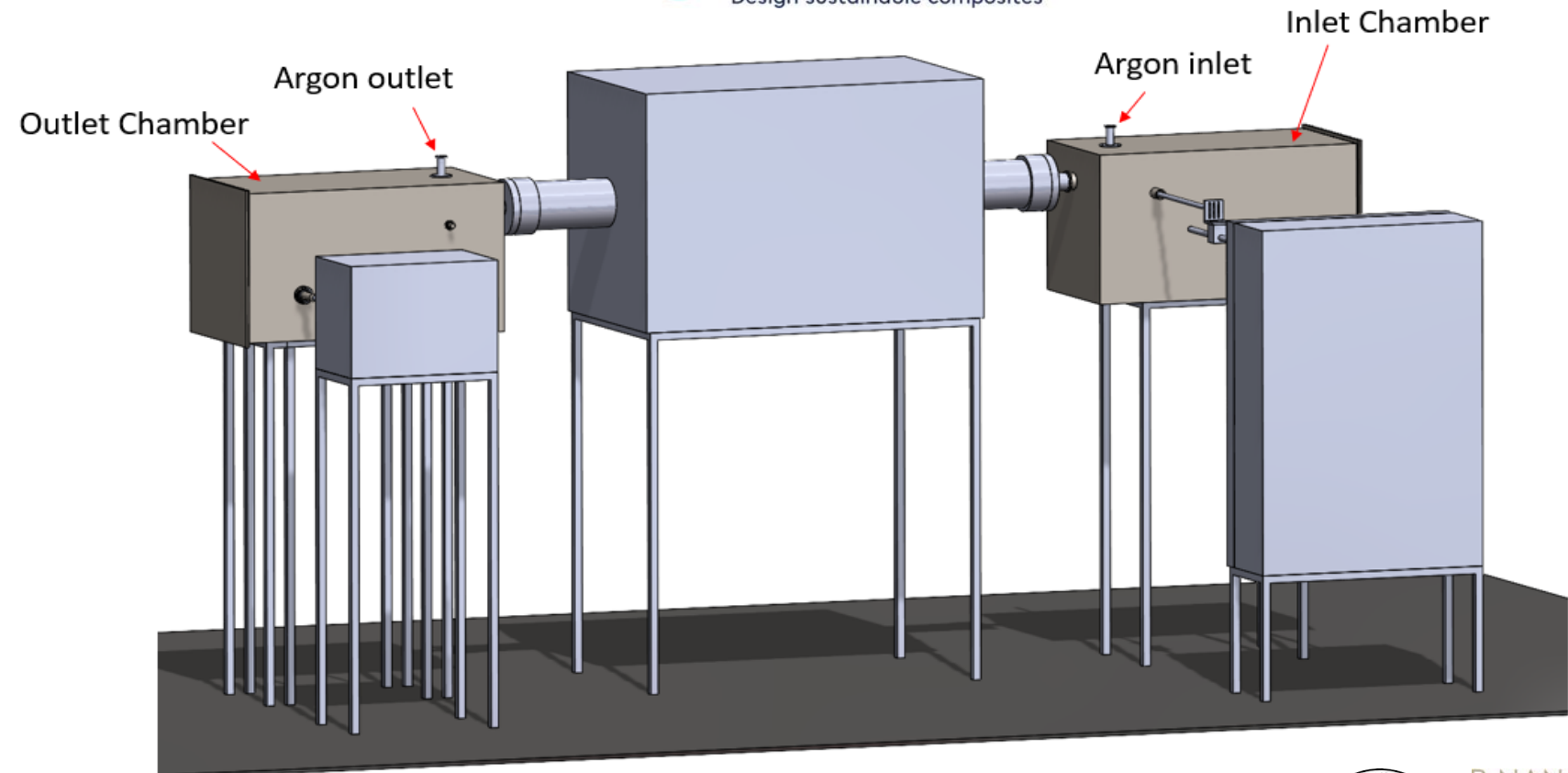
# Innovative pyrolysis pilot line in NTUA - SUSPENS



## Design Layout



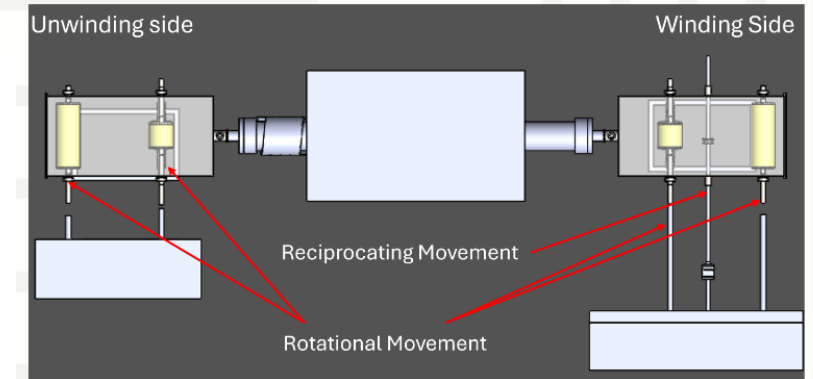
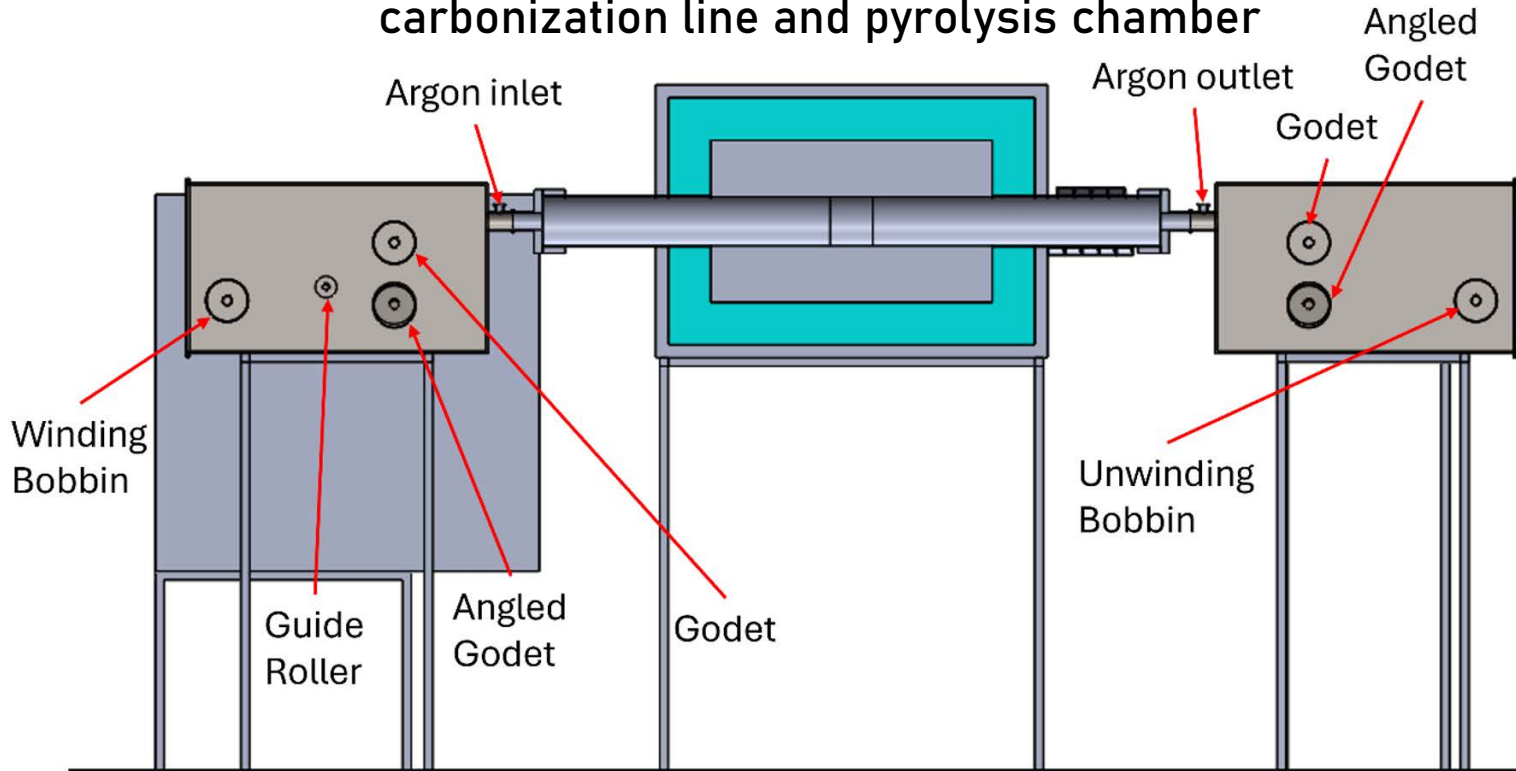
- ✓ Redesign of inlet and outlet system of CF carbonization furnace
- ✓ Manufacturing of inlet system and assembly
- ✓ Design optimization and manufacturing of pyrolysis chamber
- ✓ Connection between the two systems
- ✓ Measurement trials of emissions during pyrolysis at lab scale



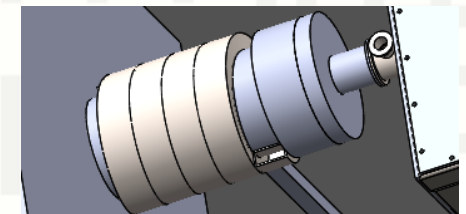
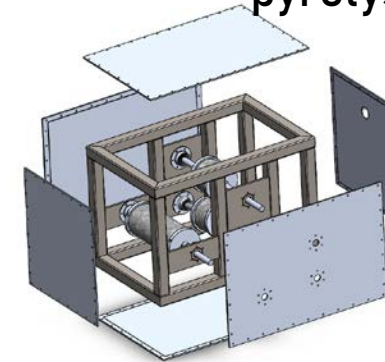
# Innovative pyrolysis pilot line in NTUA - SUSPENS



Modification of the connection between carbonization line and pyrolysis chamber

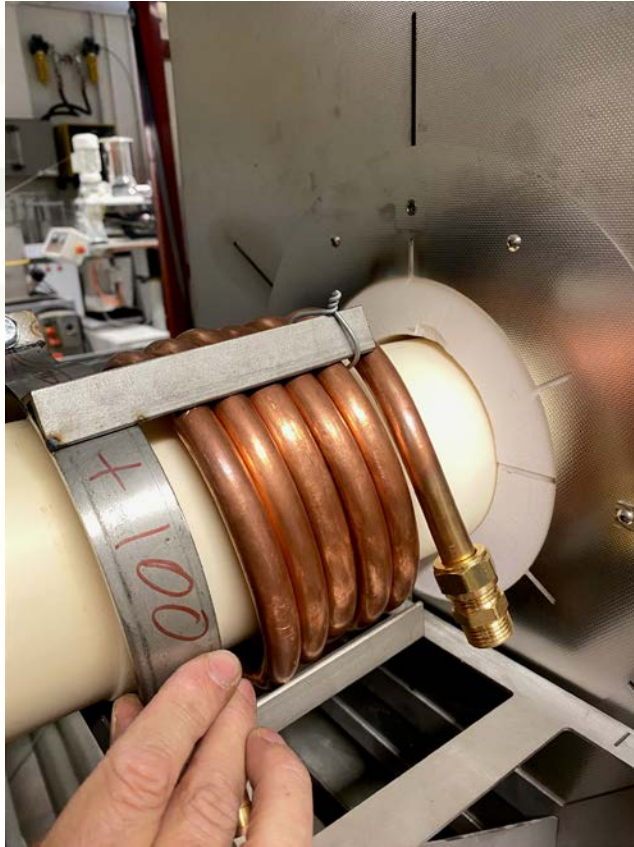


Spiral at the outlet of the furnace to heat external inert gas and deliver it in the pyrolysis chamber

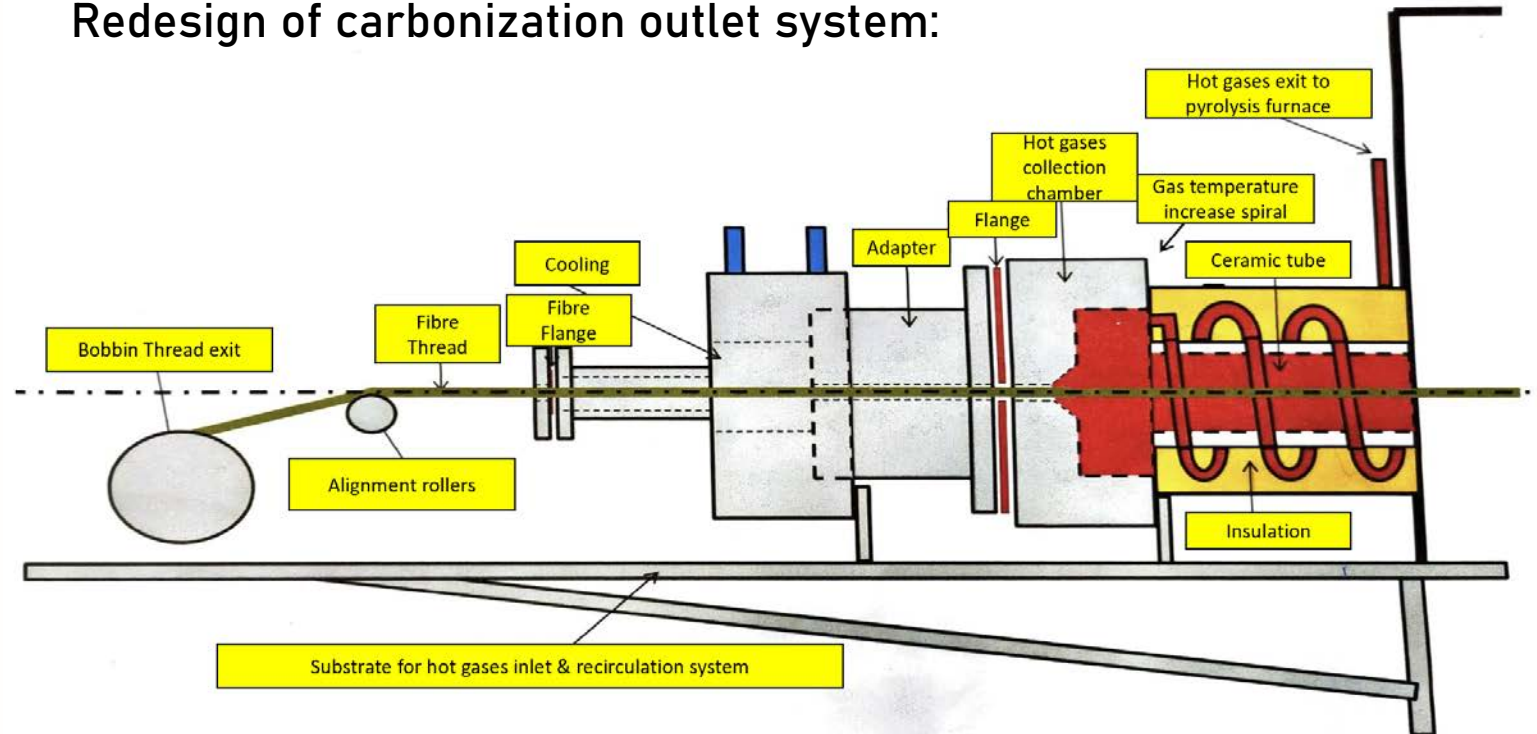




# Innovative pyrolysis pilot line in NTUA - SUSPENS



Redesign of carbonization outlet system:



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# Innovative pyrolysis pilot line in NTUA - SUSPENS



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# Innovative pyrolysis pilot line in NTUA - SUSPENS



## Pyrolysis chamber

- ✓ EoL CFRPs of 30X30 cm can be treated to obtain CF fabric patches
- ✓ 3 panels per batch can be treated simultaneously
- ✓ Chopped fibres can also be pyrolyzed or whole objects that can fit in the chamber
- ✓ Stand-alone operation (up to 800°C) or coupling with carbonization line for energy savings
- ✓ Collection of pyrolysis oils for further valorisation through trays



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# Innovative pyrolysis pilot line in NTUA - SUSPENS



Gas transferring  
from  
carbonization  
furnace to  
pyrolysis furnace



# Real Pyrolysis Experiment of CFRPs



Epoxy CRFPs (Carbon Fibre Reinforced Composites)

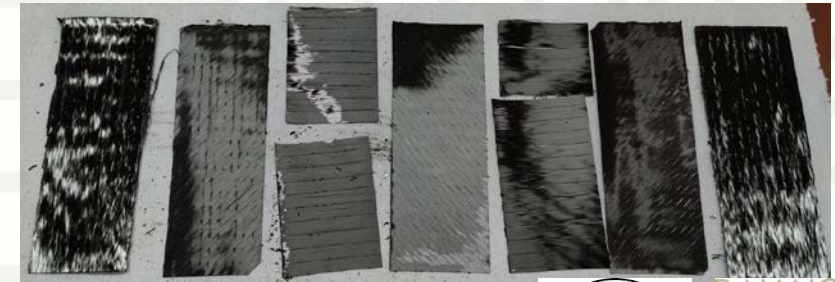
CFRPs  
pyrolysis

550 °C, 5h  
(N<sub>2</sub>)



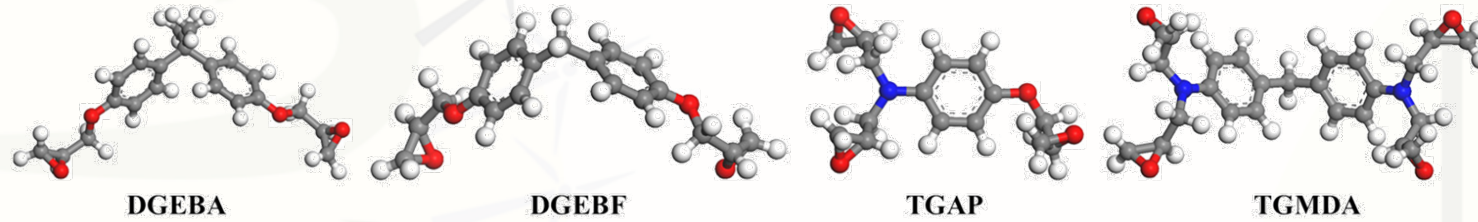
500 °C, 1h  
(Air)

Post pyrolysis  
CFRPs

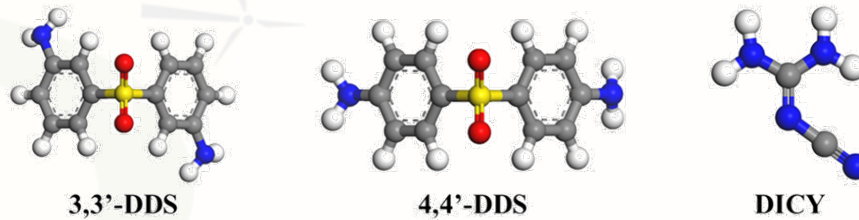




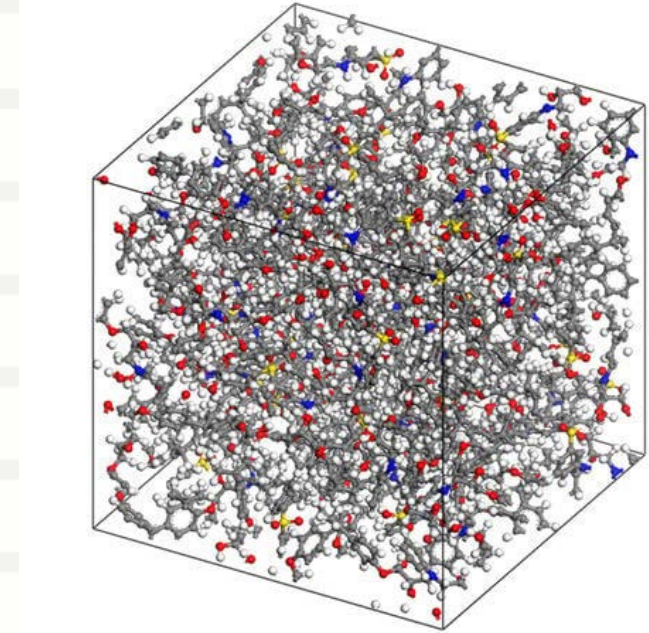
# Chemistry of Epoxy Composites



(a) Base resins

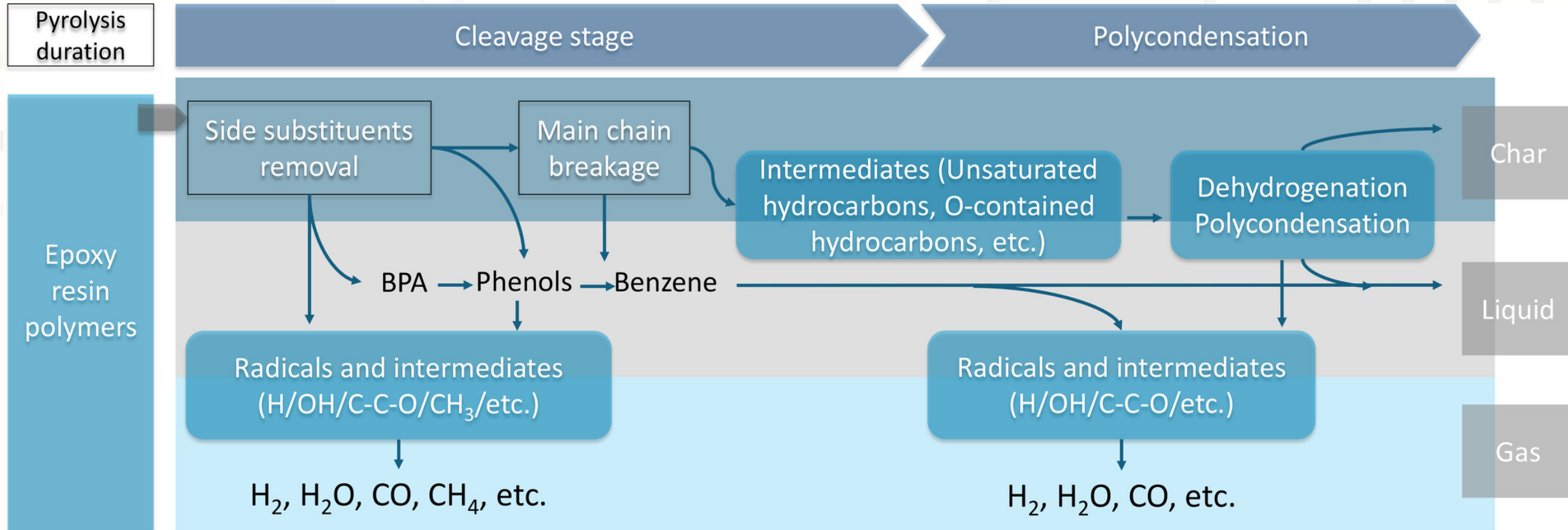


(b) Curing agents

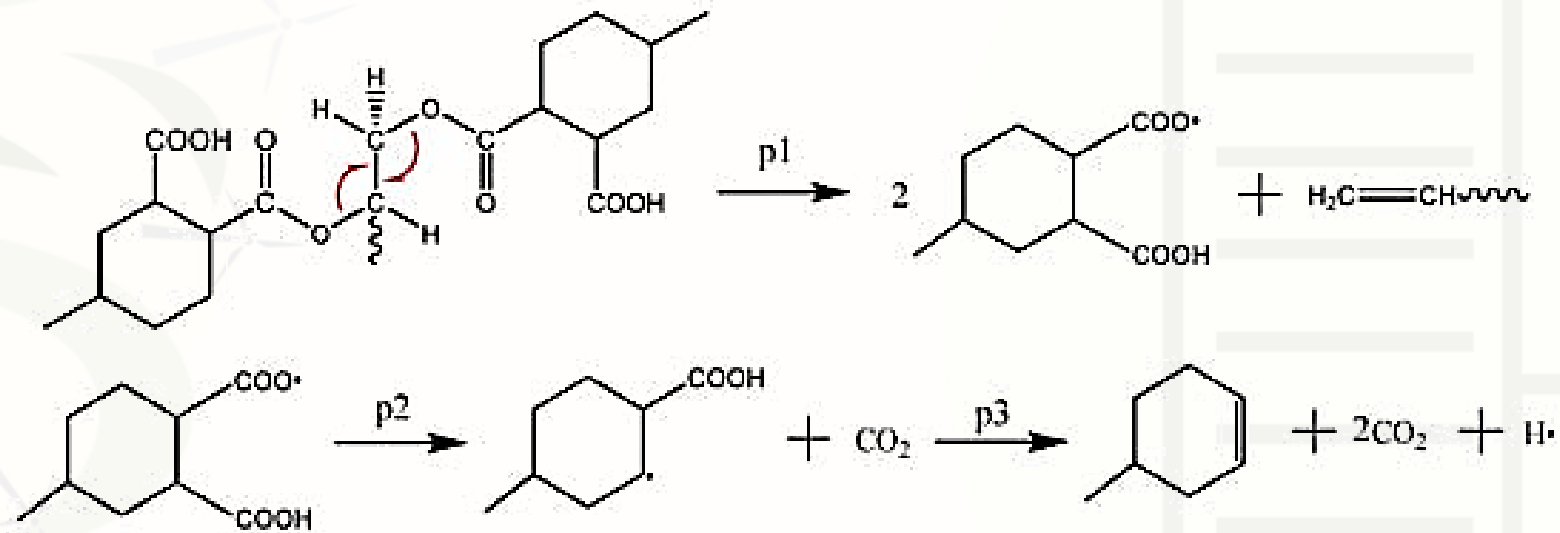


Compound containing glycidyl ether functionality, characterized by the presence of an active epoxy or oxirane ring capable of undergoing cross-linking processes when initiated by base reagents such as amine or thiol groups

# Pyrolysis Mechanism for Epoxy Composites

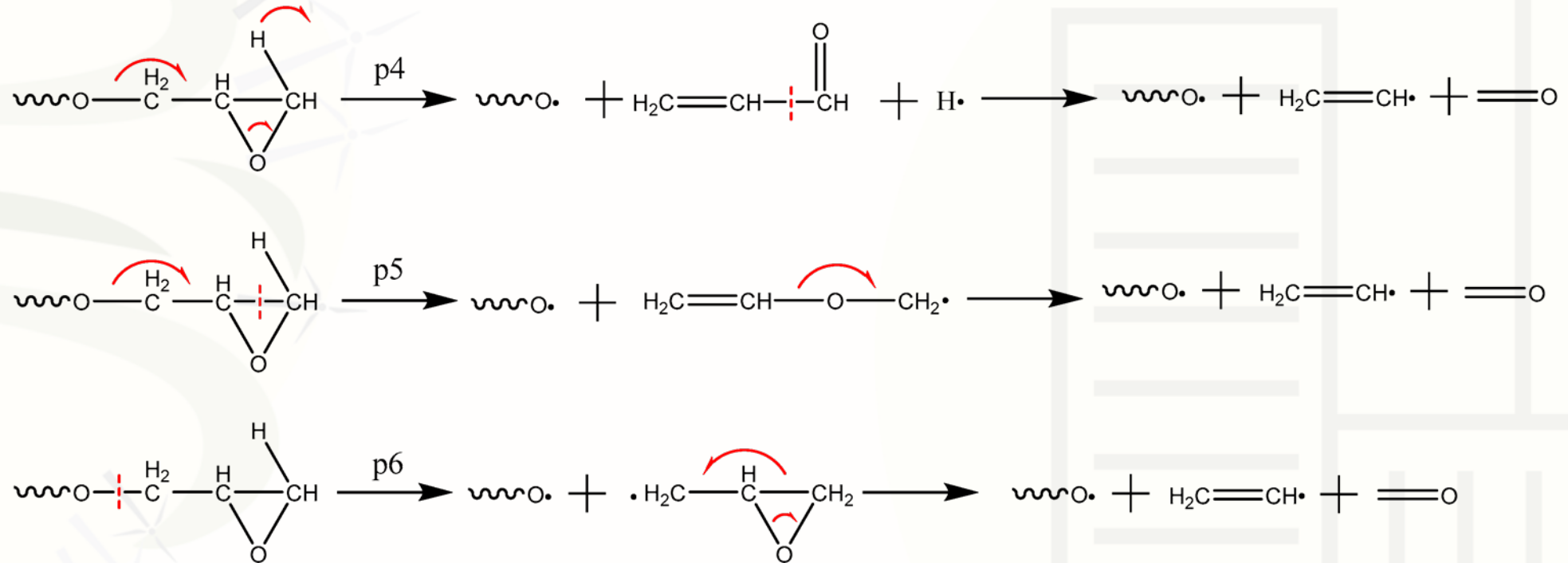


# Pyrolysis Mechanism for Epoxy Composites



The main mechanism of  $\text{CO}_2$  formation.

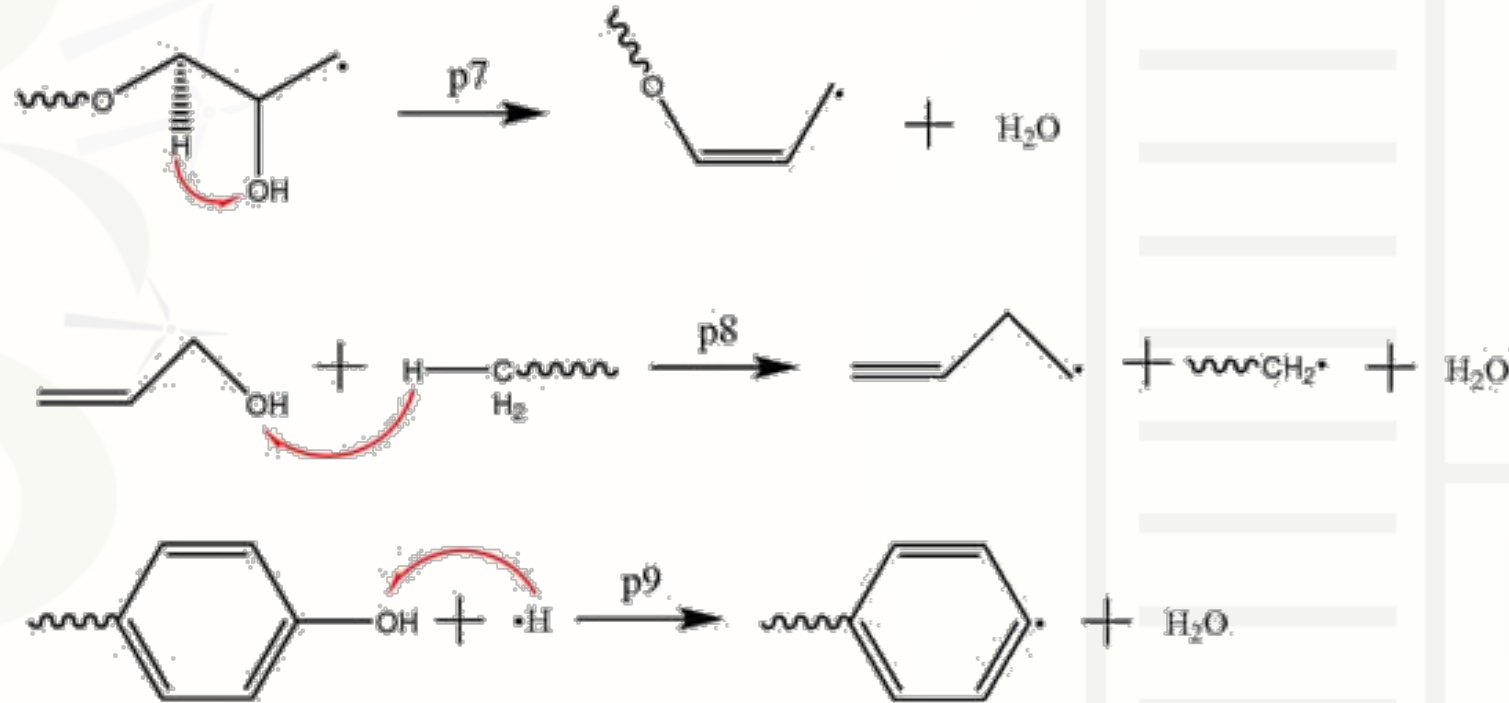
# Pyrolysis Mechanism for Epoxy Composites



The main mechanism of  $\text{CH}_2\text{O}$  formation.



# Pyrolysis Mechanism for Epoxy Composites



The main mechanism of H<sub>2</sub>O formation

# Real Pyrolysis Experiment of GFRPs



Shredded epoxy GFRPs (Glass Fibre Reinforced Composites)

GFRPs  
pyrolysis

550 °C, 5h  
(N<sub>2</sub>)



Pyrolyzed GFRPs

Post pyrolysis  
GFRPs

500 °C, 1h  
(Air)



Reclaimed  
GFs

# Pyrolysis Mechanism for Polyester Composites

## 1. Pyrolysis Oil (Condensable Liquids)

Typically the largest fraction (60% to 70% of the output), consisting of a complex mixture of aromatic and oxygenated organic compounds that can be used as a petrochemical feedstock or alternative to naphtha:

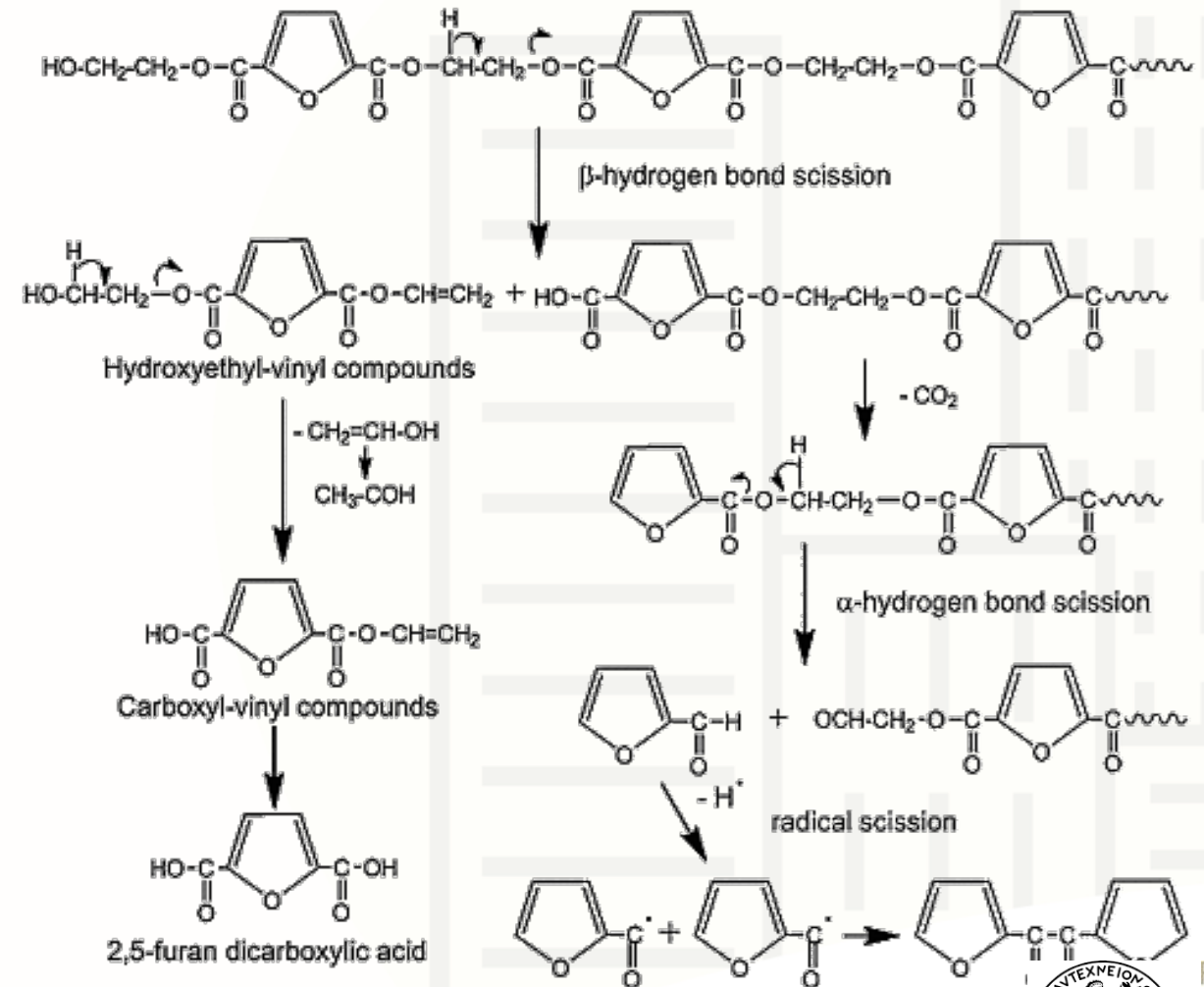
- Terephthalic acid (the primary monomer of PET)
- Benzoic acid
- Styrene
- Toluene
- Phenol and Acetone
- Acetaldehyde (a common thermal breakdown product)

# Pyrolysis Mechanism for Polyester Composites

## 2. Non-Condensable Gases

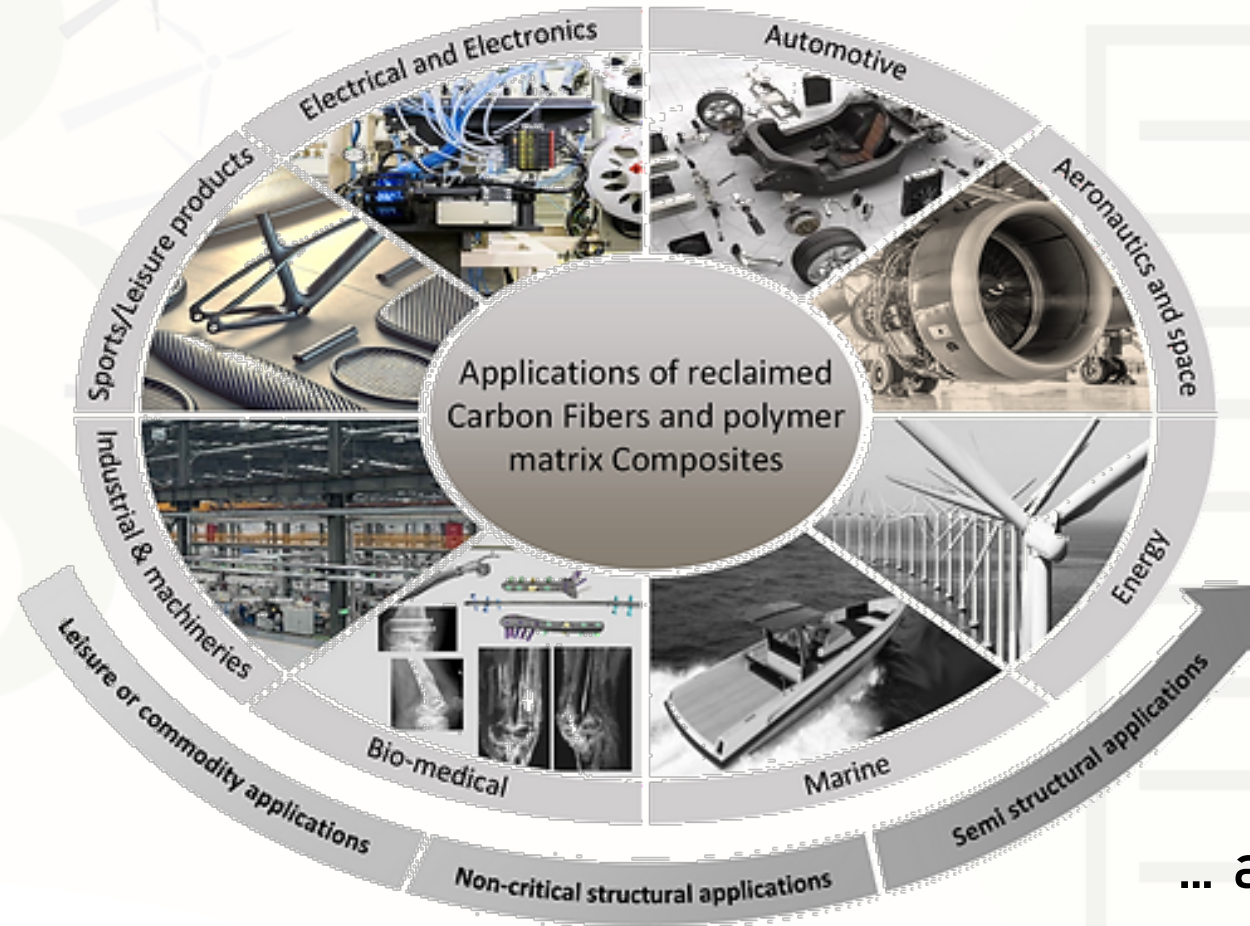
Accounting for 10% to 15% of the output, this gaseous fraction is highly oxygen-rich due to the polymer structure and provides a low-to-medium calorific value:

- Carbon dioxide CO<sub>2</sub>
- Carbon monoxide CO
- Hydrogen H<sub>2</sub>
- Methane CH<sub>4</sub>
- Light hydrocarbons





# Applications of reclaimed fibres



... and much more!

# Thank you!



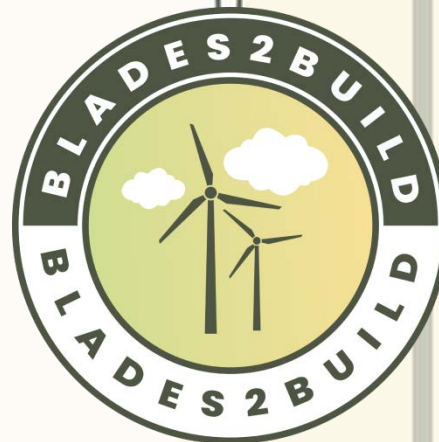
ktrompeta@chemeng.ntua.gr



<https://r-nano.gr/>



NTUA



[www.blades2build.com](http://www.blades2build.com)

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# BLADES2BUILD

Recycle, repurpose and reuse end-of-life wind blade composites – a coupled pre- and co-processing demonstration plant



## Composites Recycling through Solvolysis

Maria Modestou



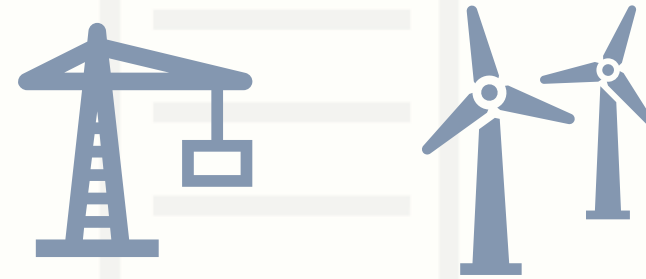
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# Introduction



End-of-Life



Global Production Volume: Exceeds 12 million metric tonnes annually.

Thermosets FRP products dominate the market, with global production volumes of more than 2.4 million tonnes per year.



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# Problem



Global FRP waste exceeds 2 million tonnes annually, with production residues and EoL products like WTBs and aircrafts.

Because thermoset resins make them difficult to process, less than 20% of FRPs are currently recycled.



Up to 40% of FRP material are wasted during the initial manufacturing and trimming processes.

The U.S. & Europe collectively by 2050 will have more than 800,000 tonnes of waste from aviation & WTBs.

The vast majority of FRP waste is currently sent to landfills or incinerated, which has significant environmental and economic drawbacks.



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*Fiber-reinforced Plastic (FRP) Recycling - Market Share Analysis, Industry Trends & Statistics, Growth Forecasts (2025 - 2030)*

<https://www.researchandmarkets.com/reports/5025766/fiber-reinforced-plastic-frp-recycling>





# Goal



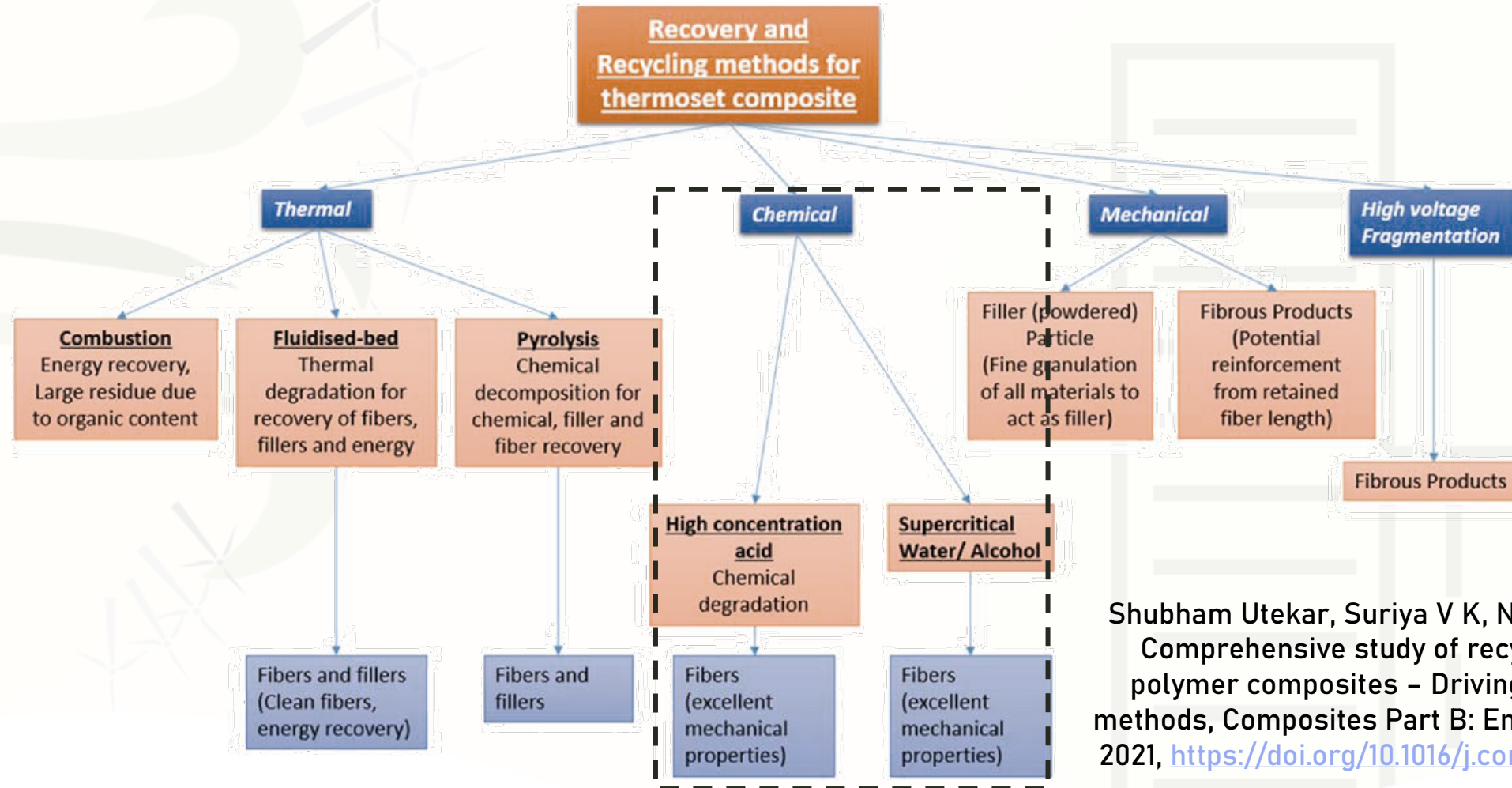
*"Recover the fibres in their optimal state for subsequent reuse in the fabrication of new materials"*



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# Classification of recovery and recycling technologies for thermosetting polymer composites



Shubham Utekar, Suriya V K, Neha More, Adarsh Rao,  
Comprehensive study of recycling of thermosetting  
polymer composites – Driving force, challenges and  
methods, Composites Part B: Engineering, Volume 207,  
2021, <https://doi.org/10.1016/j.compositesb.2020.108596>.



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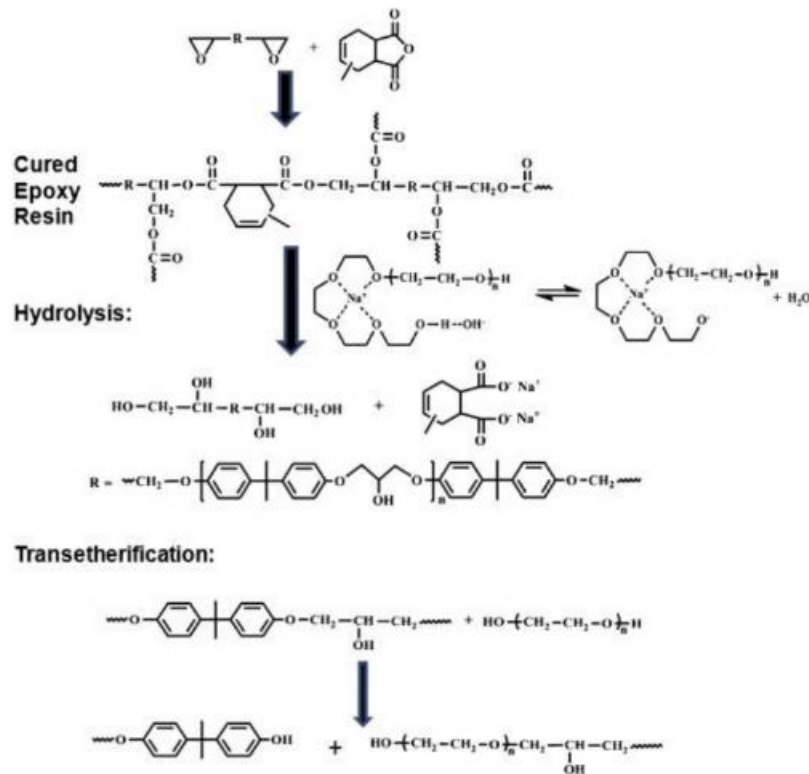




# Mechanism of Solvolysis

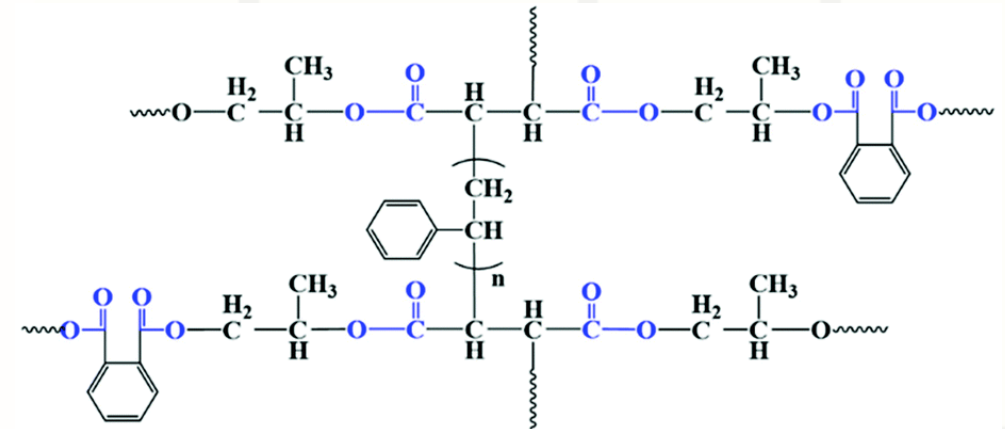
## Epoxy Resin

Transesterification through a Nucleophilic Substitution



## Polyester Resin

Transesterification through a Nucleophilic Substitution





# Comparison of Chemical Processes

## Low Temperatures and Ambient Pressure

### Pros

- Milder operating conditions
- Lower energy demand and simpler equipment

### Cons

- Often requires catalysts, acids or organic solvents
- Longer reaction times
- Solvent recovery and waste treatment needed
- May give incomplete matrix removal

## Near- or Super-Critical Conditions



### Pros

- Faster and more efficient matrix decomposition
- Improved solvent penetration and reactivity
- Can reduce the need for catalysts or toxic solvents
- Cleaner fibre recovery possible

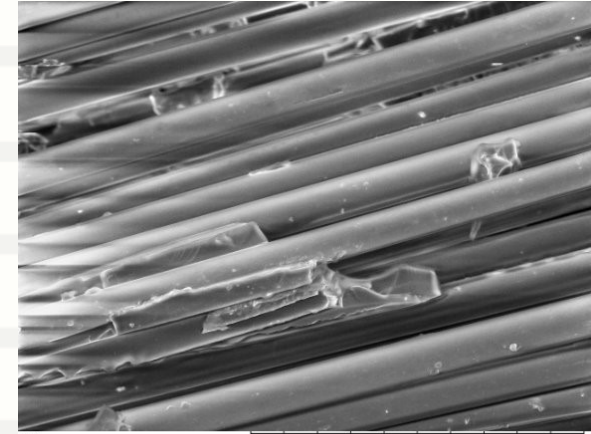
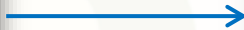
### Cons

- High temperature and pressure requirements
- Higher energy demand and equipment cost
- More complex scale-up and safety requirement

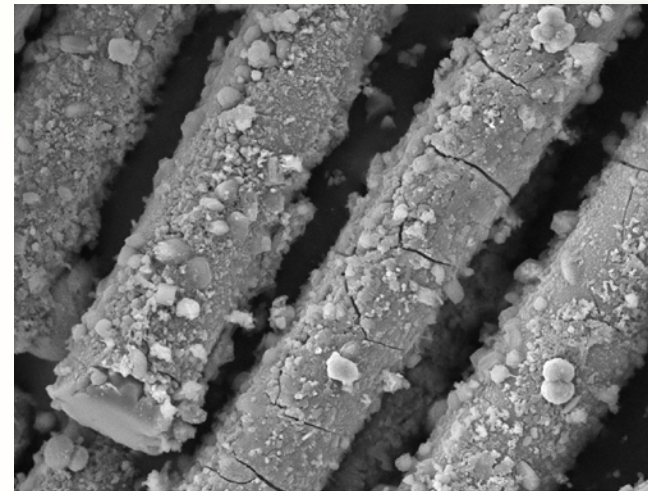
# Low Temperatures and Ambient Pressure



Upscaling



Test2048 2023/03/14 NL UD7.2 x500 200 µm  
Hitachi TM3030Plus



Test2438 2023/05/25 NMUD7.5 x1.5k 50 µm  
Hitachi TM3030Plus



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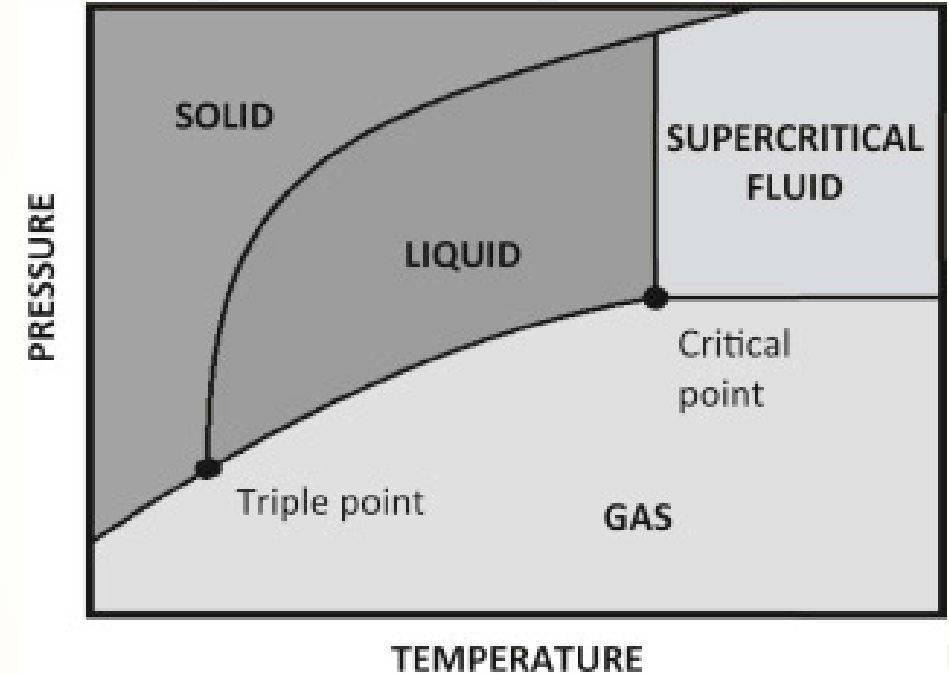
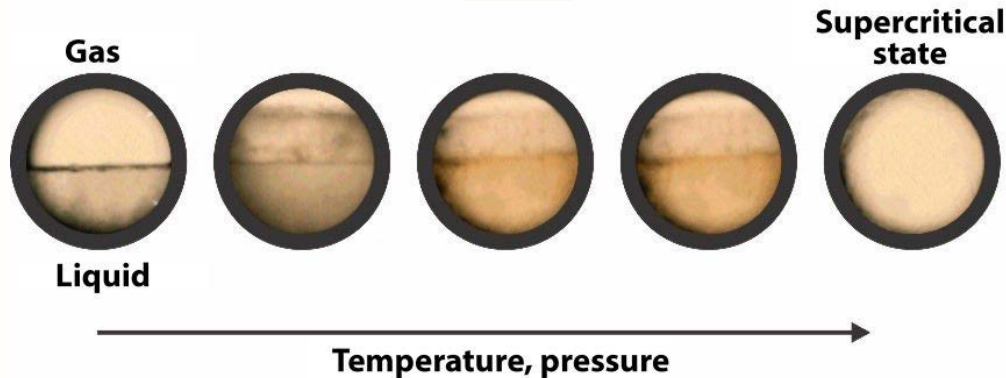
# Near- or Super-Critical Conditions

## Supercritical Fluids (SCFs):

- Fluids above their critical temperature and pressure
- Unique properties: low viscosity, high diffusivity, tunable solvation power.
- Environmentally friendly & effective in decomposing polymers.

SCW ( $T_c = 374.14\text{ }^\circ\text{C}$ ;  $p_c = 221.2\text{ bar}$ )

SCA ( $T_c = 235\text{ }^\circ\text{C}$  and  $p_c = 46.9\text{ bar}$ )

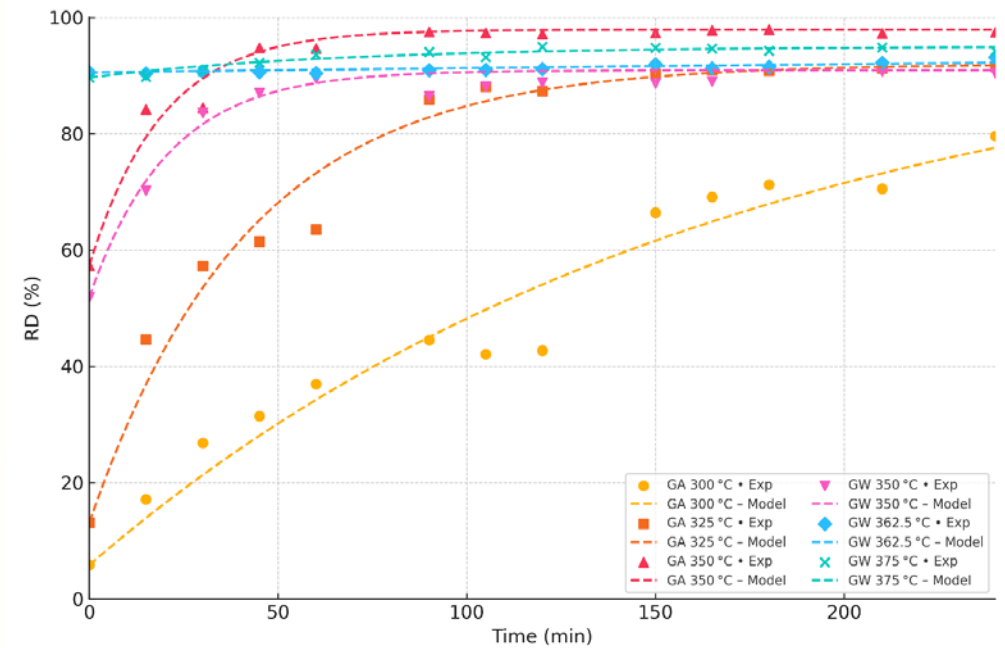




# Near- or Super-Critical Conditions



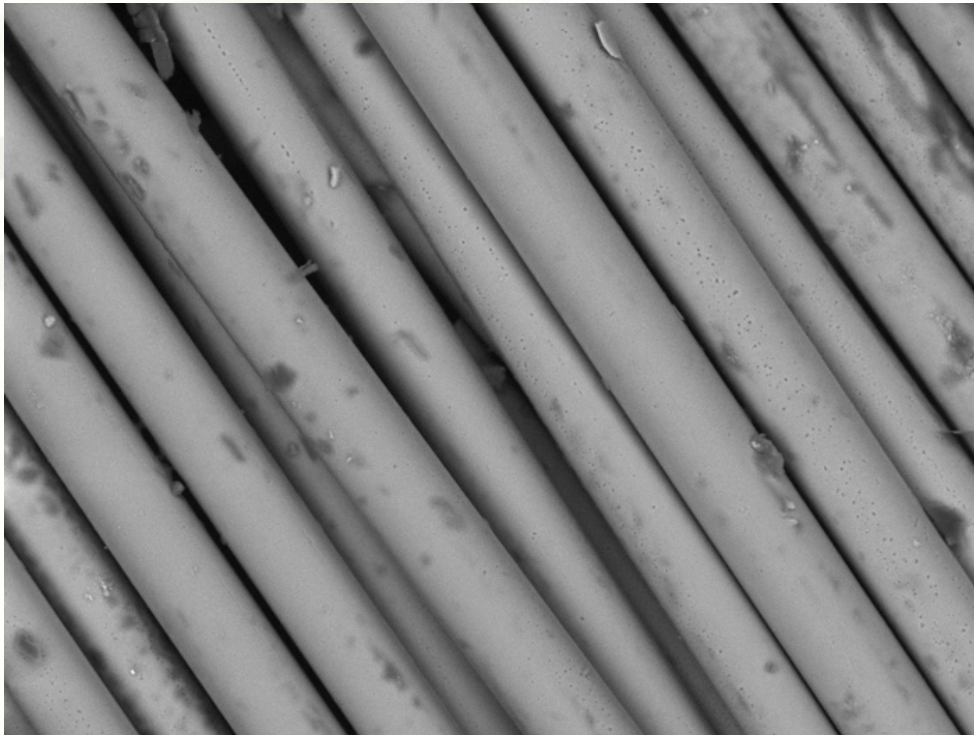
Upscaling





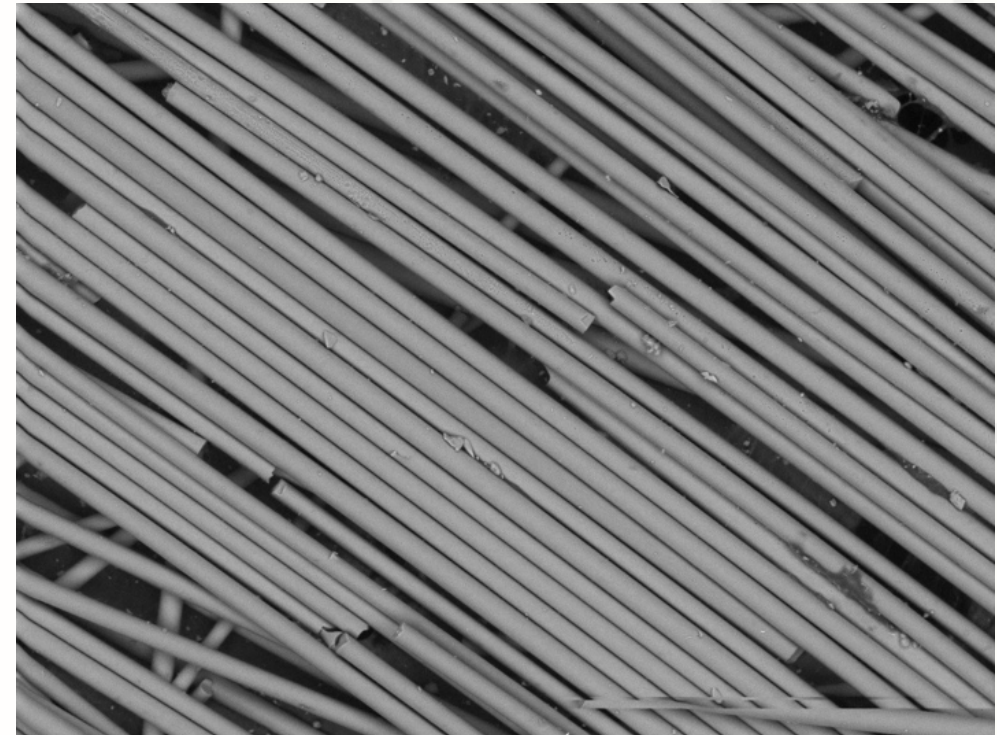
# Near- or Super-Critical Conditions

## Cleaner Fibres



Test3524 2025/06/26 NL D7.9 x600 100 µm

Hitachi TM3030Plus



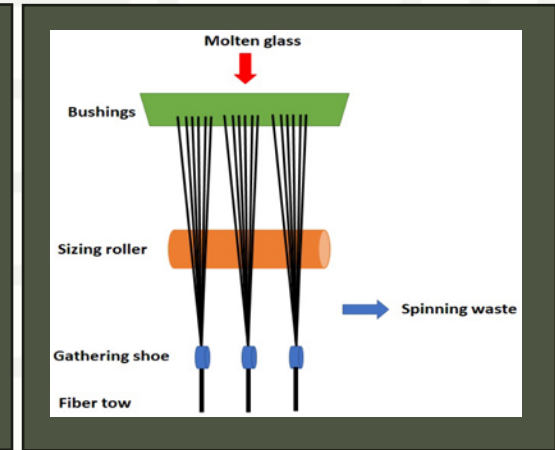
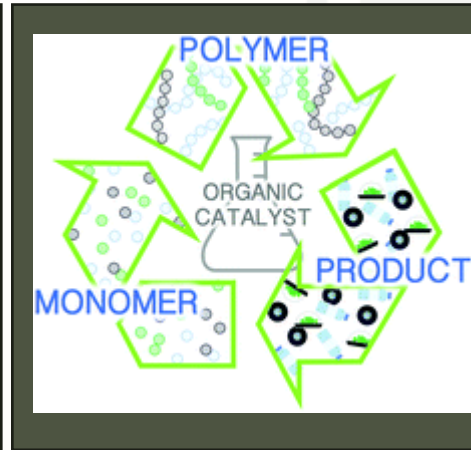
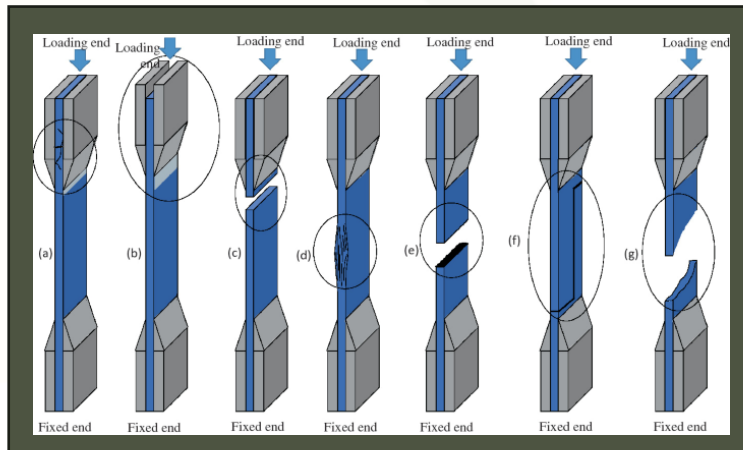
Test3577 2025/06/27 NL D8.0 x250 300 µm

Hitachi TM3030Plus

# Future Goals



- o Evaluate the mechanical properties of recovered fibres in new composite applications or by fibre characterization techniques.
- o Explore the valorization of liquid-phase by-products for repolymerization or new material synthesis.
- o Assess the processes through LCA & LCC.
- o Investigate fibre resizing and surface treatments for better resin compatibility.



# Thank you!



modestou@chemeng.ntua.gr



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R Nano NTUA

## Questions?



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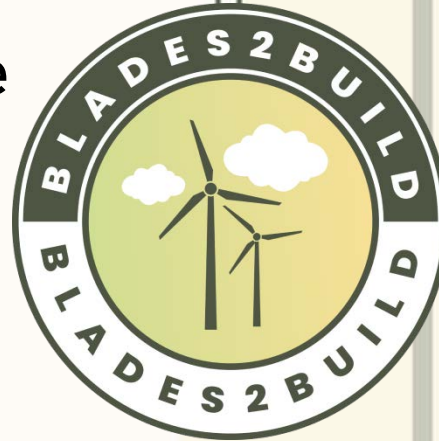


# BLADES2BUILD

Recycle, repurpose and reuse end-of-life wind blade composites – a coupled pre- and co-processing demonstration plant

## *Lecture 1:*

## Carbon Fibre Production & Surface Treatments





# What Are Carbon Fibers?

## o Definition:

Carbon fibers are high-performance fibers composed predominantly of carbon atoms (>90% C), arranged in a graphitic or turbostratic structure. They exhibit exceptional strength-to-weight and stiffness-to-weight ratios.

## o Key Characteristics:

Lightweight ( $\rho \approx 1.6\text{--}2.0 \text{ g/cm}^3$ )

High tensile strength (up to 7 GPa)

High Young's modulus (up to 900 GPa)

Chemically inert and thermally stable

## o Applications:

Aerospace: fuselage, wings, turbine blades

Automotive: lightweight frames, panels

Sports Equipment: bicycles, rackets, skis

Civil Engineering: structural retrofitting, concrete reinforcement

Energy Sector: wind turbine blades, hydrogen tanks

*o Carbon fibers are used primarily in composite form (CFRPs) to achieve superior mechanical performance while reducing weight.*

# Carbon Fiber Production: General Overview

## Precursors:

**PAN (Polyacrylonitrile):** ~90% of today's production; good balance of strength and cost. **or Pitch (Mesophase pitch):** High modulus, excellent thermal conductivity **or Rayon:** Historically used; lower performance, now obsolete.

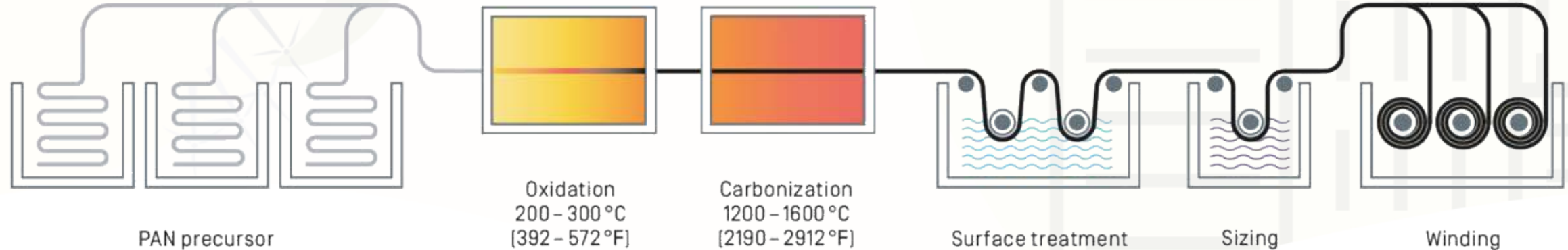
## Production Steps:

1. **Stabilization:** Oxidative crosslinking at ~200–300°C in air.
2. **Carbonization:** Pyrolysis at 1000–1500°C in inert atmosphere (N<sub>2</sub>/Ar).
3. **Graphitization (optional):** >2500°C for high crystallinity (pitch-based).
4. **Surface Treatment:** To enhance fiber-matrix bonding.
5. **Sizing Application:** Protective coating (polymeric or reactive) to preserve integrity during handling and improve compatibility with resins.

## Process Parameters Influence:

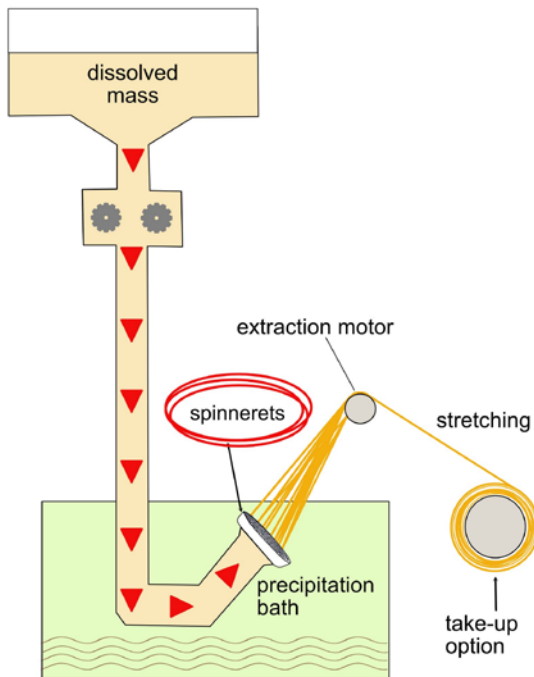
- Final modulus and strength.
- Degree of graphitic ordering.
- Surface chemistry and fiber-matrix adhesion.

*The choice of precursor and thermal treatment directly determines the final fiber properties.*



# Precursor fiber spinning

## wet spinning process



## Why this step matters

- PAN is usually wet- or dry-jet wet-spun; pitch-based precursors are more compatible with melt spinning.
- Spinneret geometry, coagulation and draw ratio set filament diameter, molecular orientation and defect population.
- Downstream heat treatment can only refine what spinning has already created; it cannot erase poor precursor uniformity.



Example of steam stretching / drawing equipment

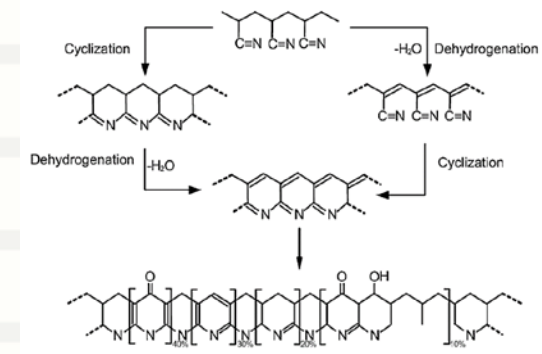
## Why PAN is not the “simple extruder” case

PAN begins cyclization before it can be cleanly melt-processed, which is why solution spinning dominates conventional PAN-precursor production.

# Stabilization makes PAN infusible before high heat

## What happens in this stage

- Usually performed in air for PAN, roughly in the 200–300 °C range and often under tension.
- Cyclization, oxidation and dehydrogenation convert the linear precursor into a ladder-like, infusible structure.
- This step is strongly exothermic and must be controlled carefully to avoid radial gradients, skin–core mismatch and defect formation.
- The goal is not just a color change: the fiber must survive carbonization without melting or fusing.



## Why it matters industrially

Oxidation / stabilization is often the largest footprint and most energy-demanding step in the line, so quality and economics both hinge on this stage.



# Carbonization and graphitization tune order, strength and modulus



## Carbonization

- Done in inert gas (typically  $N_2$  or Ar) so the stabilized fiber pyrolyzes instead of burning.
- Low-temperature and high-temperature carbonization progressively remove H, O and N while carbon planes become more ordered.
- Mass is lost, diameter shrinks and defects such as voids, heteroatom residues or surface flaws can appear if the route is not well controlled.

### Strength-oriented grades

Usually stop at lower heat-treatment severity and retain a better balance of strength and strain to failure.

### High-modulus grades

Use higher-temperature treatment / graphitization to increase ordering and modulus, but often at the expense of strength and toughness.



Industrial furnace example

Graphitization is therefore optional: it is a property-selection step, not a universal requirement.



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# Surface treatment and sizing are essential, not optional

## Surface treatment

- Carbonized fiber is chemically inert and often bonds poorly to resin unless its surface is modified.
- Electrochemical oxidation is a common route because it can introduce polar surface groups and improve wettability and interfacial adhesion.
- Over-treatment is risky: roughness and active chemistry help bonding only if new defects are not created.



## Sizing and winding

After washing and drying, a thin sizing layer is applied for protection, handling and matrix compatibility. The product usually leaves the line as tow packages and is later converted into fabrics, braids, tapes or prepregs.

# Surface Treatment

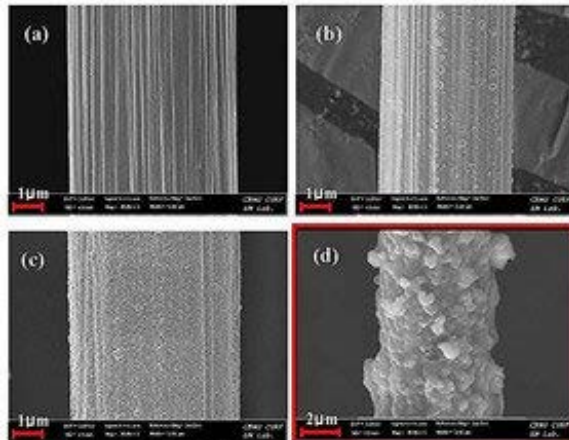
When a load is applied to the composite, stress is transferred to the fibers through the matrix. A weak bond between the matrix and the fiber leads to degraded mechanical properties



## Surface CF treatment

Too powerful bond → Brittle and fragile composite

Weak treatment → low durability composite



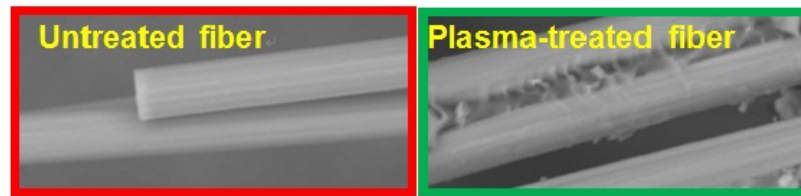
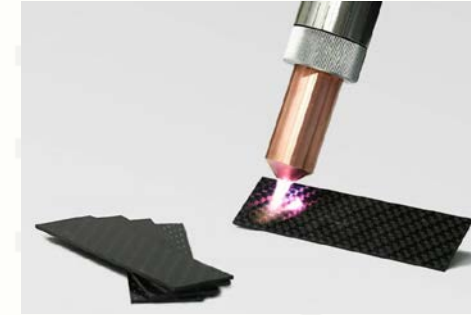
ideal adhesion  
fibre - matrix

# Surface Treatment



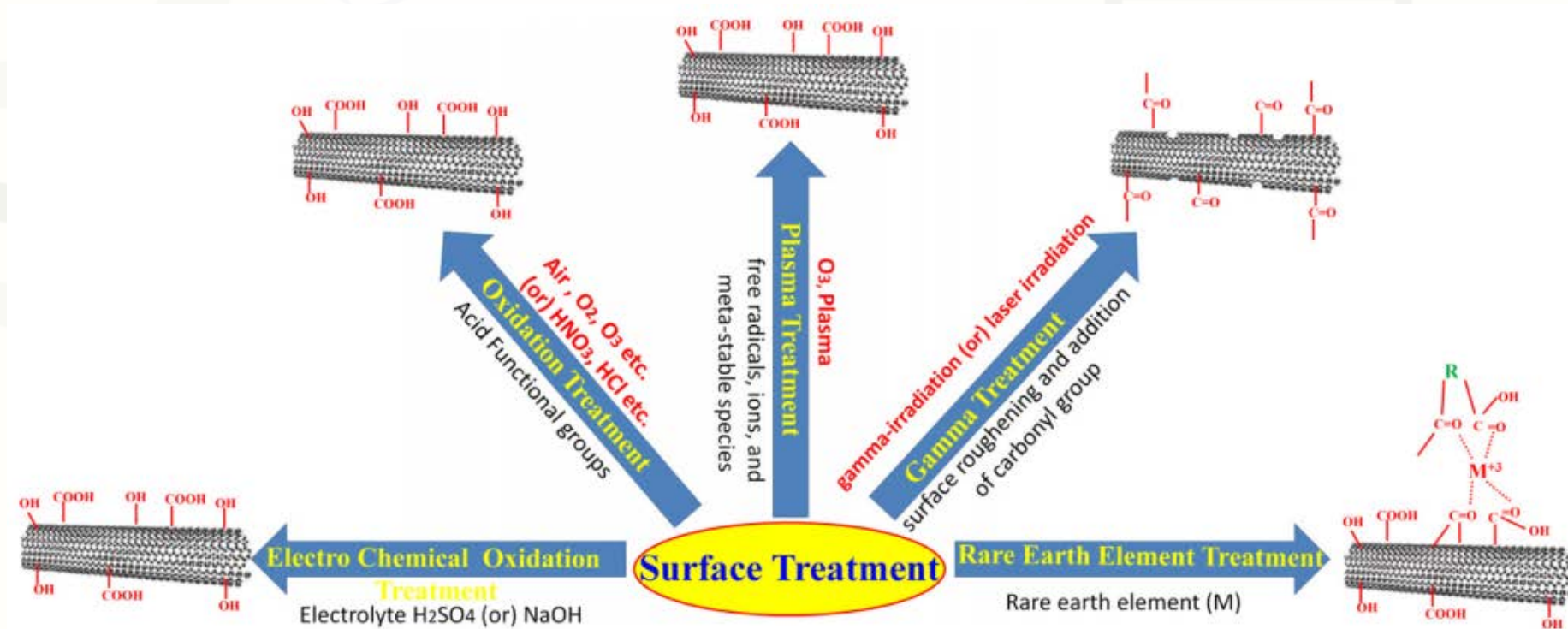
A successful surface treatment is bound to:

- a. Increase the wettability of the fiber surface by the matrix resin, often through the removal of weak boundary layers such as contaminants or adsorbed gas molecules.
- b. Enhance interfacial interactions between the fiber and the matrix, including van der Waals forces, thereby improving wetting and adhesion at the interface.
- c. Promote mechanical interlocking between the fiber and the matrix, for example by creating surface features or porosity into which the resin can penetrate.
- d. Increase the surface roughness, leading to a higher effective surface area and improved mechanical interlocking at the fiber-matrix interface.
- e. Provide or support the application of a thin coupling-agent layer that can chemically bond to both the fiber and the matrix, acting as a molecular bridge between them.





# Surface Treatment



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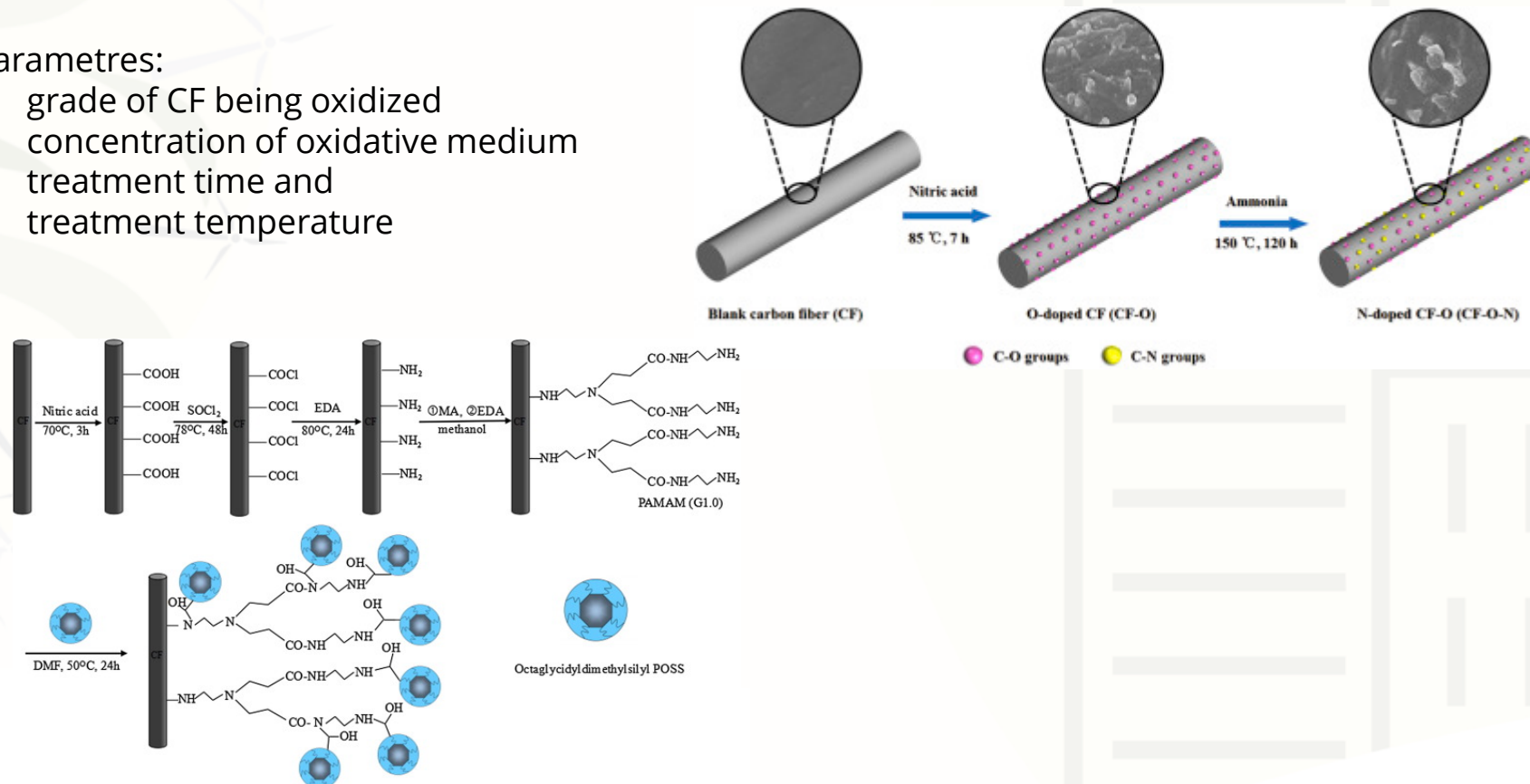
# Oxidation



The basic means of achieving oxidation is through gases (by air, oxygen, ozone, etc.) or solutions (by HNO<sub>3</sub>, hydrochloric acid, etc.).

Parametres:

- grade of CF being oxidized
- concentration of oxidative medium
- treatment time and
- treatment temperature



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# Electrochemical oxidation

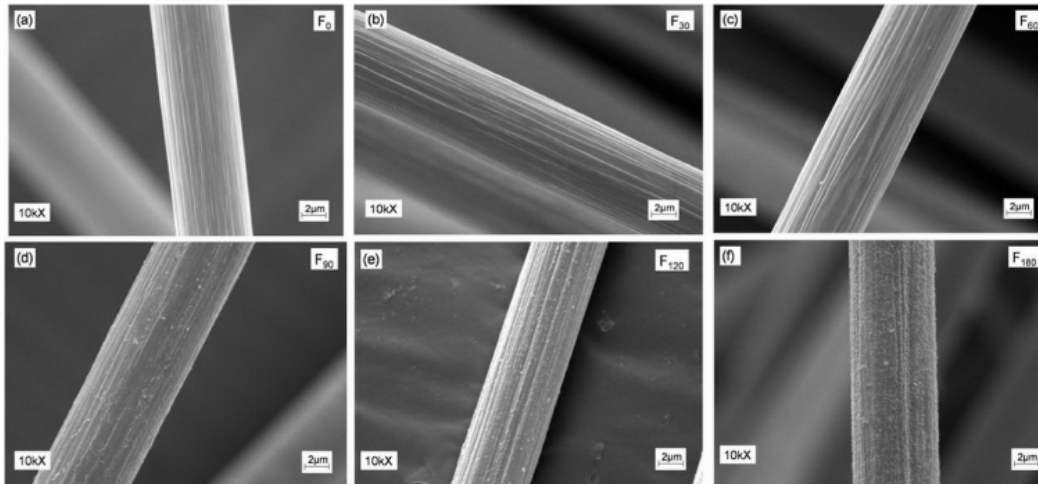
Electrochemical oxidation is used the most often in industrial practice. The oxidation can be carried out in various electrolytes under the most diverse conditions.

Parameters:

- type of electrolyte,
- its pH,
- the polarization potential,
- the duration of the treatment and
- the morphology of the surface

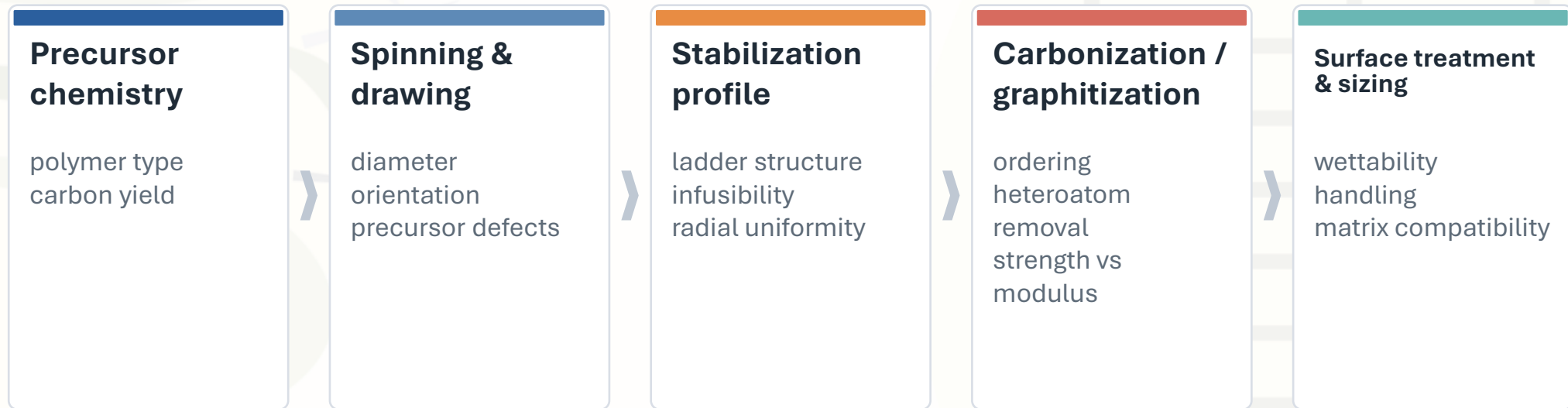
$\text{H}_2\text{SO}_4$  or  $\text{NaOH}$

- Oxidation may occur in acidic or basic electrolytic solutions
- Galvanostatic or potentiostatic
- Most commonly used  $\text{NaOH}$ ,  $\text{HNO}_3$ ,  $\text{H}_2\text{SO}_4$ ,  $\text{H}_3\text{PO}_4$ ,  $\text{KNO}_3$  and ammonium salts



Increase in the number of surface functional groups in the fibers

# Process → structure → property map





# Production line architecture: why the factory is long



## 1. Stabilization needs residence time

Multiple oven zones and controlled airflow are used because chemistry and heat release must be uniform across the whole tow band.

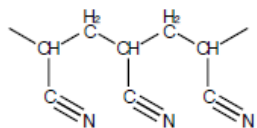
## 2. Carbonization needs atmosphere control

The fiber then enters inert furnaces, often in more than one temperature regime, while tension and transport remain tightly controlled.

## 3. Post-treatment is still production

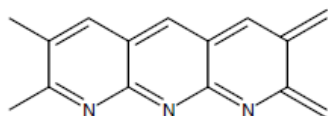
Surface treatment, drying, sizing and packaging are part of the line because the fiber must leave compatible with its next manufacturing step.

# Microstructure: Crystallinity & Graphitic Structure



Polyacrylonitrile (PAN) acrylic fiber

200~300°C

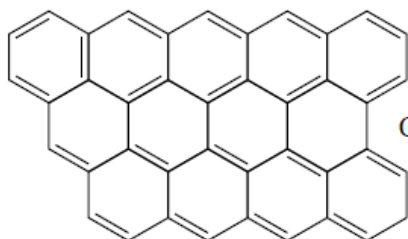


1000~2000°C



Carbonized yarn

2000~3000°C



Graphitized yarn

## Core Structure:

CFs are composed of stacked graphene-like layers of carbon atoms arranged in hexagonal arrays. These layers are aligned along the fiber axis, providing stiffness and strength in that direction.

## Turbostratic Structure:

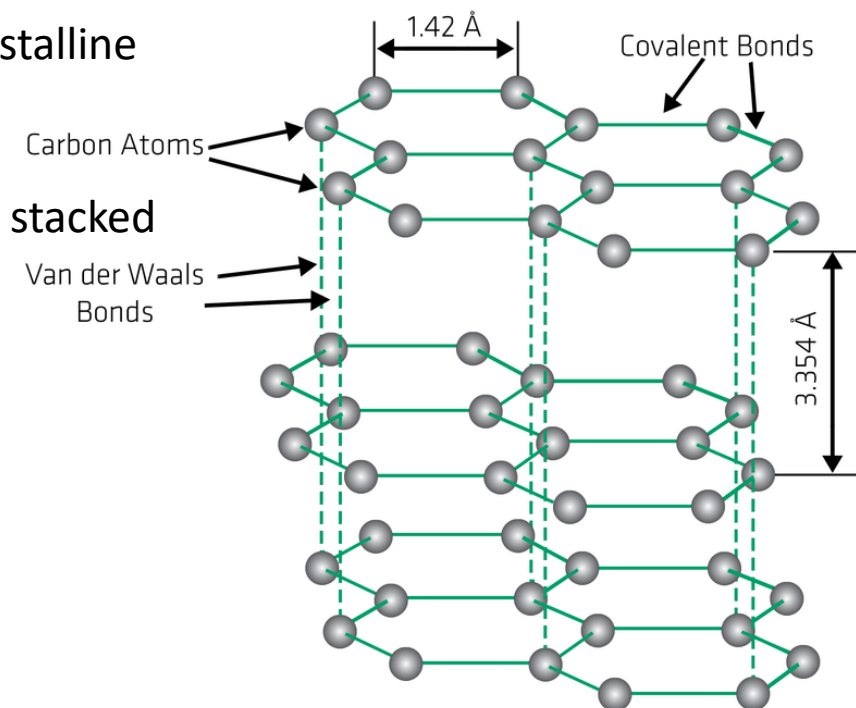
Most carbon fibers do not possess a perfect crystalline graphite structure. Instead, they exhibit a turbostratic arrangement, where:

- Graphene layers are misaligned or randomly stacked
- The interlayer spacing is greater than in ideal graphite (~3.44 Å vs 3.35 Å)
- No long-range order along the c-axis
- (perpendicular to layers).

## Degree of Crystallinity:

A critical factor determining performance. Higher crystallinity means:

- Better load transfer between layers.
- Higher Young's modulus and stiffness.
- Greater electrical and thermal conductivity.





# Microstructure: Crystallinity & Graphitic Structure

## Low Temp Carbonization (~1000–1500°C):

Fibers remain partially disordered (turbostratic).

Better tensile strength due to more defects that inhibit crack propagation.

## High Temp Graphitization (>2500°C):

Increased **crystalline order and alignment** of graphene planes.

Higher modulus, but more brittle.

## Microstructural Parameters:

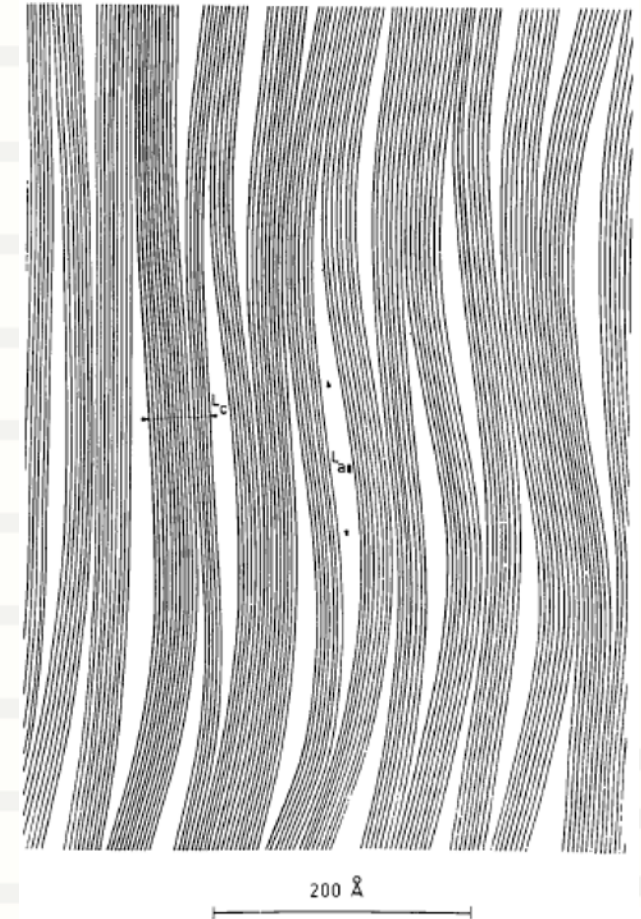
$L_a$  (in-plane crystallite size) and  $L_c$  (stacking height) used to quantify ordering. These can be estimated using **XRD** (X-ray diffraction) or **Raman spectroscopy**.

## Anisotropy:

Properties differ significantly **along** vs **across** the fiber axis.

Axial direction: High modulus, high conductivity.

Radial direction: Poorer load transfer, lower conductivity.



*Crystallinity and anisotropy are defining characteristics of carbon fibers and can be tuned through precursor choice and processing.*

# Mechanical Properties of CFs

## Tensile Strength

Typically ranges from **2.5 to 7.0 GPa** depending on fiber type.

**PAN-based HS fibers:** up to 5.5–6.0 GPa while **Pitch-based fibers:** lower strength (~2.5–3.5 GPa) due to brittleness.

Influenced by: Surface flaws and voids. Degree of graphitization. Fiber diameter (thinner = fewer flaws, higher strength).

## Young's Modulus

Stiffness or resistance to elastic deformation.

Varies between **200 GPa (standard PAN)** to **~900 GPa (pitch-based)**.

Directly related to **crystallinity** and **graphene plane alignment**.

## Strain-to-Failure

Low elongation: typically **~1–2%**.

PAN-based fibers offer higher ductility vs pitch-based.

Important for **impact or cyclic loading** environments.

## Key Points

Carbon fibers are **anisotropic**: exceptional strength along fiber axis, weak transverse.

**Microstructural defects** (voids, misalignment) reduce performance.

**Fiber-matrix interface** plays a major role in composite mechanical performance.

## Property

Tensile Strength (GPa)

Young's Modulus (GPa)

Strain to Failure (%)

Fracture Behavior

## PAN-Based (HS/IM)

4–6

200–350

~1.5

Tougher, less brittle

## Pitch-Based (HM)

2.5–3.5

500–900

~0.5–0.8

Brittle, low toughness

*Optimizing mechanical properties requires control over precursor, processing temperature, and surface treatment.*



# Thermal Conductivity & Anisotropy

## Thermal Conductivity in Carbon Fibers

Carbon fibers exhibit **high thermal conductivity along the fiber axis**, due to the ordered arrangement of  $sp^2$  carbon atoms in **graphitic domains**.

Typical range:

- **PAN-based CFs:** 5–10 W/m·K (axial), <1 W/m·K (transverse)
- **Pitch-based CFs:** up to **400–1000 W/m·K** (axial)

## Anisotropy

Carbon fibers are **highly anisotropic** in thermal properties:

- **Axial direction (||):** high thermal conductivity due to phonon transport along graphitic layers.
- **Radial direction (⊥):** much lower conductivity due to interlayer resistance and disorder.

Anisotropy ratio (axial/transverse) can exceed **100:1** in highly graphitized pitch-based fibers.

## Effect of Structure

**Higher graphitization** → better phonon alignment → increased conductivity.

**PAN-based fibers** have more turbostratic structure → lower conductivity.

**Pitch-based fibers:** highly aligned → used as **thermal interface materials, brake pads, heat spreaders**.

# Electrical Conductivity of CFs

## Nature of Electrical Conductivity

Carbon fibers are **electrically conductive**, especially along the fiber axis.

Conductivity arises from the **sp<sup>2</sup>-hybridized carbon atoms** in the graphene-like layers → delocalized  $\pi$ -electrons enable charge transport.

## Anisotropy in Electrical Conductivity

**Axial direction (||):** high conductivity.

**Transverse direction (⊥):** very low due to poor interlayer connectivity.

Just like thermal conductivity, **graphitic alignment = higher axial conductivity**.

## Factors Affecting Conductivity

**Graphitization temperature:** ↑ temp → ↑ order → ↑ conductivity.

**Precursor:** pitch leads to better alignment than PAN.

**Defects & porosity:** reduce electron mobility.

## Typical Conductivity Values

| Fiber Type        | Electrical Resistivity ( $\mu\Omega\cdot m$ ) | Conductivity (S/m)                   |
|-------------------|-----------------------------------------------|--------------------------------------|
| PAN-based CFs     | 100–300                                       | $\sim 3 \times 10^4 - 1 \times 10^5$ |
| Pitch-based CFs   | 10–50                                         | up to $\sim 1 \times 10^6$           |
| Metals (e.g., Cu) | $\sim 0.017$                                  | $\sim 6 \times 10^7$                 |

# Where the field is moving



Example of alternative precursor feedstock

## Alternative precursors

Lignin, polyethylene / polyolefins, textile precursors and precursor blends are attractive because they target cost before the hot line ever starts.

## Faster stabilization

Improved airflow, split-zone ovens, steam stretching, microwave and plasma-assisted concepts all try to cut oxidation time without sacrificing uniformity.

## Process intensification

The goal is higher throughput per unit energy and floor area, not just a new chemistry for its own sake.

## Application-specific finishing

Future production is also about matrix-compatible sizings and surface systems, especially for thermoplastics and high-volume manufacturing.

## Big picture

The same three levers appear again and again in current R&D: cheaper precursors, shorter oxidation time, and lower total energy per kilogram, while keeping defects and property scatter under control.



***Thank you for your time***



**Funded by  
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# Chemical and Electrochemical Recycling of Composite Materials

Dr. S. Soulis, LST NTUA



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# INTRODUCTION

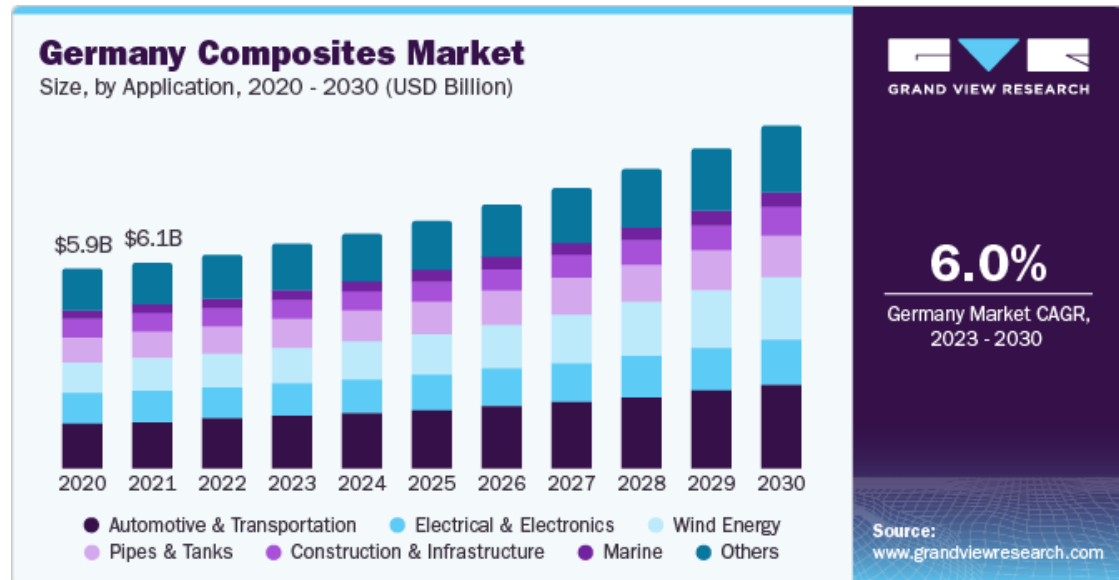
- The continuously increasing demand for composites in many sectors is not a secret.
- Indicatively, the size of the European composites market was valued at USD 19.35 billion in 2022 and is expected to grow at a compound annual growth rate (CAGR) of 6.3% up to 2030.

REF: <https://www.grandviewresearch.com/industry-analysis/europe-composites-market> (5/5/2026)



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- This can be attributed to the increasing demand for lightweight materials across diverse industries, including wind energy, automotive and transportation, aerospace and defense, which is projected to provide substantial impetus to the market.

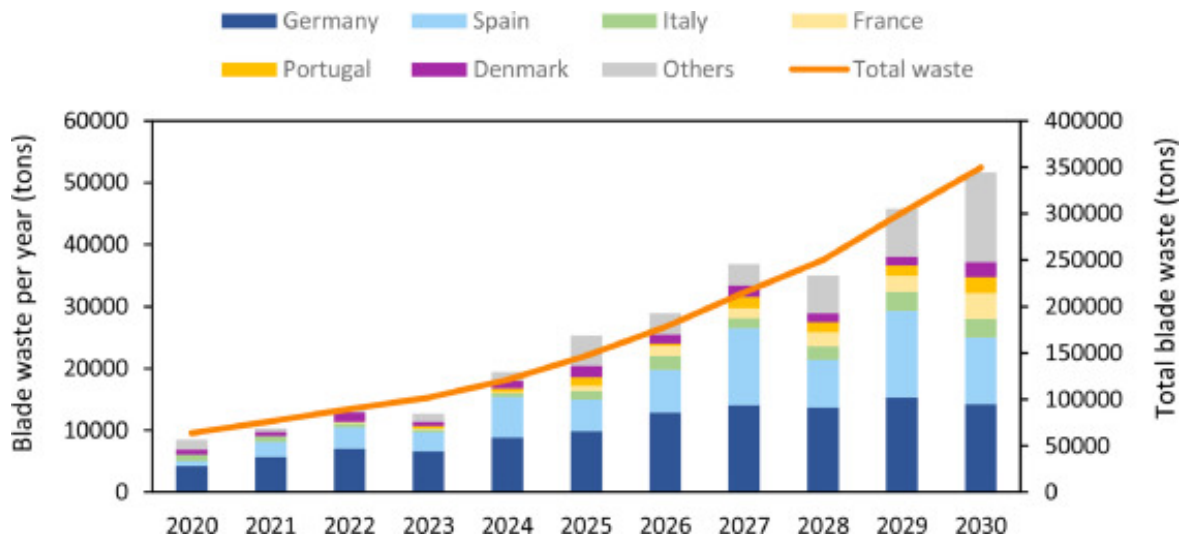


REF: <https://www.grandviewresearch.com/industry-analysis/europe-composites-market> (5/5/2026)



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- It is inevitable that this growth consequently leads to a problem with the end-of-life for these materials.



**Example:** Expected Volume of Decommissioned Wind Turbine Blades in Europe

REF: <https://doi.org/10.1016/j.cep.2022.109015>

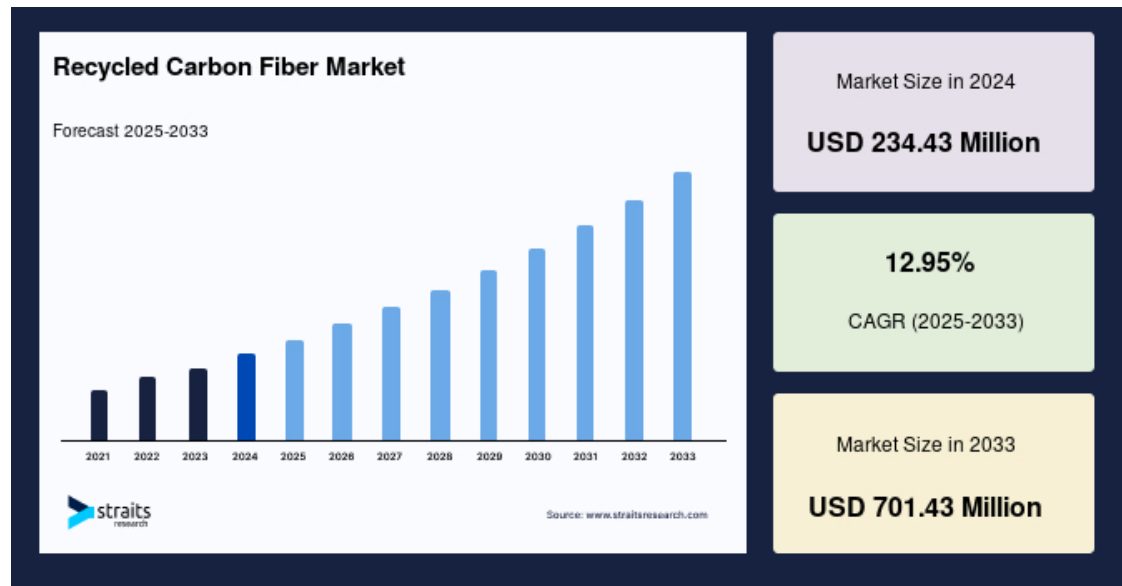


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# INTRODUCTION

- This problem is actually a hidden opportunity.
- Most of the times the failure of a composite is due to matrix deterioration and the reinforcing fibers remain practically intact.
- They also represent a high added value product that could (and should) be utilized.



REF: <https://straitresearch.com/report/recycled-carbon-fiber-market> (5/5/2026)



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- The fundamental obstacle for efficient recycling of the FRCs is the matrix.
- In the wide majority of the cases, it is a thermosetting polymer:
  - By definition does not melt and does not dissolve.
- Thus, the separation of the two phases is not an easy task!

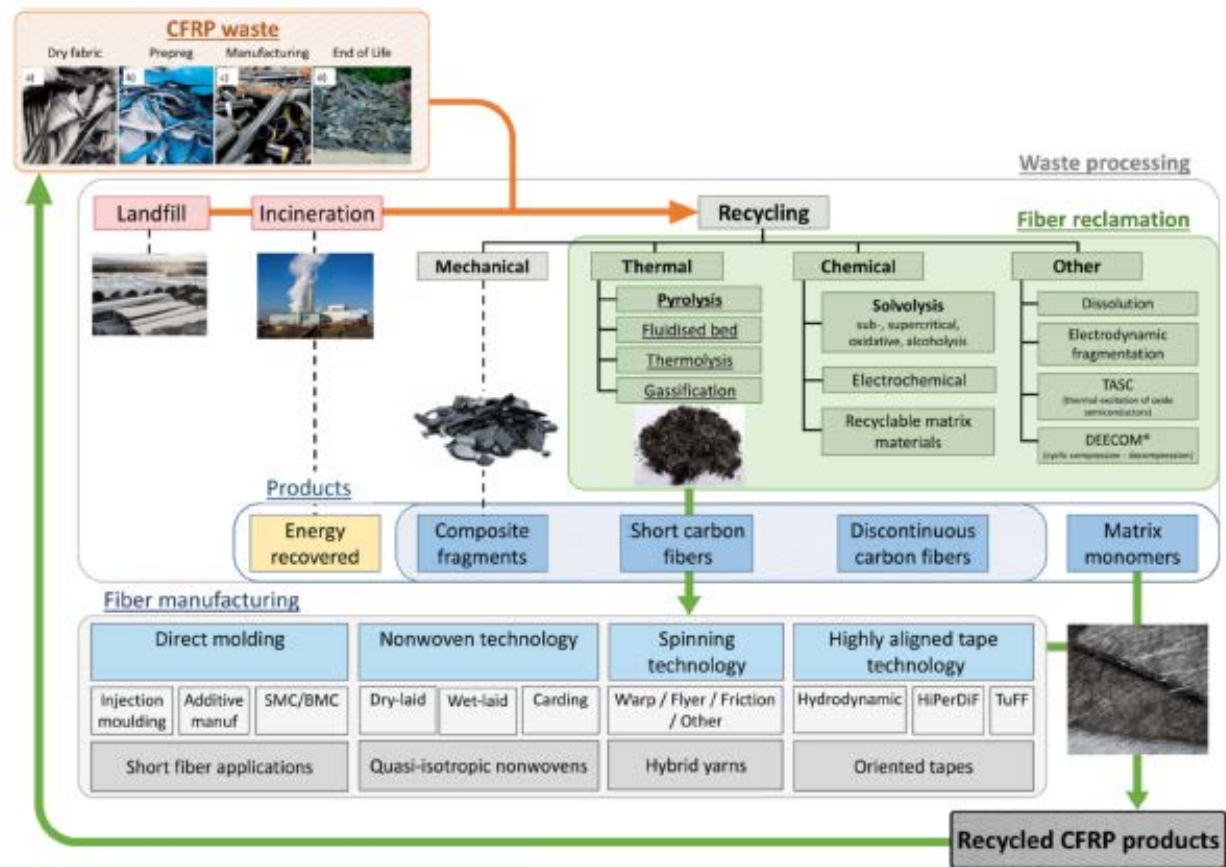
REF: <https://doi.org/10.1007/s44246-024-00192-3>



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- There are already several methods proposed for fiber-reinforced composites (FRCs)
- Indicative : CFRPs



REF: <https://doi.org/10.1016/j.wasman.2026.115352>



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## Comparison of advantages and disadvantages of main FRCs recycling methods

| Recycling mode       | Advantages                                                                                                                                                     | Disadvantages                                                                                                                                                                                                     |
|----------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Mechanical recycling | Simple<br>Low cost<br>Not producing toxic and harmful substances                                                                                               | Severe fiber damage<br>Low application value of recycled materials                                                                                                                                                |
| Chemical recycling   | Controllable fiber size<br>High retention rate of fiber mechanical properties<br>Resin matrix can be reused                                                    | Long reaction time<br>Strict recycling conditions<br>High solvent cost<br>The generated waste liquid is toxic and difficult to treat<br>Not environmentally friendly                                              |
| Thermal recycling    | Low cost of using no chemical reagents<br>High retention rate of fiber mechanical properties<br>Controllable fiber size<br>Suitable for carbon fiber recycling | Mechanical property damage of recycled fibers<br>Generating toxic and harmful gases<br>There may be residues on the surface of recycled fibers<br>Fiber performance is affected by recycling condition parameters |

- Every group of techniques has its advantages and disadvantages
- The selection of the proper recycling method relies in the combination of technical (eg. nature of the raw material) and economic (eg. Energy cost) terms.

REF: <https://doi.org/10.1007/s44246-024-00192-3>



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# AIM OF THE PRESENTATION

- Present the primary research results for promising recycling methodologies:

Case #1 : Formic acid (FA) hydrolysis for recycling wind blade waste (WWW)

Case #2 : Electrochemical treatment as a method that could be efficient for recycling CFRPs.

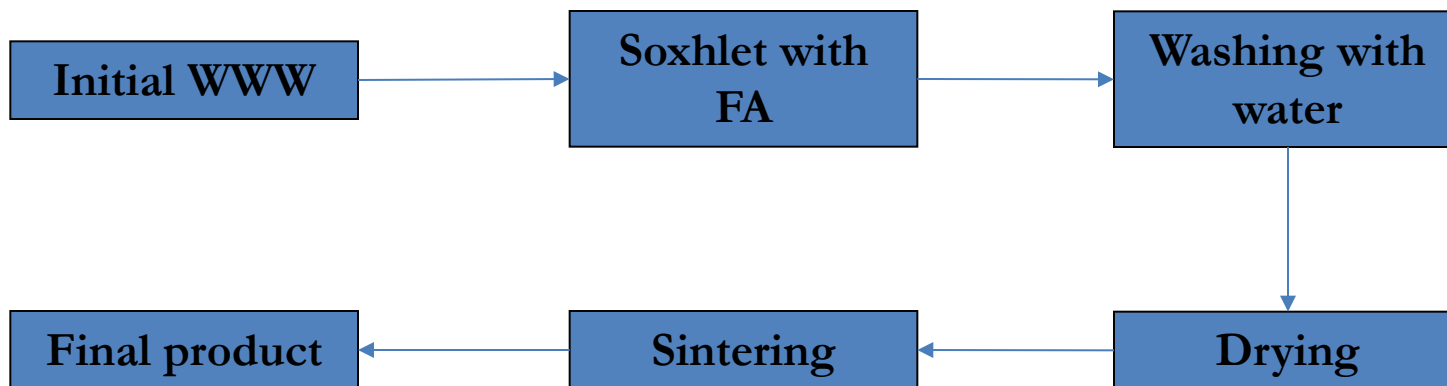


# CASE #1: FORMIC ACID HYDROLYSIS FOR RECYCLING WWW

- The main chemical FRC recycling methodologies are separated to solvolysis and digestion.
  - Solvolysis: use of solvents at high temperature and / or pressure.
  - Digestion: use of corrosive solutions (e.g. concentrated inorganic acids).
- The main idea for investigating formic acid (FA,  $\text{HCOOH}$ ) is that is more reactive than the organic solvents and more corrosive (combines both of two methodologies).



# PROCESS



# PROCESS

- **Initial WWW**: the fraction with size  $>20$  mm, handpicking of the GFRC chunks.
  - Mixture of glass-fiber composites with different matrixes (at least unsaturated polyester and epoxy).
- **Soxhlet**: initially it was selected as a stopgap method.
  - Testing at room temperature immersion of WWW chunks in FA showed that the matrix dissolved slowly (low reactivity, large immersion time).
  - Autoclave is a high-cost process.
  - Due to its nature of the process, during Soxhlet reflux the liquid is at boiling temperature thus the reaction proceeds faster (i.e. theoretically, the highest possible for pressure of 1 atm).
  - Large scale batch process (2-lt active volume, up to 500 g of WWW per batch).





# PROCESS

- **Washing**: tap water flow, until the effluent reach  $\text{pH} \geq 4$
- **Drying**: under vacuum ( $\sim 20$  mmHg),  $51^\circ\text{C}$ , 1-2 h
- **Sintering**: this is necessary in order to remove the residual resin  $650^\circ\text{C}$ ,  $\sim 1$  h
- The residual liquid has a reddish color.
  - Initial tests showed that it is not easy to separate or precipitate any solid by fractionation with water or aqueous solutions.
  - The solution remains stable even after 1 year.
  - Possible composition: low-MW fragments from the different resins used as matrix.





# PROCESS

Soxhlet  
device (2-  
lt active  
volume)



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Packing of  
the WWW  
in the  
sohxhlet



# PROCESS

Operation  
of the  
Soxhlet  
device /  
FA reflux



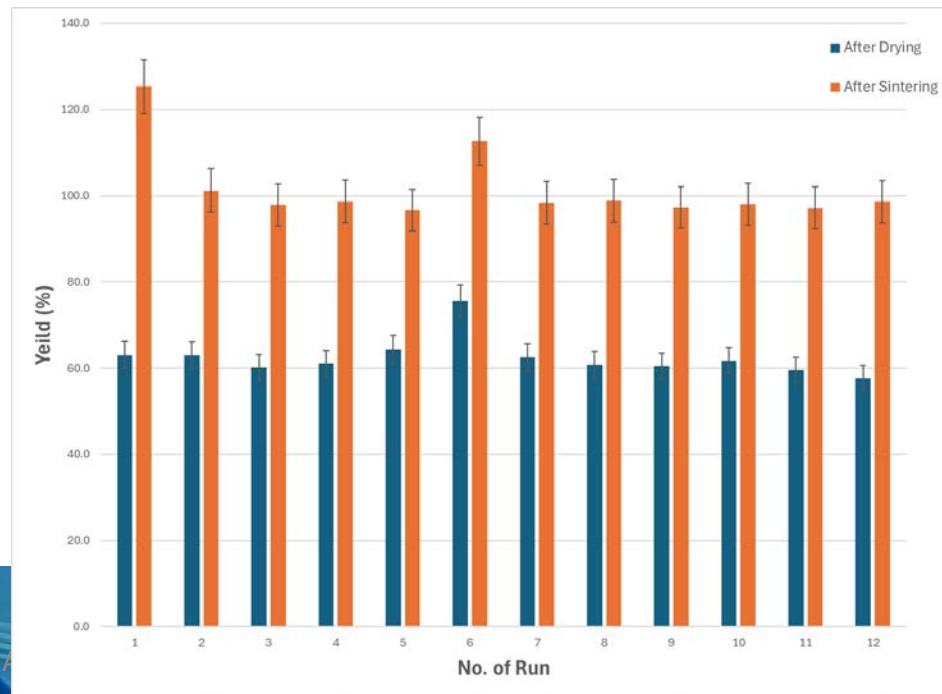
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Residual  
liquid  
(mixture of  
low-MW  
fragments)

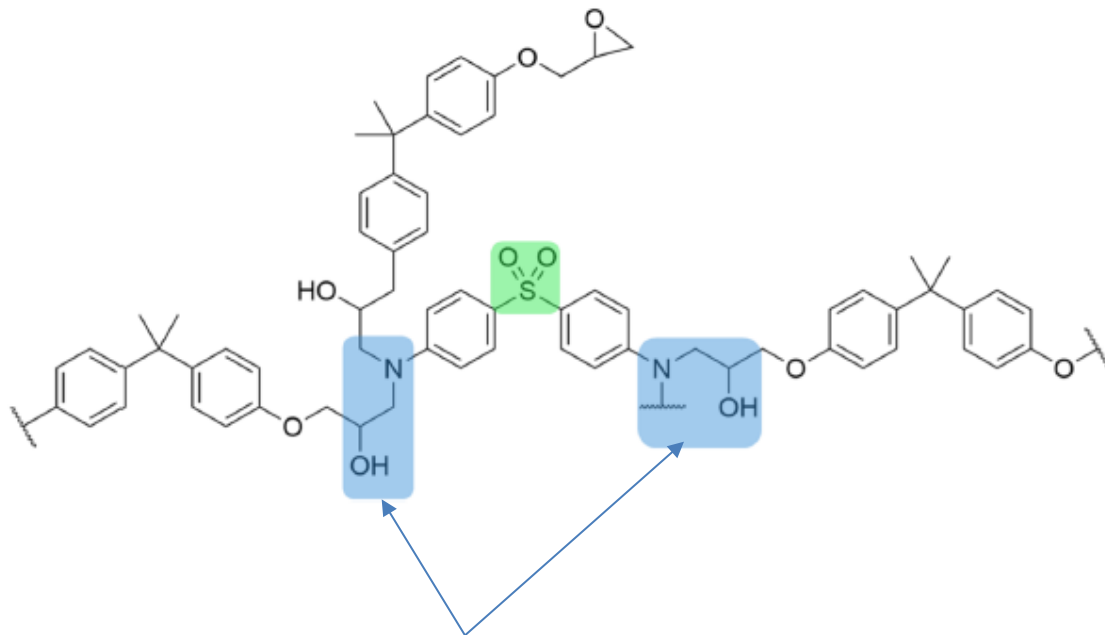
# PROCESS

- The yield after drying is around 100 % - despite clear delamination of the resin.
  - This is an indication that FA reacts with at least one of the resins.
- Final overall yield (after sintering): ~60-65%
  - Represents the typical percentage of GF in the composite.





Molecular structure of a common amine-epoxy system (product of DGEBA and DDS crosslinking)



Epoxy-amine (relatively stable structure, can be attacked under harsh conditions)

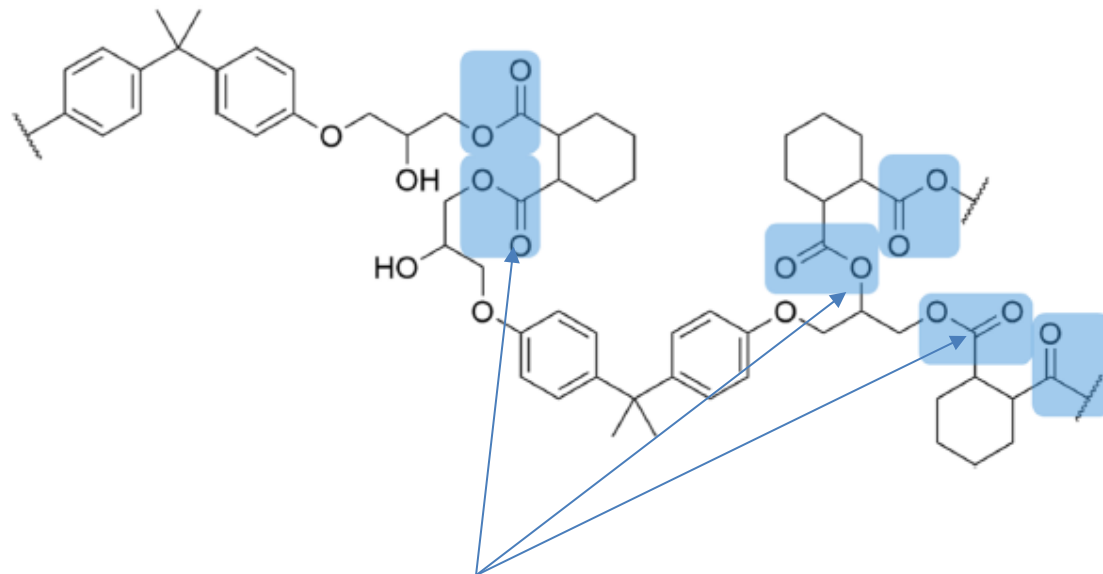
REF: <https://doi.org/10.1016/j.polymdegradstab.2023.110447>



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# CHEMISTRY

Molecular structure of a representative anhydride-epoxy (DGEBA hardened with 1,2-cyclohexanedicarboxylic anhydride)



Ester linkages (weak points, susceptible to cleavage)

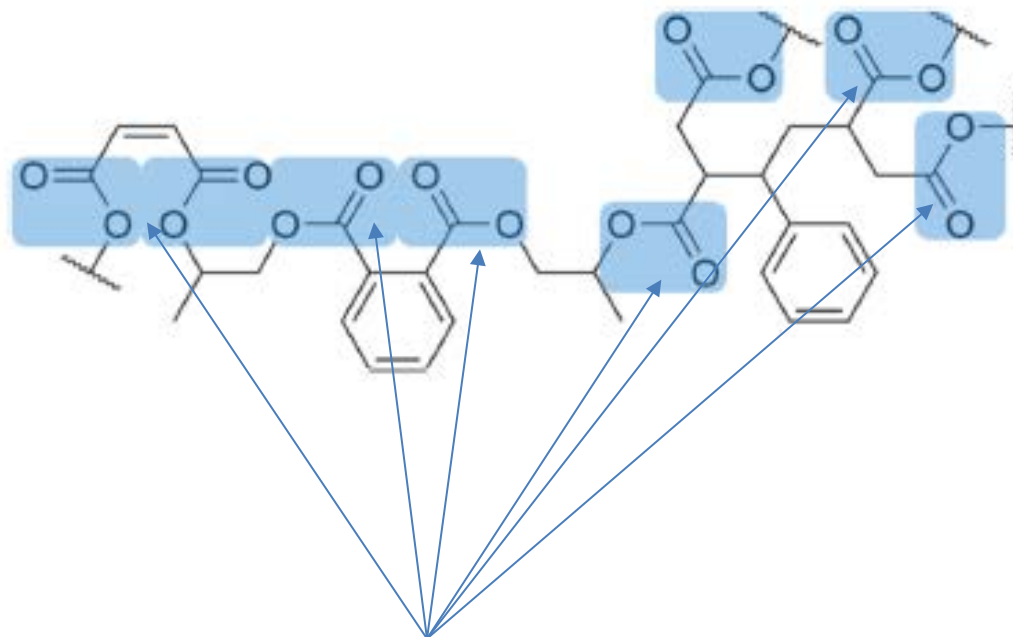
REF: <https://doi.org/10.1016/j.polymdegradstab.2023.110447>



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# CHEMISTRY

Molecular structure of cured unsaturated polyester (based on maleic anhydride, propylene glycol, phthalic anhydride and cured with styrene)



Ester linkages (weak points, susceptible to cleavage)

REF: <https://doi.org/10.1016/j.polymdegradstab.2023.110447>



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# CASE #2: ELECTROCHEMICAL TREATMENT FOR RECYCLING CFRPS

- The idea is to take advantage of the CFs high electric conductivity and cause partial (or total) delamination of the fibers and the matrix through electrochemical or chemical degradation.
- Different conditions were investigated.

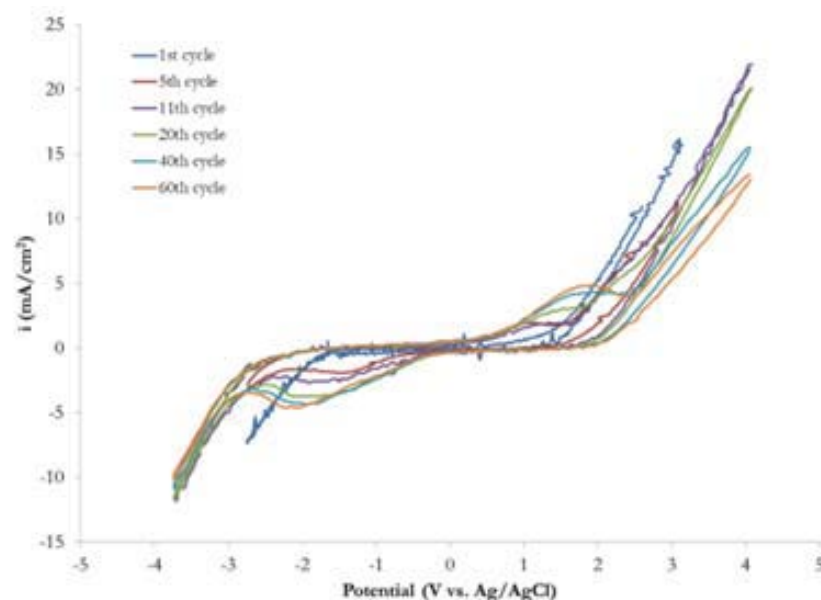




# PROCESS

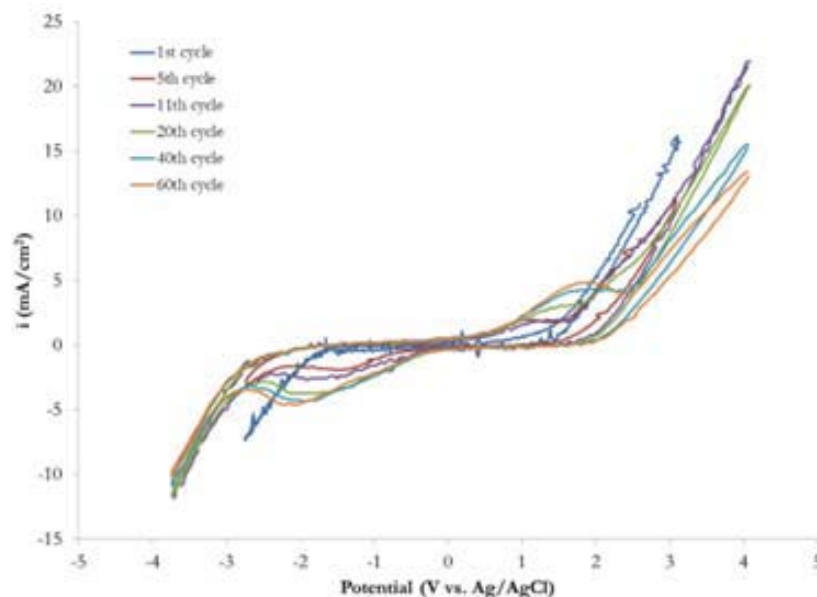
- The CF composite used in this work contained 60% w/w of CF reinforcement; it consisted of epoxy resin matrix and reinforcement with 8 layers of CF plain weave cloth.
  - It was manufactured with typical vacuum-assisted resin transfer molding (VA-RTM).
- The electrochemical treatment of the CF composite was performed using a potentiostat.
  - A three- electrode setup was used, with the CF composite as the working electrode, a Pt-plated Pt wire as the counter electrode and an Ag/AgCl electrode as the reference.
  - Cyclic Voltametric (CV) conditions were used.
- After each testing, the CF composite sample was thoroughly washed with distilled water and acetone.





- Treatment of CF composite sample with repetitive scanings in aqueous 0.5 M NaOH solution.
- Gradual increase of the active current (i.e. the area enclosed by the curve of the CV).
  - This is an indication of an increase of either the surface area of the CFs, or of their electrochemical activity or both.
  - However, upon optical inspection, there was no indication of matrix disintegration in the CF composite, neither in the surface nor internally.

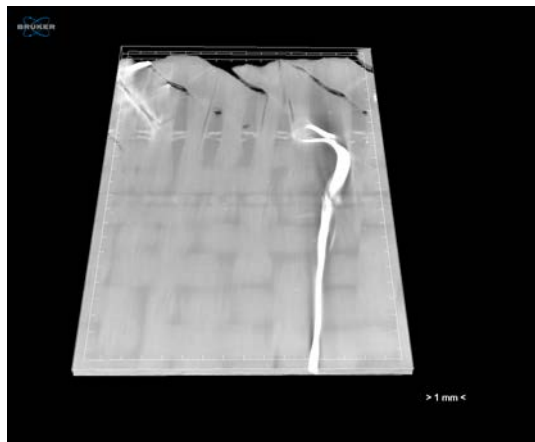




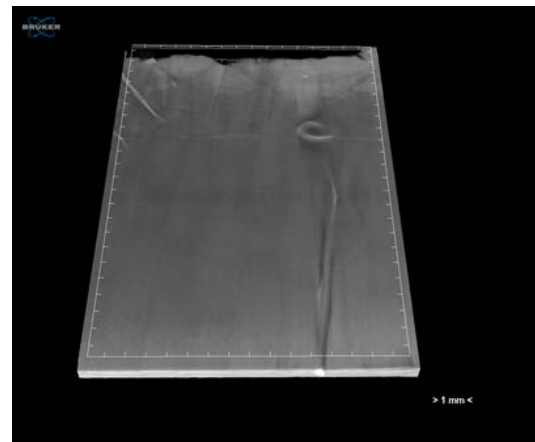
- Further treatment was followed, this time for another 50 CV scanings in the even wider region of potentials .
  - Even higher active current was measured, which also increased by the number of the treatment cycle, but the optical investigation did not find any sign of degradation in the CF composite.



(a)



(b)

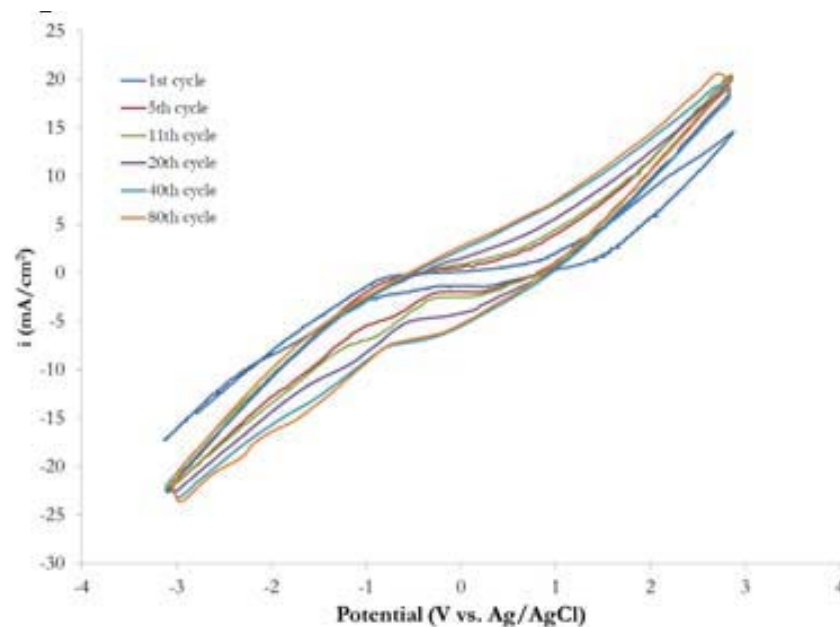


m-CT analysis of the CF composite sample after the electrochemical treatment with aqueous 0.5 M NaOH solution (a) external surface of the composite, (b) internal surface.

- The CVs of the treatment indicate that there is an increase of the electrochemical activity
- This could indicate an increase of the CF active surface via the formation of small cracks (invisible to the naked eye) in the bulk of the composite.
- However, m-CT analysis show that the CF composite sample remained intact after the treatment with the NaOH solution.





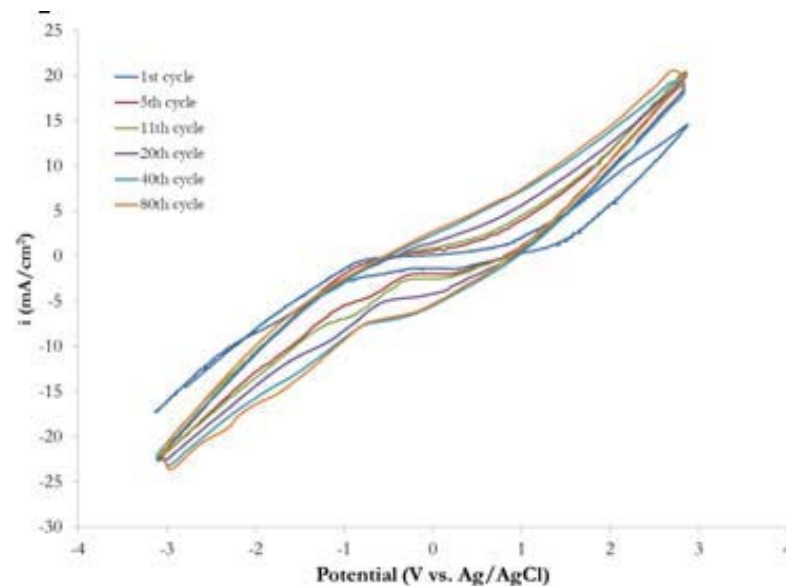


Treatment of CF composite sample with repetitive scannings in concentrated  $\text{H}_2\text{SO}_4$  (96%).

- The rationale was that electrochemical treatment of CF fibers in acidic solutions could lead to targeted surfacial oxidation, with possible subsequent partial reduction (under CV conditions).
- Up to 100 repetitive potential scannings were performed.



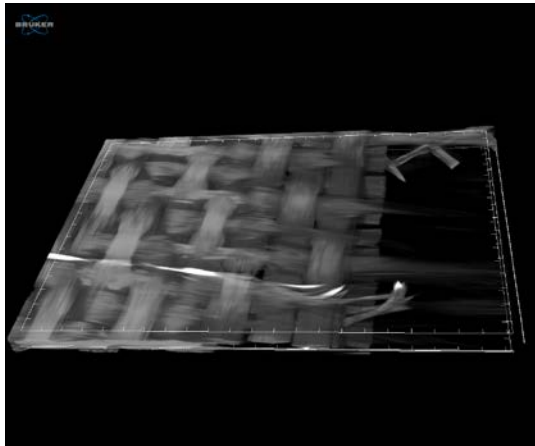
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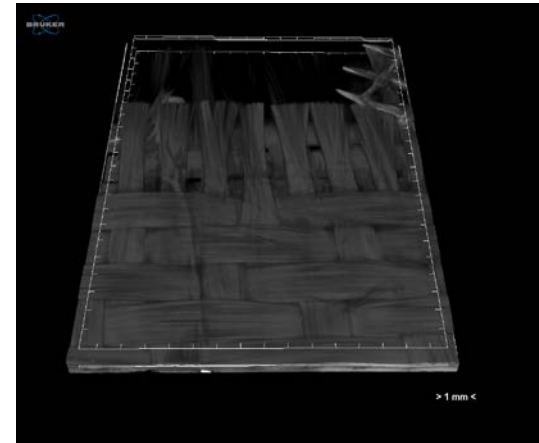
- The increase in the active current is clear and more prominent compared to the 0.5 M NaOH solution.
  - The electrochemical activity of the CF composite sample increases during the treatment.
- Moreover, during the CVs the colour of the electrolyte solution progressively darkens, starting from pale yellow and reaching to dark brown.
- After the CF composite sample was removed from the solution, it was found that the matrix had almost completely disappeared and that the CF cloth layers appeared intact.



(a)



(b)



m-CT analysis of the CF composite sample after the electrochemical treatment with concentrated  $\text{H}_2\text{SO}_4$  (96%) (a) external surface of the composite, (b) internal surface.

- The m-CT measurements confirmed the optical observation, with the epoxy resin removed from the outer surface and the bulk of the sample.
- This is a clear proof that **electrochemical treatment can be an efficient method for recycling CFRPs.**



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# CONCLUDING REMARKS

- The initial results showed that two composite recycling methods have interesting prospects.
- Further investigation necessary:
  - Case #1: correlation of the chemical nature of the matrix with the decomposition mechanism.
  - Case #2: mechanism of electrochemical decomposition of the matrix.



**Thank you !**  
**Questions???**

# Chemical and Electrochemical Recycling of Composite Materials

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