

École polytechnique de Louvain

Recycled plastics in structural engineering

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Abstract

In this master thesis, a green sustainable material made of recycled plastics and bioplastics has been created and analyzed to determine applications in structural engineering.

Recycled PMMA and bioplastic PLA were combined into a miscible blend, enhancing each of its components' properties. Proving to be rigid enough to be utilized in structural engineering, the newly created polymer was integrated in a modelization of roof beams for a carport. Also, guadua bamboo's stems were interlocked into the polymer matrix to explore potential enhanced mechanical properties. Two sections were retained and appeared to be a very good substitute to timber. However, reinforcement with bamboos did not show substantial improvement.

This thesis embraces the global worldwide circular economy strategy.

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Table of content

PART 1	INTRODUCTION	1
1.1	MOTIVATIONS	1
1.2	OBJECTIVES	2
1.3	ORGANIZATION	3
PART 2	LITERATURE REVIEW	4
2.1	PLASTICS/POLYMERS.....	4
2.1.1	<i>Thermoplastics</i>	<i>5</i>
2.1.2	<i>Thermosets</i>	<i>6</i>
2.1.3	<i>Important characteristics of thermoplastics and challenges.....</i>	<i>7</i>
2.1.4	<i>Manufacturing processes</i>	<i>10</i>
2.1.5	<i>PMMA.....</i>	<i>11</i>
2.2	BIOPLASTICS	13
2.2.1	<i>PLA.....</i>	<i>17</i>
2.3	RECYCLED PLASTICS	20
2.3.1	<i>Recycling plastics in numbers</i>	<i>20</i>
2.3.2	<i>From waste collection to material recovery.....</i>	<i>23</i>
2.3.3	<i>Recycling of PLA/PMMA</i>	<i>28</i>
2.4	USE OF RECYCLED PLASTIC IN STRUCTURAL ENGINEERING; STATE OF THE ART REVIEW.....	29
2.5	FINDINGS.....	38
2.6	BAMBOO.....	38
2.6.1	<i>Bamboo characteristics.....</i>	<i>38</i>
2.6.2	<i>Bamboo applications.....</i>	<i>40</i>
PART 3	COMPOSITION OF THE NEW MATERIAL	41
3.1	PRE-TEST AND EARLY FINDINGS	41
3.2	CHALLENGES.....	43
3.2.1	<i>Rigidity</i>	<i>43</i>
3.2.2	<i>Stability (keep rigidity properties within the range of temperatures for utilization).....</i>	<i>44</i>

3.2.3	<i>Miscibility and compatibility of the components</i>	45
3.2.4	<i>Recyclability of the new composition (circular economy)</i>	45
3.3	FINAL COMPOSITION, MANUFACTURING PROCESS AND RECYCLING	45
3.3.1	<i>Blend rigidity</i>	46
3.3.2	<i>Blend Stability</i>	47
3.3.3	<i>Blend miscibility</i>	47
3.3.4	<i>Blend recyclability</i>	48
3.4	REINFORCE THE NEW MATERIAL WITH BAMBOOS	49
3.5	COSTS AND CO ₂ FOOTPRINT	50
PART 4	EXPERIMENTAL TESTS	52
4.1	TEST THE MECHANICAL PROPERTIES OF NEW COMPOSITION PLA/RPMMA.....	52
4.2	CREATION OF PROTOTYPES BAMBOOS INTERLOCKED IN PLA/RPMMA	54
4.3	TEST THE MECHANICAL PROPERTIES OF THE REAL SCALE ELEMENTS	56
4.3.1	<i>Traction on bamboos</i>	56
4.3.2	<i>Pull-off to characterize the adherence</i>	59
4.3.3	<i>Flexion</i>	62
4.4	CONCLUSION OF THE ANALYZED RESULTS.....	65
PART 5	MODELLING FOR APPLICATIONS	66
5.1	NUMERICAL FLEXURAL TESTS	68
5.2	DESIGN THE TOP BEAM OF CARPORT	69
5.2.1	<i>Theory behind the design</i>	69
5.2.2	<i>Modelling the sections</i>	71
5.3	DESIGN OF A CARPORT.....	79
PART 6	CONCLUSION	86
TABLE OF FIGURES		88
TABLE OF TABLES		92
BIBLIOGRAPHY		93
APPENDICES		105
APPENDIX A	TABLE OF PROPERTIES.....	106

I.	References.....	111
APPENDIX B	FOUR POINTS FLEXURAL TEST ON ECO-OH! SPECIMENS.....	113
APPENDIX C	MATERIALS TECHNICAL DATA SHEETS.....	116
I.	Action Plan PLA-rPMMA.....	116
II.	PLA Ingeo 2003D (Resinex, 2020).....	117
III.	PMMA PLEXIGLAS Heatstop (Röhm GmbH, 2020).....	122
APPENDIX D	RESULTS FLEXURAL TESTS OF NEW COMPOSITION – INNOLOGIC.....	125
APPENDIX E	CASTING FORMWORKS.....	127
APPENDIX F	RECAPITULATIVE TABLES OF EACH TEST.....	128
I.	Traction on Bamboos.....	128
II.	Pull-off.....	141
III.	Flexural tests.....	144
APPENDIX G	SECTIONS MODELIZATIONS.....	155
APPENDIX H	TABLE OF CONTACTS	156

PART 1 INTRODUCTION

1.1 Motivations

Both worldwide production of primary plastic and generation of plastic waste drastically increase over the years.

Most of this waste is still not recycled today and causes huge environmental problems, with these plastics ending in the landfills and the natural environment. It is estimated that if nothing is done, there will be more plastics than fishes in the oceans (weight estimation by 2050) (Wearden, 2016) There is thus a need to act in terms of production but also in recycling.

From plastic blocks used as partitions between offices, to bricks made of plastic bottles to build houses in poor city suburbs in Argentina, or the replacement of wood bridges for cyclists and pedestrians by new plastic bridges in Rotterdam, or projects for roads made of recycled plastics, there are many initiatives but they are still embryonic at the worldwide scale.

With 89% of post-consumer waste recycled, Belgium is the number one European country in terms of recycling. However, only 40% of plastic packaging are recycled and there is thus a huge improvement to do, beginning with a better selective sorting by citizen (Première, 2018).

Furthermore, a European initiative at a larger scale, “Recycling of secondary raw materials for a sustainable optimization of construction processes in Civil Engineering”, tries to increase the use of « Secondary Raw Materials (SRM) », and notably the plastic waste, and is driven by not less than 35 companies and academic entities, in more than 7 European countries (Commission, 2014).

In this framework, it is necessary to create innovative solutions in the structural engineering process, in connection with the constraints imposed by the sector. These solutions will be driven by the need to recycle, and thereby create circular economy.

1.2 Objectives

The overall objective of the master thesis is to find a sustainable composition of recycled plastics to be used in construction and structural engineering, evaluate its load-bearing capacities, and apply it to a case study.

Through a literature review, we first search on the mechanical characteristics of plastics and recycled plastics, their encountered challenges, and their use in construction.

We then define a sustainable and green composition made of recycled plastics and bioplastics.

Thereafter, we test the mechanical properties of the created new material and analyze the results.

And finally, through modelization, we design potential applications for the new materials.

1.3 Organization

Since we had no deep understanding of plastics, it was first important to learn and understand the world of plastic, the researches made in construction structural engineering and all potential links already made between both worlds. This has taken place through a wide **literature review of scientific researches and projects** around the world.

Afterwards, the importance to develop a new composition for a material made of recycled plastics led up to **contact companies from the industries and academic entities**, reputable in that field. There is always a lot to learn from experienced persons and each meeting was a step forward in the process of the research. The aim was to create a new material that would be sustainable, rigid, strong, made up of recycled plastic and recyclable at the end of its life.

The Belgian and North of France plastic industry is a wide but nested network, where everyone knows everyone, where companies and academic entities are used to work together on research and development. Every contribution has been important for the development of the researches and the progress of the master thesis, to finally find the right miscible blend for the composition to develop.

The main challenges were indeed to find the right composition but also to find companies and entities that could mold specimens according to standards for the mechanical tests, as well as to find recycled raw material to be used for the blend.

As shown in details in APPENDIX H, in total, contacts were taken with **29** companies or academic entities, some of them also connecting us to others. Out of these, **13 companies or academic entities played a critical role at various levels**. Sincere and warm thanks to these are presented in Acknowledgements at the very beginning of the present report.

Unless for the preliminary pre-tests (performed late February), tests were to be started mid-March, and were thus highly impacted by the Covid-19 general containment (unavailability of the laboratories). Besides that, we managed to produce a new material and to test them in due time thanks to the close collaboration of companies as well as the academic laboratories of UCLouvain, and to then proceed to the modellization as per the tests results.

PART 2 LITERATURE REVIEW

In parallel to the below review of the existing and relevant literature, we produce in APPENDIX A a detailed table of characteristics (*A3 format*) of plastics and bamboos used in the tests, another table with all major plastics, and finally of other major materials used in construction and structural engineering.

Some conclusions and comparisons can be drawn from the recapitulative table's properties.

Thermosets are more rigid (greater young modulus), slightly heavier and have greater tensile strength than thermoplastics, but they are not recyclable and are thus of non-interest.

PE, HDPE, LDPE, and PP also known as polyolefins, are already largely recycled, but present a smaller rigidity than other thermoplastics or thermosets, a lower density and a smaller tensile strength.

Other thermoplastics have a tensile strength greater than many materials like timber, glass, concrete and brick, but a smaller rigidity: timber has a rigidity ranging from 6 to 15 [GPa], whereas for thermoplastics, it ranges from 2 to 4 [GPa] only. Thermoplastics are heavier than timber, but lighter than all the other materials and nearly 4 times lighter than steel. Finally, thermoplastics present a larger thermal expansion.

2.1 Plastics/Polymers

Many misunderstandings exist around the name **plastic and/or polymer**. In common language, “plastics” are used to define the polymers (Courard, s.d.), to which many additives¹ had been added to modify the material properties and meet the specifications (Duval, 2009).

The principal element in plastic chemistry is **carbon**; it links easily with other atoms to create monomers. The wider source of carbon used remains yet the **gasoline** (except for plastics made of chlorine, usually from sea salt, like PVC).

Polymers are made of long molecular chains or macromolecules, themselves composed of **monomers**² (organic composite). The monomers are an arrangement of atoms linked by a strong or covalent bound, with co-sharing of electrons. After polymerization, monomers are linked by covalent bounds and create macromolecules, while the overall chains are entangled but not free from each other; they are linked through Van der Waals bounds or weak bonds

¹ The additives are mostly charges, plasticizers, reinforcements, but also pigments, initiators, catalyzers, flame retardants, stabilizers (UV and heat), lubricants, antistatics, fungicides, ... (Duval, 2009)

² Monomer (Cambridge Dictionary, s.d.): a chemical substance whose basic molecules can join together to form polymers.

about 10 times weaker than strong ones, but of higher numbers, making the material cohesive ((A. Simar, 2017), (Duval, 2009)).

Regarding the structure, there are several lengths of chains and the mean length characterize the degree of polymerization. The higher the degree, the higher density, rigidity and resistance in solid state, and the higher viscosity in liquid state. **Branched and linear macromolecules exist**; branched molecules lead to lower density, but mechanical resistance is ensured by their entanglements.

Two types of structures define the two main classes of polymers (Courard, s.d.):

- The **thermoplastics** or free polymer chains: no primary links between chains, only secondary links, entanglement and cohesion working together to obtain a cohesive material.
- The **thermoset** or bridged polymer chains: primary links at some position along the chains to link them together and form a 3D network. The primary links are obtained through cross-linking or vulcanization. Cohesion of the material is mainly covered by the high energy bounds, but also the entanglement.

2.1.1 Thermoplastics

The most common plastics are **thermoplastics**. Their structure is either amorphous or semi-crystalline (see Figure 1), depending on the cooling rate and what happens when the molecular agitation decreases (shaping temperature does not matter much). The slower the **cooling rate**, the higher the linearity of molecular chain will be, the higher the degree of crystallinity will be. With a self-organization of chains in parallel segments as crystal lamellas in-between amorphous zones, the structure is semi-crystalline, bi-phase material (most cases). If the liquid molecular state has frozen, macromolecules are messy and the structure is amorphous (Duval, 2009). If volume fraction of crystalline phase is high, the polymer is dense and opaque (A. Simar, 2017).

When heated, thermoplastics undergo an increase in molecular agitation. The amorphous phase **undergoes a glass transition at T_g** , where the weak bounds break and lead to a gradual softening (Duval, 2009). The modulus of elasticity decreases, characterizing the viscoelastic behavior. The crystalline phase is not impacted and conserves its high modulus of elasticity. If there exist many crystalline zones, it is possible to define a **fusion temperature T_m** (higher than T_g) where the weak bounds will all break together in that narrow temperature range (Duval, 2009). The density of crystalline phase increases suddenly above T_m and characterizes the viscoplastic behavior (A. Simar, 2017). If the temperature reaches 400°C, the polymers disintegrate (Duval, 2009).

Thermoplastic is a solid at ambient temperature and a viscous fluid above glass temperature (usually about a hundred degree).

Thus, an important parameter of thermoplastics is that they can only be used in a certain range of temperature, as they soften and lose mechanical properties above T_g .

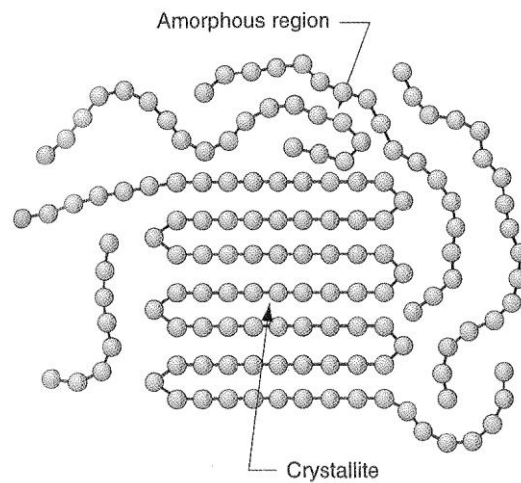


Figure 1 Structure of a semi-crystalline polymer (A. Simar, 2017)

Thermoplastics are easily recyclable into new products (participating in the circular economy concept) by heating or adding a solvent to break the links; they can undergo many fusion and solidification cycles without significant deterioration of their properties (A. Simar, 2017).

Some common thermoplastics are: PVC, PS, PMMA, PE, PP, Polyamide (nylon), PTFE (Teflon), ... (see APPENDIX A).

2.1.2 Thermosets

The **thermosets** undergo irreversible chemical reactions linking the chains by hard covalent bounds and creating a unique macromolecule; the material is **reticulated** or **cross-linked**. The degree of reticulation is a function of the number of bounds and can still increase during the fabrication. Thermosets have an amorphous structure as there is no organization in the chains, and hence they are isotropic materials. They have better thermo-mechanical properties than thermoplastics (A. Simar, 2017).

Fabrication process starts with non-reticulated polymer that undergo a chemical reaction, either by being heated, initiated by a catalyzer, or mixed with a reactive polymer. The thermoset behaves like amorphous thermoplastic as long as it does not cool down under T_g (A. Simar, 2017).

The chemical cross-linking reaction that thermosets undergo is not reversible. It isn't possible to break down the links by heating or adding a solvent (if severe warming, both weak

and strong links will break and degrade the polymer) ((Duval, 2009), (Courard, s.d.)). Hence, **thermosets are usually not recyclable**.

Thus, an important parameter is that thermosets are stronger against heat and cross-linking helps to decrease plastic shear. They are stronger than thermoplastics (Courard, s.d.).

Examples of thermosets : epoxy resin, unsaturated polyester, reticulated polyurethane

2.1.3 Important characteristics of thermoplastics and challenges

Polymers are very resistant and durable material, also easy to manufacture. This is the reason why they are so popular and have massively developed the last decades.

They are usually waterproof, not corrosive, very bad at conducting heat or electricity. Change their properties by adding additives is quite easy and they can undergo bigger elastic deformations than other material that would reach failure faster (Simar, 2019). However, they cannot work at high temperature like steel, they have a low rigidity and undergoes creep at room temperature.

The **Young Modulus E** characterizes the rigidity of the material. It is usually evaluated through traction tests.

Polymers have a smaller density and a Young Modulus usually 50 times smaller than those of metals (Simar, 2019). Comparing Young Modulus of different materials (see Figure 2) shows us that polymers can be equally performant to natural materials (like wood) but will always have a smaller Young Modulus than metals or ceramic, and hence smaller performance.

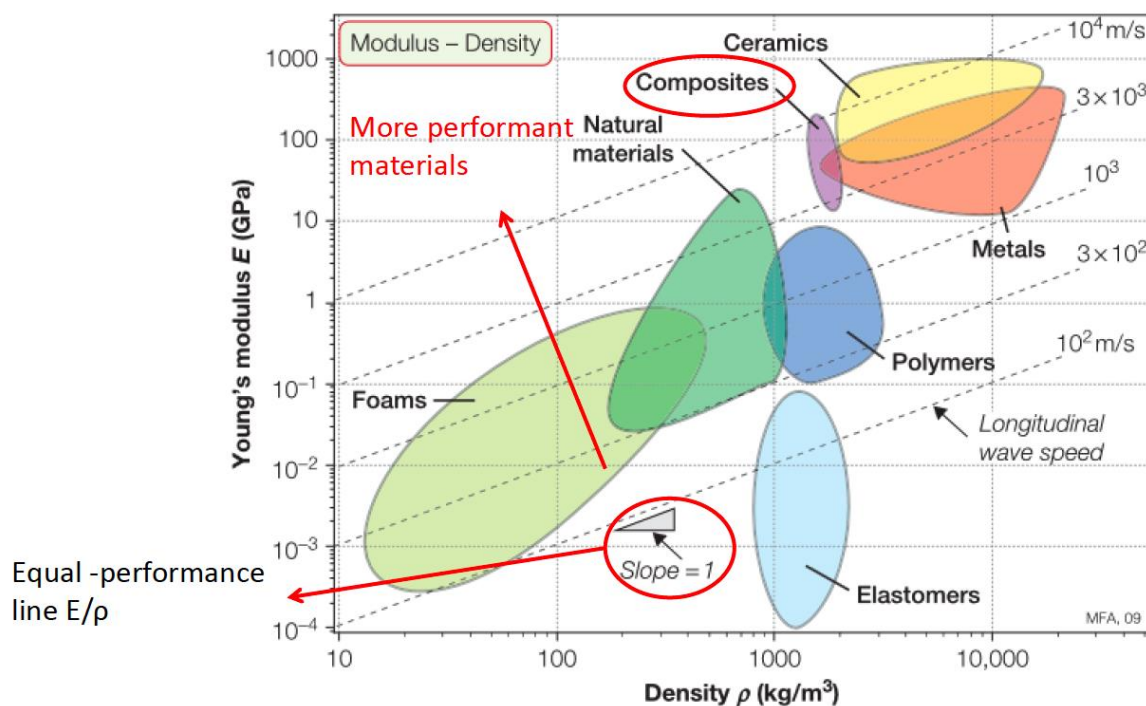


Figure 2 Young's Modulus vs Density Plot and performances (Simar, 2019) (Ashby, 2011)

The Young Modulus of polymers are low because of their intrinsic properties: indeed, the number of bonds per unit and their stiffness play an important role in the rigidity. Polymers present covalent strong bonds but also Van der Waals weak bonds, the latter lead to a stretching of the material during deformation (Ashby, 2011). Hence, polymers undergo bigger elastic deformation than other materials like metals for example, and delay the failure.

The density also plays a role in the Young Modulus: as we can observe on the diagram, density of polymers is lower than metals and is a consequence of the weight of atoms. As seen before, mainly carbon and hydrogen atoms are present in polymers, with only 1 atomic weight for hydrogen (and 12 for carbon) (Ashby, 2011). All the hydrogen lower thus the weight of the material.

Finally, the Young Modulus is also strongly dependent on the temperature. One or two specific temperatures will change the behaviour of the material according to its intrinsic structure (see Figure 3).

For *semi-crystalline polymers*, two zones coexist: amorphous and crystalline. Hence two temperatures will change the behaviour of the material: first glass temperature T_g that will influence the amorphous zone, and second fusion temperature T_f that will influence the crystalline zone (Courard, s.d.).

Before T_g , the polymer is **rigid**, has a small ductility and an elastic behaviour. **At T_g** , the rise in temperature increases the mobility of the chains in the amorphous area, and hence the specific volume³ that leads to a decrease in rigidity. The polymer pass **from rigid to viscoelastic material**. After T_g , specific volume continues to increase with temperature before reaching T_f **where the crystallites melt**. It is characterized by a brusque increase of specific volume and a brusque drop in rigidity, characterizing the change **from viscoelastic material to viscous liquid** (Courard, s.d.).

For *amorphous polymers*, there is no crystalline zone and hence no precise temperature of fusion, even if the material will change to a liquid state after a certain point (Courard, s.d.).

The evolution of modulus and specific volume depending compared to temperature are pictured in Figure 3 for semi-crystalline and amorphous polymers.

³ Specific volume is the inverse of the density [cm^3/g] (polymers) (Courard, s.d.)

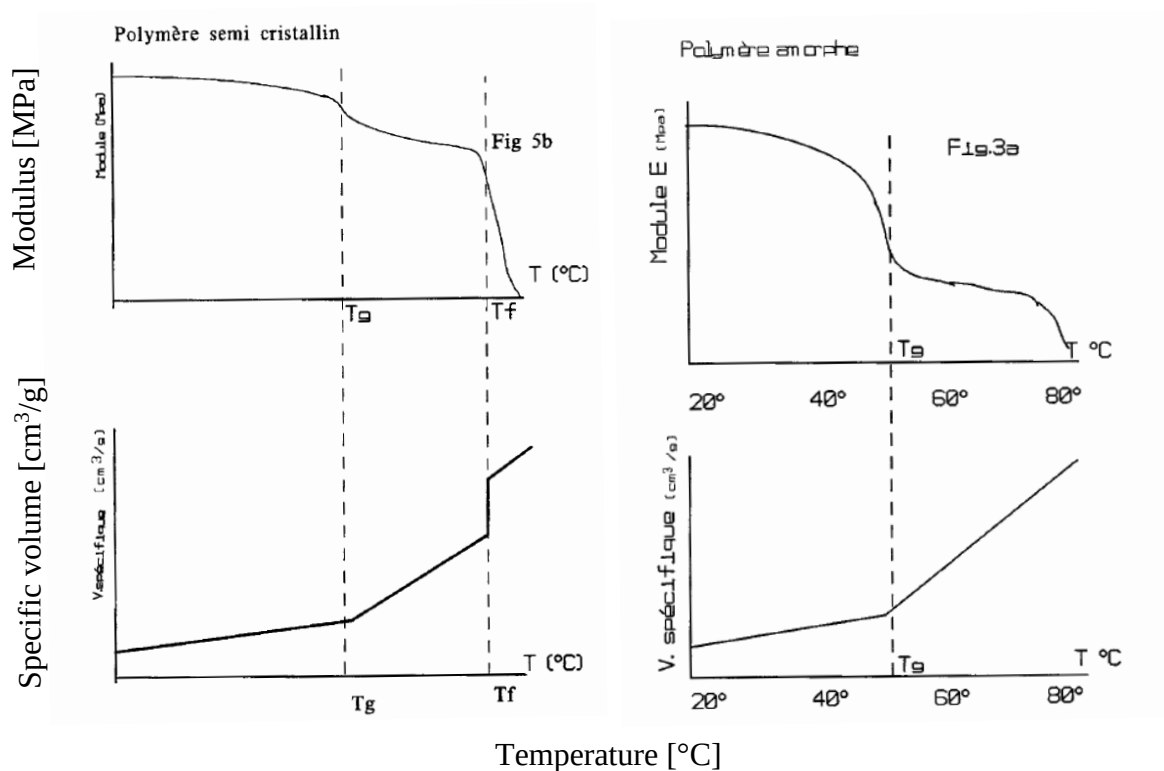


Figure 3 Evolution of rigidity and specific volume of semi-crystalline polymers (left) and amorphous polymers (right) with temperature (Courard, s.d.)

As a consequence, the utilization of the polymers has to be restricted to a certain range of temperatures lower than T_g to ensure its rigidity.

A plot of the evolution of certain common and further used (in this master thesis) thermoplastics is pictured at Figure 4.

The amorphous PMMA has its T_g around 120 °C, where it loses its rigidity, and the semi-crystalline PLA has its T_g around 60 °C. At glass transition, the drop of rigidity in semi-crystalline polymers is smaller than the drop of amorphous polymers, due to their smaller fraction of amorphous zone (Courard, s.d.).

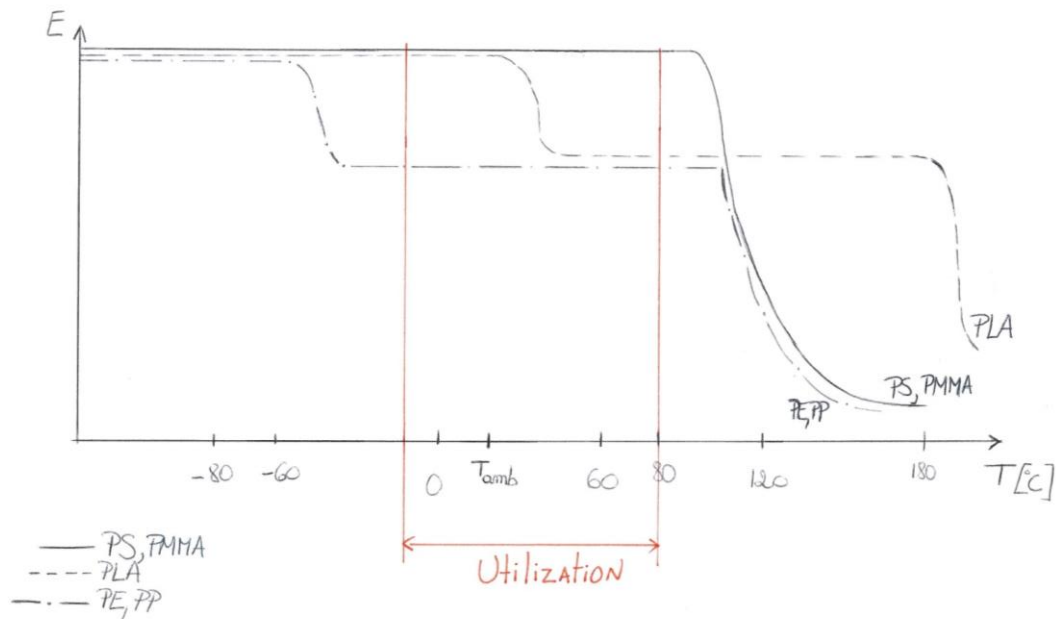


Figure 4 Young Modulus vs Temperature for relevant thermoplastics

Finally, both amorphous and semi-crystalline polymers can be subjected to increasing or decreasing evolution of temperature. Hence, it can change state in both direction: from viscoelastic to viscous and vice versa. That's why thermoplastics are recyclable (Courard, s.d.), they can undergo many fusion and solidification cycles.

2.1.4 Manufacturing processes

Many conventional polymer conversion processes exist to transform them into finished objects. They are divided into three main categories: closed, partially-open and open processes, each of them composed of several processes.

The **closed processes** category is the most used manufacturing process and among them, extrusion, injection or compression molding, injection blow molding and rotational are the main ones. However, there exist also **partially-open processes** for film or coating extrusion, and **open processes** used for fiber reinforced plastics (Development, 2009).

Thermoplastics are usually first extruded to reach the melting stage, and then the hot component is processed to form an object (A. Simar, 2017).

The processes used in the purpose of the thesis are closed processes (extrusion, injection and compression) for thermoplastics.

First, the **extrusion process** (Figure 5): it is a continuous process used to create constant section profiles or to create a thread cut into pellets. Granules are inserted in the hopper (at the beginning of the extruder) and the endless screw turning in the cylinder of the extruder carries, heats the polymer to its melting temperature by friction on the walls, mix and

compress the polymer. The melted polymer is pushed through a die and soaked at the exit to fix its geometry and avoid an elastic shrinkage. If several polymers are extruded together for a composite material, it is helpful to use a twin-screw extruder that better mix the components and avoid heterogeneities (damaging the material) (A. Simar, 2017).

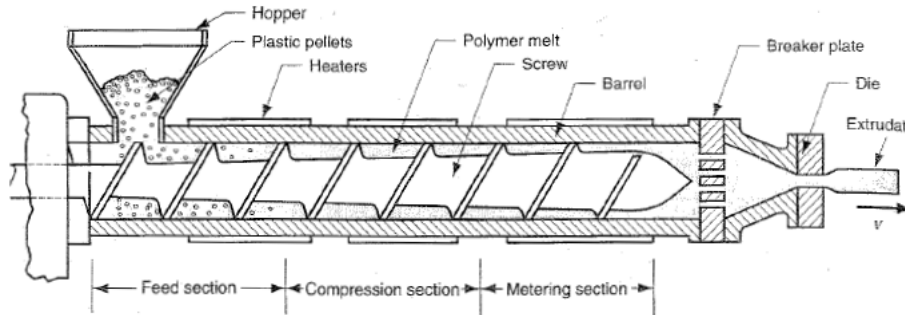


Figure 5 Extruder (A. Simar, 2017)

Secondly, the **injection molding process**, is the most popular thermoplastics manufacturing process, representing 30% of thermoplastics processing (Development, 2009), with the advantage to produce at the highest speed. First, reciprocating screw applies friction on the polymer and melts the polymers, the screw moves back in that bath and is then moved forwards like a piston to fill up the metal mold (A. Simar, 2017) under high pressure. After, the plastic hardens when the mold cools down (Fibertech, s.d.).

Finally, **compression molding process** is more often used for thermosets but can also process thermoplastics: a sheet of heated polymer is placed into a mold and compressed. The closed mold is maintained under pressure for the heating step (Development, 2009) to ensure a maximum strength. This process gives strong and durable plastic pieces and is thus often used in automotive industry to replace metal parts (Fibertech, s.d.).

2.1.5 PMMA

The poly(methyl methacrylate) (PMMA), completely amorphous polymer, is commonly known under its plastic name as **Plexiglass**, is an amorphous acrylic and thermoplastic polymer created through the free-radical polymerization of the monomer methyl methacrylate (MMA) with chemical notation $[\text{CH}_2=\text{C}(\text{CH}_3)\text{COOCH}_3]$, showing the double bond (=) between two carbon atoms in the middle (see Figure 6) (GARZON, 2018). During polymerization, one of the bound from that double bond breaks and links to another middle carbon atom of MMA. This is the beginning of a chain; repetition of the process will

finally create the polymer PMMA (PMMA, 2020). Commercial PMMA is found under an atactic⁴ configuration, and its structural configuration is shown in Figure 7.

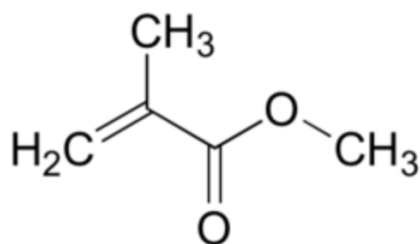


Figure 6 Structure of methyl methacrylate (MMA) (PMMA, 2020)

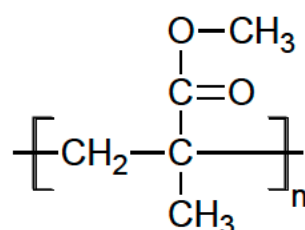


Figure 7 Chemical structure of polymethyl methacrylate (PMMA) (GARZON, 2018)

Thanks to the rigidity of its chain, PMMA has a relatively **high viscosity** and T_g (110-130 [°C]). It is known for its high intrinsic mechanical properties (high hardness, good tensile strength) and thermal resistance (GARZON, 2018), resistance to ageing through UV, resistance to scratches, and long-term stability (Cedric Samuel, 2013). Furthermore, it has a very good thermal insulation. It presents a low impact strength and can be used for applications that does not require impact resistance (Resinex, 2020).

With its **high transparency**, its **waterproofness**, and its **resistance to outdoor exposure**, it is widely used as a light substitute to glass, for windows and camera lenses, for airplane windshields, for skylights, for automobile taillights, but also for bathroom units and electrical insulation. Thanks to its **biocompatibility**, the PMMA is commonly used in medical sector as prostheses, ocular lenses, ... It is also widely used in advertising signs because of its total internal reflection (Crawford, 1981).

PMMA is usually bought under thermoplastic pastilles that can be injected, extruded or blown (Resinex, 2020).

⁴ Atactic: having random sequence of the stereochemical arrangement of groups on carbon atoms in the chain; not stereospecific (Collins, 2020)

PMMA is **easily workable**: it can be colored, molded, cut, drilled, and formed (PMMA, 2020).

PMMA is already recycled but the complicated chemical processes to recycle it makes it not the favorite one to focus on in the industries. Actually, about 300 000 tons of PMMA are created in Europe each year, and only 30 000 tons are recycled and valued each year, representing only 10% of production (InnovaTech, 2018). So the room for improvement in that sector is still enormous. Moreover, being in connection with the present global crisis due to COVID-19, PMMA used as glass to protect the workers in shops and companies, will have to be recycled and the demand will consequently increase in the following months.

PMMA should thus not be set aside, but to explore for new applications. Current researches for the large European project MMAtwo (from the larger initiative Horizon 2020) are made, with a consortium of 13 stakeholders and notably CERTECH (InnovaTech, 2018), to develop a **new innovative process to recycle PMMA waste (PI post-industrial and PC post-consumer) by depolymerization** to create high quality PMMA prime material (Certtech, s.d.).

Usually, the raw material waste of PMMA comes from the sanitary facilities, where all protection films were removed (no need to wash or sort the materials). The most convincing **PMMA recycling process is done through pyrolysis**: heat the pieces up to 450-500 [°C] (Duval, 2009) by throwing them in a molten metal bath without oxygen, to break down the PMMA into its monomer, the methyl methacrylate (MMA); it is a depolymerization process. After a few minutes only, 97% of MMA at gaseous phase is recovered and condensed. Later, because the liquid out of the pyrolysis is so pure, the MMA can be polymerized again to create PMMA, without other treatment (Duval, 2009), but experiments in Greece concludes the opposite after analysis of the direct polymer reproduction (Francis, 2017).

Other recycling processes than chemical recycling can also be used to recycle PMMA and will be further explored in the thesis.

2.2 Bioplastics

The principal source to obtain carbon and hydrogen needed to create plastics nowadays is oil. But other substantial products appear on the market: biomass, coal and natural gas. Biomass can notably be used to create bio-based plastics.

“Bioplastics” are polymers defined according to two characteristics: their **bio-based status** (derived from biomass) and their **biodegradable status** (derived from either biomass or fossil based).

European Bioplastics (EUBP, European association representing the interests of Europe’s bioplastics industry) defines bioplastics as followed: “Bioplastics – plastics that are bio-based, biodegradable, or both – have the same or similar properties as conventional plastics but offer

additional benefits, such as a reduced carbon footprint, better functionalities, or additional waste management options, such as organic recycling.” (Bioplastics, s.d.).

The **biomass**⁵ is a natural annually renewable resource, in the form of sugar, starch or lipid, that is used to create bio-based and biodegradable or not plastics (depending on their structure). This organic matter is already widely used for food, textile and energy, but also as biofuel to replace gasoline. Concerns like the reduction of greenhouse gases to lower the carbon footprint of materials, the willingness to reduce energy consumption, but also enhance the recyclability at the end of life of the product, are burning reasons to eliminate the huge oil dependence of people and develop high performance bio-based materials (GARZON, 2018).

The **biodegradability** of bio-based plastic is an important parameter at the end of the product life. Biodegradation⁶ is a degradation of natural polymers through a long process: fragmentation of material, further the destruction of macromolecules into monomers and oligomers⁷, and finally the assimilation by micro-organisms capable to transform it into carbon dioxide (CO₂) or methane (CH₄) (Duval, 2009) (GARZON, 2018)⁸. All this process is done under specific conditions. The compostability of the polymer is assumed if 60% of its carbon content is biodegraded into carbon dioxide under 180 days (ASTMD6400 (GARZON, 2018)).

There exist thus **three groups of bioplastics** (Bioplastics, s.d.):

- **Bio-based** (or partially bio-based) & **non-biodegradable** plastics: bio-polyethylene (PE), bio-polyethylene terephthalate (PET), bio-polypropylene (PP), bio-polyamide (PA)
- **Bio-based & biodegradable** plastics: polylactic acid (PLA), polyhydroxyalkanoate (PHA), polybutylene succinate (PBS), and starch blends
- **Fossil-based & biodegradable** plastics: polybutylene adipate terephthalate (PBAT), ... that could be bio-based in the future

Bio-based and non-biodegradable plastics have equivalent properties to their fossil-based siblings, and usually offer new properties as increased strength, reduced thickness and breathability.

⁵ Biomass: Ecology. The amount of living matter in a given habitat, expressed either as the weight of organisms per unit area or as the volume of organisms per unit volume of habitat. (Dictionnary, s.d.)

⁶ NB: Bio-fragmentation or dispersion is a process where macromolecules are only just fragmented, but not destroyed. Thus not to confound with biodegradation (Duval, 2009).

⁷ Oligomers: short chains with a few monomers (Duval, 2009).

⁸ NB: even if some common plastics from oil industry are biodegradable, they are not bio-based.

At their end-of-life, bio-based plastics can be mechanically recycled or composted. If these last options are not suitable anymore, they can be used for the production renewable energy (Bioplastics, s.d.). A fourth option is to chemically recycle them. Most recycling industries have still to adapt to these new end-of-life processes. With the important growth of bioplastics in the nearest future, they will have no choice than to adapt as well.

Attractiveness of bioplastics is in constant expansion, as the European Union allocated funds for research and development, and as bioplastics anchor in circular bioeconomy,

lowering ecological footprint. Mainly used in food packaging, bioplastics are at the heart of researches in many diversified applications to create materials with demanding specifications. The proportion of bio-based and biodegradable plastics used in construction are still

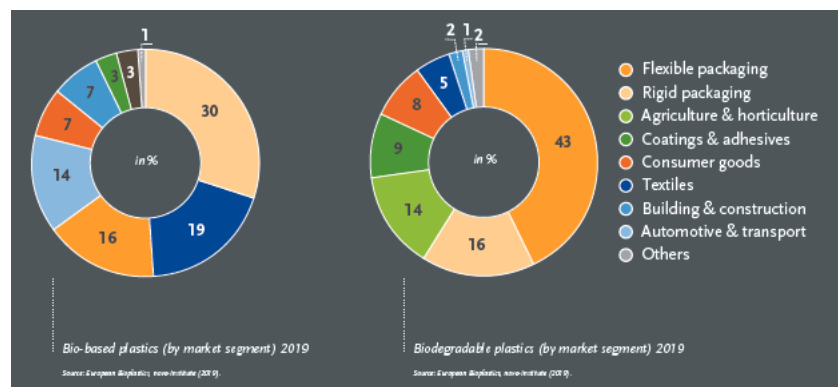


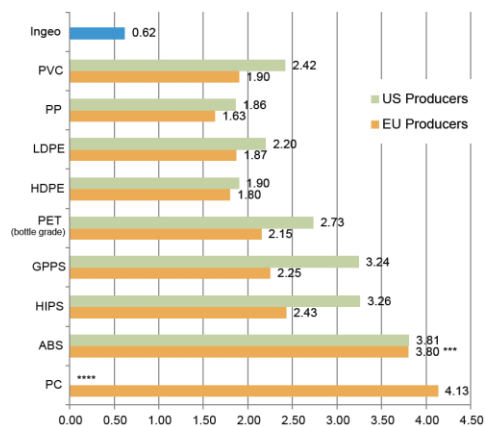
Figure 8 Market of bio-based and biodegradable plastics (Bioplastics, s.d.)

very low, and there is a huge room of improvement in the sector. Only 7% of bio-based plastics market and 2% of biodegradable plastics market are for building and construction applications in 2019 (see Figure 8, (Bioplastics, s.d.)).

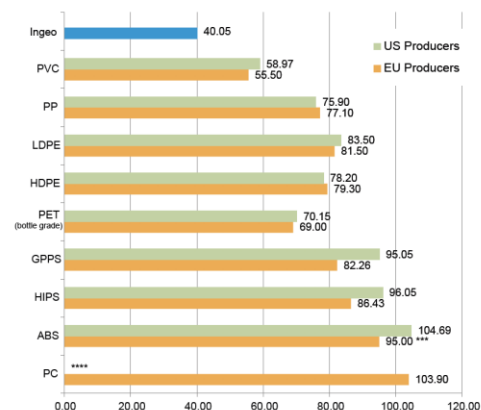
Among all bioplastics, PLA is currently the best green bioplastic on earth with the less fossil energy used (only 56 MJ/mol compare to 80 MJ/mol for PET) (Duval, 2009). Materials made of PLA reduces a lot their carbon footprint.

NatureWorks has reported the life cycle analysis (LCA) made with GaBi LCA software (Thinkstep), according to relevant standards (ISO 14040 & 14044), comparing two main indicators of the environmental footprint of PLA Ingeo and traditional polymers: the greenhouse gases (GHG's) and the non-renewable energy. It is clear from Figure 9 & Figure 10 that the PLA (Ingeo) has a better overall ecological footprint than common plastics. Only 0,7 kg of CO₂ emitted per kg of plastic for Ingeo, against almost 3 kg for PET.

**Production Greenhouse Gas Emissions
Including Biogenic Carbon Uptake ***



**Primary Energy of Non-Renewable
Resources ****



Note:

*Uptake of atmospheric CO₂ during crop production, which ends up in the biopolymer produced.

** Total use of primary energy sources like natural gas, coal, oil and nuclear.

*** Boustead data, not recently updated.

**** Not available for the U.S.

Figure 9 LCA of different plastics comparing data from America and Europe (PlasticsEurope, APC and NaturWorks Data) (NaturWorks, 2016)

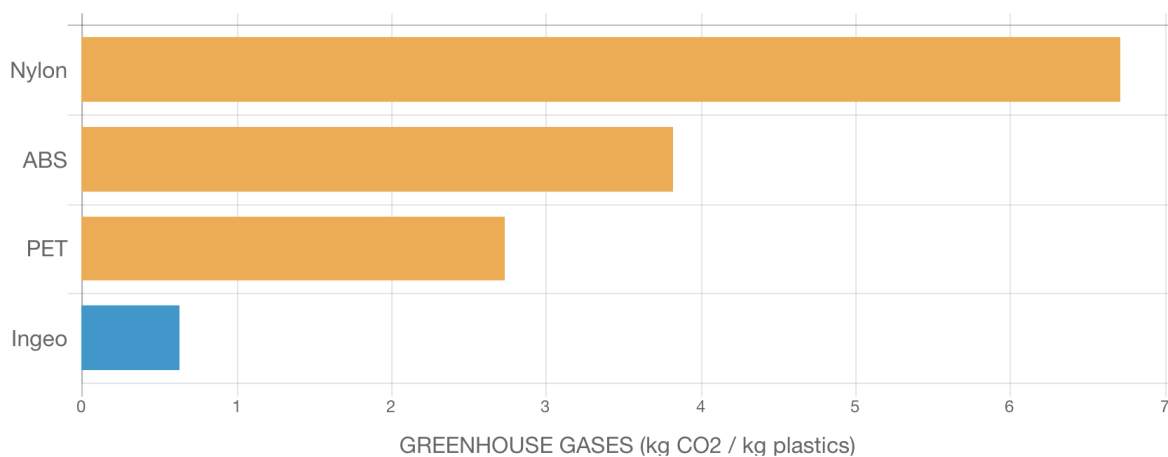


Figure 10 Carbon footprint of Ingeo compare to over common plastics (NaturWorks, s.d.)

2.2.1 PLA

The polylactic acid (PLA) is a **bio-based** and **biodegradable** plastic, usually used in applications requiring high mechanical properties, as it presents very good tensile and flexural properties. It is a sustainable material with slow degradation rate, reduced ecological footprint as it is made from annually raw renewable resources and with an easy processability for injection pieces. Moreover, it has a high water permeability. The low production costs make it relatively affordable (see 3.5). However, PLA is a brittle material that has very poor thermal properties (see APPENDIX A).

The process of creation begins by CO₂ being captured by the plants and transformed into long-chain sugar. Through a milling process, the starch (glucose, from cereals (corn)) or sugar (sucrose, from beets or sugar canes) is extracted. Hydrolysis process transforms the glucose (or sucrose) into dextrose, by the help of enzymes. The **lactic acid** (monomer of PLA) is then obtained through the lactic fermentation of dextrose by microorganisms (NatureWorks, s.d.).

The lactic acid possess two stereoisomeric⁹ forms (lactic acid L(+) and lactic acid D(-) isomers¹⁰) (see Figure 13) due to the asymmetry of one carbon atom (GARZON, 2018).

After fermentation step, the lactic acid is either directly polymerized (polycondensation) into PLA (but it is leading to a low molecular weight), or either dimerized, then polymerized by polycondensation, and finally cyclized and purified to obtain the **lactide** (see Figure 11). The lactide is then dried to eliminate the water, and finally polymerized through an opening of the cycle, creating a high molecular weight¹¹ **polylactic acid (PLA)** (see Figure 12). The polymer chains are linked together to form a long chain of PLA (NatureWorks, s.d.). PLA is thus a thermoplastic of high molecular weight that offers good mechanical properties (see 2.3.2).

⁹ Stereoisomerism (Dictionnary, s.d.): the relationship between two or more isomers that have the same structure (the same linkages between atoms) but different configurations (spatial arrangements), in contrast to constitutional isomerism in which the isomers have different structures. Stereoisomers are further classified into enantiomers, those having molecules that are mirror images of each other, and diastereoisomers, those that do not.

¹⁰ Isomer (Cambridge Dictionary, s.d.): any one of a group of chemical substances which all have the same number and type of atoms but in which the arrangement of the atoms is slightly different between each substance

¹¹ Molecular weight (Merriam-Webster, s.d.): the average mass of a molecule of a compound compared to ¹/₁₂ the mass of carbon 12 and calculated as the sum of the atomic weights of the constituent atoms.

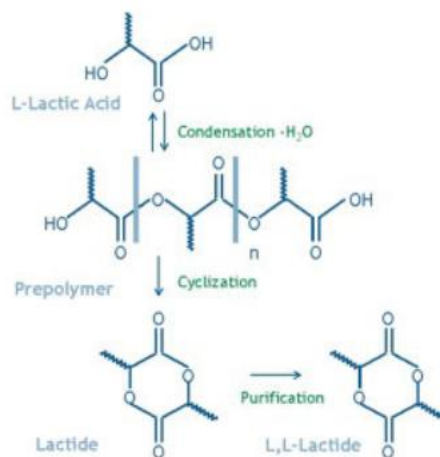


Figure 11 Synthesis of the lactide (Futero, s.d.)

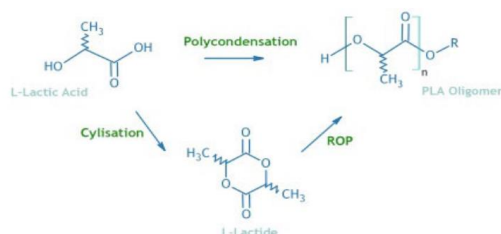


Figure 12 Both ways to create PLA (Futero, s.d.)

Thanks to both lactic acid isomers, the lactide possesses **three isomers** (see Figure 13) : LL-lactide produced with two L-lactide (giving later the PLLA), the DD-lactide produced by two D-lactide (giving later the PDLA), and the LD- or meso-lactide produced by a combination of L-lactide and D-lactide (giving later PDLLA) (GARZON, 2018).

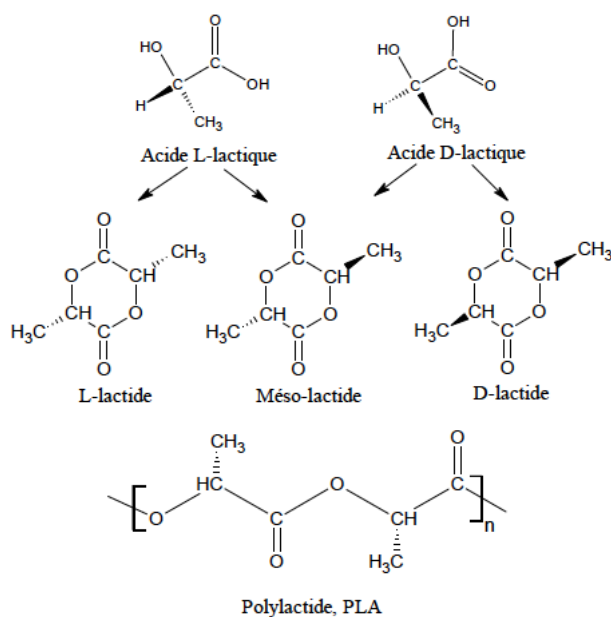


Figure 13 Chemical structure of lactic acid and lactide, and PLA (GARZON, 2018)

NatureWorks is the principal producer of PLA in the world (PLA from corn starch), and Galactic (linked to Total) is the principal one in Belgium. The PLA Ingeo 2003D from NatureWorks used for the tests are pellets containing 4,1% of D-lactic acid monomer (see PLA Ingeo 2003D).

Due to its high mechanical properties and advantages, the PLA is widely used in a very large range of applications (NatureWorks, s.d.): in construction, it is used in floors or walls (impact protections), in carpets, but also as textile fibers in sunscreens. Outside, it is used in landscape drains and agricultural films. It is also widely used for daily applications like reusable bags, trash and vacuum bags, single-used service ware, electronic cases, but also food packaging (yogurt pot, infusion bags, coffe capsule, ...) and cartons. But among all, PLA is well-known for its use in 3D printing (under the form of filament), and in medical applications: sutures, orthopedic pins, ... because of the biocompatibility between humans and lactic acid (Futero, s.d.). PLA is still not used for automotive applications due to its low thermal properties, critical for those applications, but it is subjected to many researches to increase them.

At its end of life, PLA can either be mechanically or chemically recycled, but also composted under certain strict conditions (under 60°C for a long time, making it currently difficult to handle). Post-consumers plastics products made of PLA (food packaging, ...) are collected, sorted & cleaned before recycling. The NIR technology (see 2.3.2) is already very efficient for PLA detection, enabling its recycling. PLA is mainly reused in non-food applications like agriculture, 3D filament, ... (Jašo, 2019).

2.3 Recycled Plastics

2.3.1 Recycling plastics in numbers

Yearly worldwide **primary plastic production** drastically increases over the years and reached 359 millions of tons in 2018 (Statista, 2019). From other sources, it already reached over 400 millions of tons in 2015 (Roland Geyer, 2017).

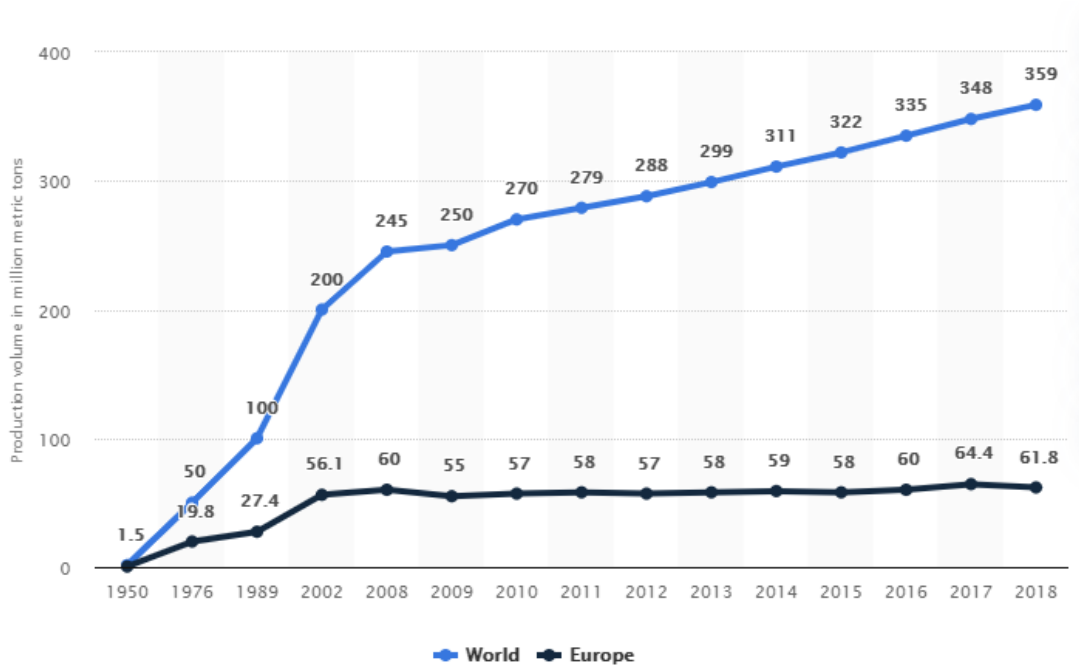


Figure 14 Global plastic production from 1950 to 2018 (in millions of matrix tons) (Statista, 2019)

Overall, ” the ensuing rapid growth in plastic production is extraordinary, surpassing most other man-made materials. Notable exceptions are materials that are extensively used in construction, such as steel and cement.” (Roland Geyer, 2017).

As far as **plastic waste** generation is concerned, estimation is that about 300 millions of tons were generated worldwide in 2015 (Roland Geyer, 2017).

This plastic waste accumulates over the years and has reached a cumulative estimated weight of 6.3 billions of tons by 2015 ((Figure 15), (Statista, 2019), (Roland Geyer, 2017)). “Of this, approx.. 800 millions of tons (12%) of plastics have been incinerated and 600 millions of tons have been recycled, only 10% of which have been recycled more than once. Around 4.9 billions of tons – 60% of all plastics ever produced – were discarded and are accumulating in landfills or in the natural environment.” (Roland Geyer, 2017).

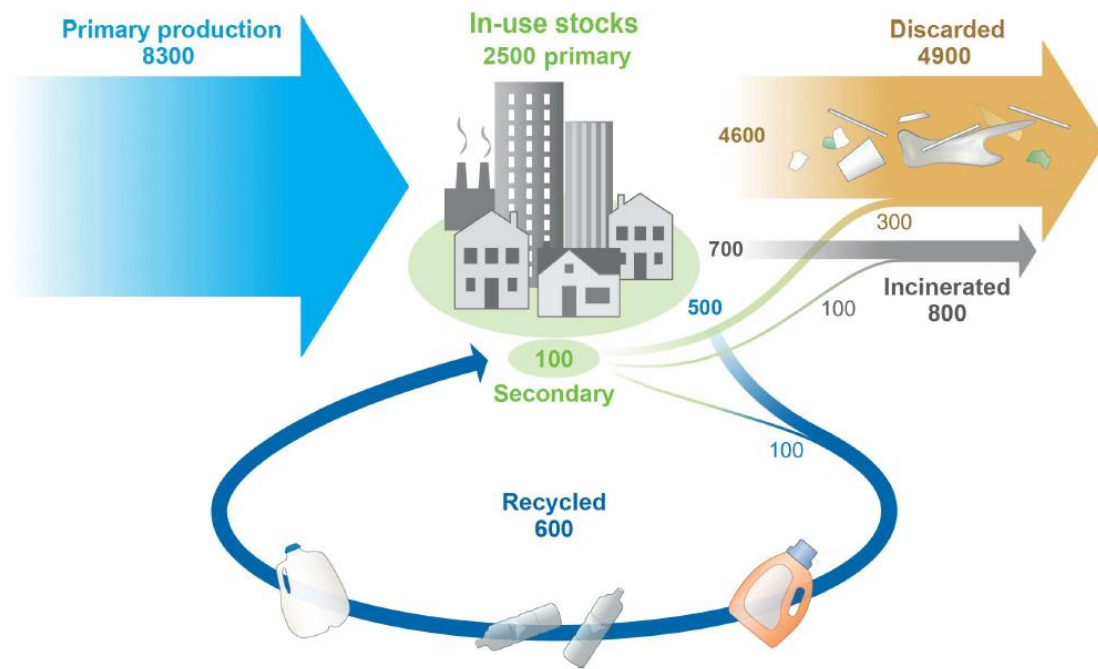


Figure 15 Global production, use and fate of polymer resins, synthetic fibers and additives (1950 to 2015; in millions of metric tons) (Roland Geyer, 2017)

It is also estimated that on average, 3% of the yearly generated plastic waste goes into the oceans, up to 8 millions tons of plastic (Jenna R. Jambeck, 2015).

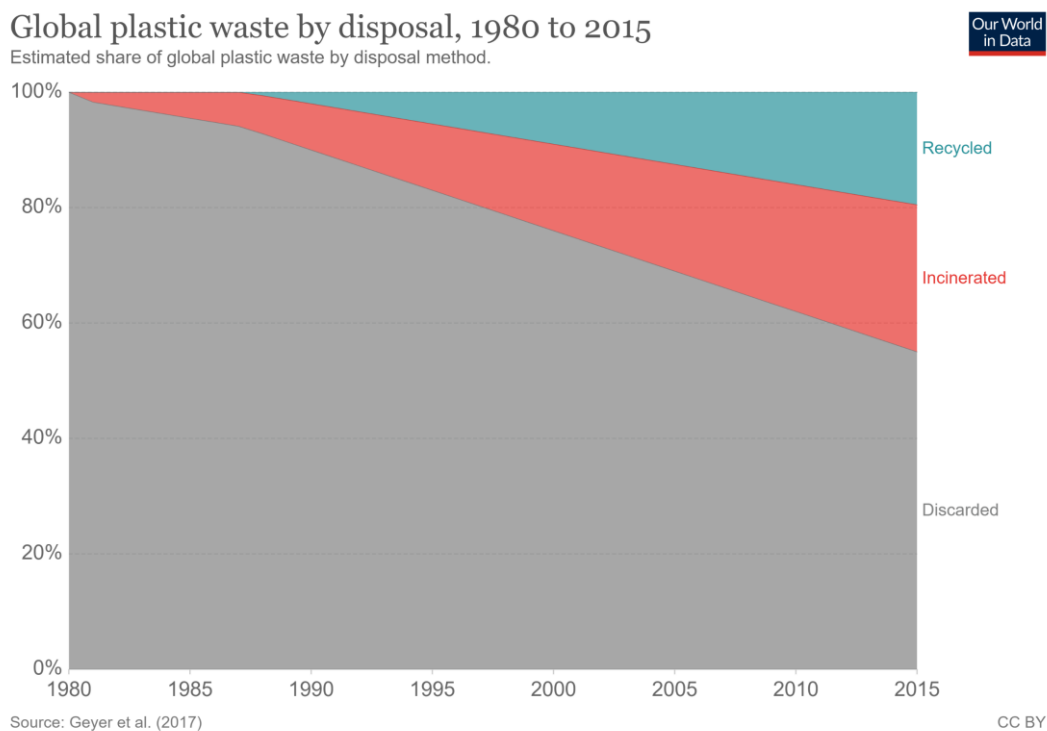


Figure 16 Global Plastic waste by disposal, 1980 to 2015, (Richie & Roser, 2018)

The proportion of recycled plastics is increasing over the years. However, it is still under 20% in 2015 (Figure 16) and there is thus a huge room for improvement. The incineration has also increased (above 25%) but its ecological footprint and impacts on the health are still very much depending on the quality of the incineration process (Roland Geyer, 2017).

The waste of plastics is integrated in a much larger crisis of waste in all aspects, and the problematic is more and more tackled by Authorities and Non-Governmental Organizations and groups of companies, as illustrated by the following examples:

- the Zero Waste Europe (ZWE), a movement of local initiatives to create a circular economy that completely eliminates waste (Foundation, s.d.).
- the Plastic Solutions Fund, an international partnership between organizations working to reduce plastic waste worldwide, in particular single-use plastic; the fund is particularly concerned by the marine litters and the disintegration of plastics into microplastics (smaller particles), that end up in our food chain and our drinking water (Foundation, s.d.);
- the “Recycling of secondary raw materials for a sustainable optimization of construction processes in Civil Engineering”, a European initiative, which tries to increase the use of « Secondary Raw Materials (SRM) », and notably the plastic waste (Commission, 2014);
- back in 2015, the EU Circular Economy Action Plan, already tried to encourage recycling and re-use of plastics (Commission Européenne, 2019).
- due the stop by China of plastic importation and thus recycling of a part of European plastic waste, at the beginning of 2018 (France Info, s.d.), the European Union (that produces 25 million tons of plastic waste every year (Commission Européenne, 2018), took several drastic decisions to reduce its plastic waste, a.o.:
to reduce plastic bags and forbid single-use plastics (cutlery, plates and straws),
to get to a 90% separate collection target for plastic bottles by 2029,
to incorporate 25% of recycled plastic in PET bottles as from 2025 and 30% in all plastic bottles as from 2030 (Commission Européenne, 2019),
all plastic packaging on the EU market to be recyclable by 2030 (Commission Européenne, 2018);
- since 2019, a group of 40 companies (among others Suez, Total, ...) joined their efforts in the Alliance to End Plastic Waste (Alliance to end plastic Waste, 2019), in order to try to solve the problem of the yearly 8 millions tons of plastics going into the oceans.

Over the years, the plastic waste ending in the oceans has formed the so-called 7th continent, **The Great Pacific Garbage Patch**, developing and polluting at an exponential rate; these debris break down by photodegradation into microplastics (National Geographic, s.d.), that are substantially harmful for our food chain. Some organizations play an important role to tackle this 7th continent issue:

- the non-profit organization Ocean Cleanup (The Ocean Cleanup, s.d.) has made many reconnaissance missions to visualize the plastic distribution in the patch and are working daily to rid the world's oceans of plastics;

- it has also been modeled that about 80 000 tons of plastics are floating , divided into 1,8 trillion pieces (representing 250 pieces for every human in the world) over 1,6 million square kilometers (L. Lebreton, 2018).

There is thus a huge opportunity to use these waste before they get into oceans and landfills, and recycle them, sometimes even more than once and hence tackle the environment issues.

As a result, the present thesis is well positioned within these global efforts. In order to be in line with the circular economy objectives, we indeed try finding a new application for recycled plastics in structural engineering. Eventually having that new material recyclable would be even better.

2.3.2 From waste collection to material recovery

Plastics have been created to be resistant and durable. Therefore, they have a great lifetime and are excellent candidates to be recycled and used more than once.

Life cycle of polymers

The Society of Plastic Industry have developed the plastic recycling codes back in 1988 (from 1 to 7, see Figure 17) to differentiate the polymers and have a better control when collecting and sorting them (AZoCleantech, s.d.).



Figure 17 Plastic recycling codes (AcmePlastics, 2018)

At the end of their life, polymers materials are collected from consumer in bags (mainly PET & HDPE). In Belgium, they are carried to sorting center and undergo the following process (FostPlus, s.d.) (Pack, s.d.):

- plastics are first mechanically sorted by color,

- then PET is pre-washed in warm water to remove impurities (& labels & glues, up to 60% eliminated),
- again the two separate fluxes (PET and HDPE) are sorted to remove the extraneous materials (usually metals) manually or automatically,
- baling (if transportation to another site is needed)
- they are then crushed (into sequins, flakes, granules or petals),
- they are washed by friction to remove remaining impurities (& paper & glue)
- the process continues with the flotation of the flux to separate lighter material (HDPE, PP, ..., floating) than heavy ones (PET, PVC, metals, ..., diving), because densities are different for each polymer.
- finally, they are spinned and dried¹²

This process is applied to **post-consumer waste** (PC waste), because the composition of polymers is unknown. **Post-industrial waste** (PI waste) are in contrast directly crushed, because their composition is known (Kim Ragaert, 2017). The quality of the grades, their purity, are different for each flux, but generally from higher grade for PI waste. However, the high accuracy of sorting and recycling process also lead to high grades. The grade also influence the properties of the recycled material: high quality grades keep good properties after recycling process.

Thereafter, the sparkles can be compound¹³ into granules or pellets (easier to convert later on) through extrusion : sparkles are heated and treated (sometimes additives are added) in the extruder.

This cycle from waste to new raw materials is named *End-of-Plastic*.

Further, these granules and pellets are used to manufacture into finished or semi-finished new objects by reprocessing them in converters (injection or compression moulding usually).

This process of **mechanical recycling** (used later in the master thesis) is very common and known as the *secondary recycling*.

¹² NB: For food applications, sparkles go through a second cycle to reduce even more the impurities.

¹³ Compounding is a process of melt blending plastics with other additives. (Anon., s.d.)

There exist **four types of recycling plastics** in reality ((Régis Kovacs Scalice, 2009) (DEVAUX, 2014)):

- primary recycling: a *mechanical recycling* of the post-industrial waste directly reintroduced into the same process, to create new plastic products,
- secondary recycling: widely spread, this *mechanical recycling* transforms solid consumer waste into raw materials to further create new plastic products,
- tertiary recycling: *chemical recycling* process, where solvents are used to depolymerize the polymers into initial monomer, and use them to re-create polymers,
- quaternary recycling: *thermal recycling* through an energetic recycling where energy is recovered from polymeric waste by controlled incineration.

Those four types of recycling are drawn on the lifecycle scheme on Figure 18. Landfill should be avoided and more solutions to recycle plastics have to be found to avoid pollution.

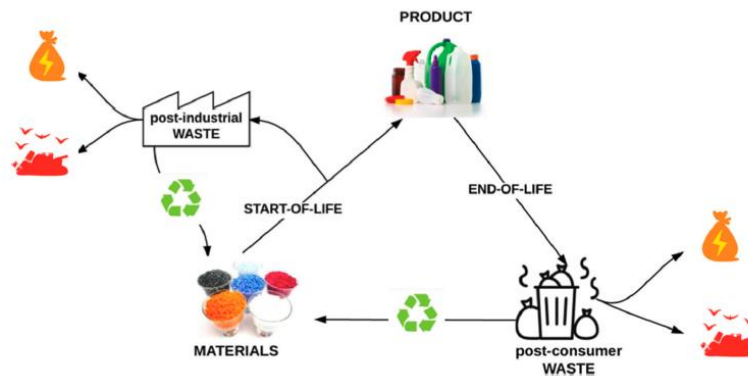


Fig. 1. Lifecycle of polymer materials. Depending on the chosen route, polymers will end up in recycling, energy recovery or landfill. Icons adapted from (PlasticsEurope et al., 2015).

Figure 18 Lifecycle of polymers (Kim Ragaert, 2017)

The following table presents the best recycling category to use with the different types of plastic waste (Figure 19). It appears that mechanical recycling is the most preferable process for single plastic waste, and chemical recycling for mixed plastic waste. These will be used further in the thesis. Moreover, for high quality grades (high purity), when plastic is not contaminated and has no paint coating, it is better to use the mechanical recycling that almost loss no quality (Régis Kovacs Scalice, 2009).

Table 1. Comparative of various methods of plastic recycling (BELLMANN; KHARE, 1999).

Type of plastic waste	Mechanical recycling	Chemical recycling	Energy recovery
Single plastic waste	++	+	+
Mixed plastic waste	+	++	++
Mixed plastic waste plus paper etc.	–	–	–

(-): not applicable (+): suitable (++) preferred.

Figure 19 Comparative of various methods of plastic recycling (Régis Kovacs Scalice, 2009)

Recycling Technologies

There exist a whole bunch of recycling technologies as near-infrared, ultraviolet, x-ray, laser,... techniques to sort conventional polymers.

The near-infrared (NIR) is the most common plastics sorting technology used in the industries as it confers a high accuracy. Along with common polymers (PE, PP, PVC, PS and PET), NIR can also identify bioplastic like PLA, carton boards and metals.

An infrared beam identifies each polymer progressing on the conveyor belt, by recognizing its unique light intensity reading. Air nozzles trigger to throw the identified polymer in the right container (Biolplastics, 2015). The high accuracy in sorting the waste with NIR technology is introduced in Table 1. The NIR technology is thus widely used because of its accuracy and thanks to the fact that some impurities in recycled polymers are usually tolerated if very little (5% max in PLA, for example) (Jašo, 2019).

Polymer	PP	PE	PET	PS	PVS	PLA	Throughput
Purity Achieved*	96%	94%	94%	87%	93%	97%	3tph

Table 1 Accuracy of NIR sorting technology (Biolplastics, 2015)

Loss of mechanical properties

The main challenges of the mechanical recycling are the degradations of polymers: lifetime degradation and thermal-mechanical degradation (Kim Ragaert, 2017).

Indeed, the long-time exposure to light, heat, oxygen, ... induce a photo-oxydation process where polymer chains are affected and hence the polymer is degraded (Kim Ragaert, 2017).

The structural changes due to this **lifetime degradation** are similar to the ones occurring because of **thermal-mechanical degradation**.

The challenge through mechanical recycling is to keep a high molecular weight. Indeed, molecular weight M_w^{14} depends on the capacity of the polymer to create links between its chains, named chain branching or cross-linking, to have a cohesive material.

During the melting process, heat and mechanical shear causes degradations through chain scissions. If the chains are not able to branch again by crosslinking, there is a loss in M_w . This

¹⁴ Molecular weight (Merriam-Webster, s.d.): the average mass of a molecule of a compound compared to $1/12$ the mass of carbon 12 and calculated as the sum of the atomic weights of the constituent atoms.

loss in M_w induces a loss in mechanical properties like elongation at break and impact properties. On the following Figure 20, the plot shows the steep decrease in molecular weight (M_w) and the elongation at break (EB), through several extrusion cycles that the plastic would undergo through multiple recycling processes (Kim Ragaert, 2017).

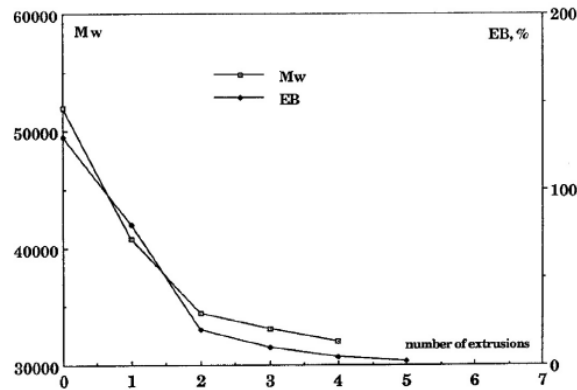


Figure 20 Change of Molecular weight and Elongation at break for PET sample through the number of recycling processes (Kim Ragaert, 2017)

Mechanical recycling affects thus mechanical properties, but also rheological, thermal and physical properties (colour, surfaces, ...). To compensate this thermal-mechanical degradation, additives are usually added (pigments, heat stabilizers, impact modifiers, ...).

Compatibility of blends

“Blending plastics is particularly an interesting solution to providing value-added products after recycling mixtures, since it is possible to obtain improved properties that could be commercially explored.” (Régis Kovacs Scalice, 2009)

Indeed, when recycling polymers, different mixture can be achieved and mixed together through an extruder for example. But all mixtures are not feasible. The polymers constituting the blend need to be compatible.

Nevertheless, two polymers are usually not compatible thermodynamically: compatibilizers and cross-linking additives are thus usually added to the blend. It increases the interfacial adhesion and hence the mechanical properties (Régis Kovacs Scalice, 2009).

The literature review showed us that researchers do not always agree on the compatibility of polymers, and the great number of additives each plastic can enclose, makes the definition of compatibility difficult to settle.

For example, Pahl & Beitz (1996) and Renault consider PE and PP as fully compatible (under certain conditions), whereas Hensen consider it as incompatible (Régis Kovacs Scalice,

2009). Also, PC and ABS are compatible, but only under certain conditions: it depends on the molecular weight of PC, processing conditions and ABS content.

Many compatibilization becomes feasible with a certain number of additives, but it only leads to a compromise. Indeed, by adding additives to increase a property, it usually goes along with decreasing another property.

Finally, find a compatible blend that enhances the properties of both polymers, without additives, is the best solution to add value at the end-of-life process.

2.3.3 Recycling of PLA/PMMA

P. Coszach, J-C. Bogear and J. Willocq have developed a chemical recycling process of PLA by **hydrolysis** (P. Coszach, 2013). The chemical recycling (or depolymerization) of a polymer blend containing PLA can be operated through the following 5 steps:

- **Grinding** of the material: the aim is to increase the specific surface area of materials, helping to speed up the dissolving step.
- **Dissolving the PLA** of the blend: the dissolution of the PLA is operated through a solvent (like benzene, chloroform, ...) not ecological.
To handle this, an alternative is to directly dissolve the PLA in lactic acid ester (methyl lactate, butyl lactate, lactic acid alky, ...) that also separates the solid impurities. The process is carried out at different temperatures up to PLA melting temperature.
The other polymer(s) (for example the PMMA or rPMMA) undissolved can be recovered for subsequent use, by filtration or other similar processes.
- **Chemical Recycling of PLA**: depolymerize the PLA to get back to its monomer, the lactic acid. The depolymerization can be made through **hydrolysis**¹⁵ under specific conditions (temperature: preferably between 120 & 140 [°C], pressure: under depression or between atmospheric and 10 [bars] or higher), enabling the creation of lactic acid.
- **Purification** of the lactic acid ester obtained through hydrolysis; purification of the lactic acid obtained from PLA hydrolysis in previous step, in order to meet high quality grades. The following steps could be used to purify: removal of ions, color and impurities, concentration, distillation, crystallization, etc. This is an easy step thanks to the very few degradation of the product due to low temperature used for hydrolysis.
- Side step: Hydrolysis of lactide acid ester: the lactic acid ester used for dissolution of PLA can be hydrolyzed (with water and under atmospheric pressure or depression).

¹⁵ Hydrolysis (Lumen, s.d.) : breakdown of polymers into monomers by using a water molecule and an enzymatic catalyst. It breaks a covalent bound holding together two components of a polymer and releases energy.

Alcohol formed after reaction has to be removed to form the lactic acid. **This lactic acid possesses good specifications and can be reused for other applications.**

2.4 Use of recycled plastic in structural engineering: state of the art review

We provide herebelow a wide listing (illustrations, description and advantages) of major existing applications that, in structural engineering, use plastics or recycled plastics.

According to J.S. KIM and V. CHANDRA (J. S. KIM, s.d.), **recycled plastic composites** were first used for railroads cross ties and are now also used for bridges, making them more sustainable and green. Many thermoplastic bridges have emerged since HDPE (high-density polyethylene) took place in the U.S. market in the 1990's



Figure 21 First vehicular bridge at Fort Leonard Wood, Missouri (1998) (J. S. KIM, s.d.)

A new **vehicular bridge** deck built from a blend of immiscible HDPE emerged in the Missouri (USA) back in 1998 to replace the old one, still supported by the steel girders structure.

Advantages: no maintenance needed nor degradation (J. S. KIM, s.d.)



Figure 22 Vehicular bridge at Wharton State Forest, New Jersey (2002) (J. S. KIM, s.d.)

Another vehicular bridge, in the New Jersey (USA), was built in 2002 to replace the actual wood bridge.

Characteristics: able to support 33 tons of Live Loads, first thermoplastics I-beams as girders.

(J. S. KIM, s.d.).



Figure 23 First bridges made of almost 100% recycled plastics at Fort Bragg, North California (2009) (J. S. KIM, s.d.)

First **bridges** made of almost 100% recycled plastics (made of HDPE – high density polyethylene and PP – polypropylene and encapsulated glass fiber reinforcement), military bridges for U.S. Army, were built in North California (USA) in 2009.

Characteristics: able to support a M1 Abrams Tank load of 65 tons. (J. S. KIM, s.d.)



First **railroad bridges** also made with the same material, and 150 tons of recycled plastics, were built in Virginia (USA) in 2010.

Characteristics: pilings, piers, crossties, superstructure all made from that recycled thermoplastic materials AND can support 118 tons live loads on 4 axles.

Figure 24 First railroad bridges made of almost 100% recycled plastics at Fort Eustis, Virginia (2010) (J. S. KIM, s.d.)

Design: limit deflection $L/600$

Characteristics of the two bridges:

Bridge No. 3 layout : 11,7 [m], 4 spans (2,4 to 2,9 [m]), 6 piles (300mm diameter and in thermoplastic) at 2 end and 2 intermediate bents.

Bridge No. 7 layout : 25,6 [m], 8 spans (2,4 to 2,9 [m]), 6 piles (300mm diameter and in thermoplastic) at 2 end and 7 intermediate bents, beam = 2 three-spans continuous units and 1 two-spans continuous unit.

Superstructure: 2 clusters of three 450mm I-beams each (made of 2 T-beams because of problem of availability at that time) + cover panels to strengthen the structure and limit the deflection.

(J. S. KIM, s.d.)



First thermoplastic **highway bridge** again made of the same material, including for the abutments and wingwalls, was built in Maine (USA) in 2011.

Characteristics : able to sustain the truck live load of a AASHTO HL-93

Figure 25 First highway thermoplastic bridge made of almost 100% of recycled plastics at York, Maine (2011) (J. S. KIM, s.d.)

The recycled material is made of :

HDPE-based Recycled Plastic Lumber (RPL) (1990, USA) → low elastic modulus, great creep. Thus development of Reinforced Structural Plastic Composite (RSPC - thermoplastic) → higher elastic modulus, better creep resistance

Because they incorporated immiscible polymer blend (IMPB) composite reinforced with polypropylene (PP) coated glass fibers.

Properties of this thermoplastic:

Table 1: Properties of Thermoplastic Material

Properties and Testing Methods	Values
Elastic Modulus (ASTM D6108)	1.75 GPa
Allowable Tensile Stress (ASTM D638)	4.2 MPa
Allowable Flexural Stress (ASTM D6109)	4.2 MPa
Allowable Comp. Stress (ASTM D695)	4.2 MPa
Allowable Shear Stress (ASTM D6109)	2.4 MPa
Coeff. of Thermal Expansion (ASTM D696)	0.0000508 m/m/deg C

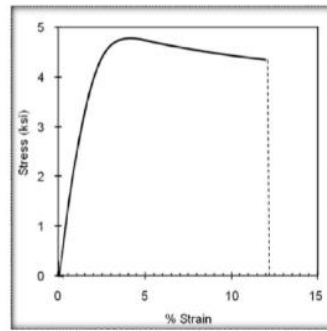


Fig. 2: Stress vs. Strain of Thermoplastic

Figure 26 Properties of the thermoplastic obtained by ASTM tests (J. S. KIM, s.d.)

density : 880 [kg/m³] (=0,88 [g/cm³]) → close to the density of the wood; ultimate tensile strength: 30 [MPa], but, because of the creep we want to deal with, only 4,2 [MPa] max will be used to keep level of stress and creep allowable → no creep for at least 25 years with constant loading. Coefficient of thermal expansion: 4 x the one of concrete. Failure strain : 30 x the one of concrete.

Other important properties about colors, degradation, ...:

it keeps its mechanical properties in humid or wet environments; environmental resistance: resistant to corrosion, rot, insects, ...; abrasion: highly resistant to abrasion (in marine environments : abrasion due to salt and sand); surface texturing: possible to add (during embossing process in line).

Advantages: less energy production for thermoplastics; material does not rot, rust, corrode or release toxins in air and water (no poisons because no carcinogens, no added chemical); product can be RECYLED AGAIN when done; construction is faster because lightweight thermoplastic material (hence no special equipment required for transportation, nor construction; cost-effective solution; low maintenance needed.

(J. S. KIM, s.d.)



Figure 27 Plastic Bridges in Rotterdam (Material Distric, 2016)

Cyclists and pedestrians **plastic bridges**, made by FiberCore Europe (FiberCore Europe, s.d.) in the Netherlands (first one in 2009 in Rotterdam, and then 90 such bridges for the city (Material Distric, 2016)) are made of fiber-reinforced polymer (FRP).

Advantages of FRP: very light thus easier and faster to set in place than a conventional steel or wooden bridge, no need of a heavy foundations, does not rust, is not sensitive to moisture, nor fatigue, nor corrosion, no need for maintenance, can last for 100 years (compared to 25-30 years for a wooden bridge), is resistant to temperature changes and UV; also, less energy (half) is used to produce plastic than steel



Figure 28 KLP recycled plastics footbridge near Rickmansworth in Hertfordshire (England) (ECS Engineering Services, 2014)

A 10 m **footbridge** (ECS Engineering Services, 2014), made by of KLP recycled plastics (a lightweight material made of recycled polyolefins and fibers (Material Distric, 2016) and reinforced with structural steel for the load bearing sections; in 2014 near Rickmansworth (England).

Advantages of KLP: more durable, with minimal carbon footprint, and less slippery than wood, excellent resistance to corrosion, no need for maintenance and easy workability, high finish quality, as well as a sustainable solution to virgin materials



Figure 29 The Easter Dawyck Bridge (Iberdrola, s.d.)

The Easter Dawyck Bridge, made up of 50 tons of waste, the longest **recycled plastic bridge**, crossing the river Tweed in Scotland, UK. The bridge is divided into 3 spans of 9 meters each and can support a load of 44 tons. Made of a 100% recycled and recyclable thermoplastic material developed by researches from Rutgers University (U.S.) (Iberdrola, s.d.), and made of HDPE, combined with polystyrene (PS) (from takeaway boxes) and rigid plastics in right quantities.

in right quantities.

Advantages of the composition: light, no corrosion, no maintenance needed, very stable and 100% recyclable, thus a sustainable material; it is very pliable when hot and can thus be shaped in many different civil engineering structures (girders, columns, bridges, ...) (Iberdrola, s.d.).



Figure 30 PlasticRoad (Material Distric, 2016)

Only at the pilot stage (not easy to convince the Authorities), 2 pilots cyclists roads of 30m length placed in 2018 in Zwolle and Giethoorn towns in the Netherlands (VolkerWessels, s.d.).

The concept is a sustainable road made of 100% recycled plastic (plastic bottles from the ocean), the “PlasticRoad” (some prefab

sections would be created in factory and assembled on site, hollow sections allow to run cables, piping and water) and was developed in 2015 by VolkerWessels, a Dutch company (VolkerWessels, s.d.).

Advantages: the road would be quicker to construct (weeks rather than months), more

durable (lifespan multiplied by 3), can be used as soon as it is placed and resist to extreme temperatures from -40°C to 80°, lightweight structure (very important on sand-based surface like in the Netherlands).



Figure 31
Polli-Bricks used to construct
the Pavillion EcoARK in
Taipei, Taiwan (2010)
(MiniWiz, s.d.).

The hexagonal cylindric bricks named “Polli-Bricks” and made of recycled PET. Usually used as honeycomb panels. Once the Polli-Bricks are set, panels are used to close the embossed walls. Developed by MiniWiz, a Taiwanese company.

In this application on the Pavillion EcoArk, 1.5 million plastic bottles were recycled (MiniWiz, s.d.)

Advantages: very easy to modulate and carry, translucent, good insulation (thanks to the air inside) from heat, cold and noise (sometimes, sand is filled inside to isolate even more); with their hexagonal 3D shape, they resist correctly to earthquakes (Guillaume, s.d.) and do not require chemical additives; weight 1/5th of conventional curtain walls; are durable and easy to clean.



Figure 32 Polli-Ber Bricks
(MiniWiz, s.d.)

The “Polli-Ber Brick”, a brick made of plastic and rice husk agro-waste, is another sustainable materials developed by the same company (MiniWiz, s.d.)

Advantages: no need of mortar as they nest in each other, it gathers many capabilities even in horizontal, vertical or curved directions.

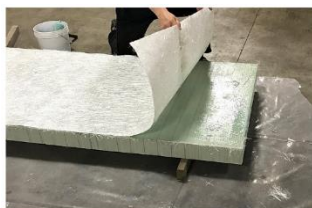


Figure 33 Structural Insulated
Panel (SIP) (Composites, s.d.)

A house in Nouvelle-Écosse, Canada. Developed by the JD Composites company. The company aimed at creating a recycled plastic composite. The house is made of, notably, more than 600,000 recycled plastic bottles. The bottles are recycled into a PET Structural Foam and covered by glass fibers to increase its solidity and decrease its fragility; the panel is named “Structural Insulated Panels” (SIP) ((Radio-Canada, s.d.), (Composites, s.d.)).

Advantages: able to sustain extreme wind (it withstands a 326mph sustained wind force, equivalent to twice a Category 5 hurricane); resistant to moisture/waterproof; lightweight; durable; good insulation performance (lowered heating bill), rapidity of assembling (one day only to settle all the walls of the house).



Figure 34 ByBlock by ByFusion (Leclercq, 2016)

“ByBlock” (initial name “RePlast”) is a semi-structural brick made of 100% of any plastic waste (even dirty and abraded), constructed in a machinery called “ByFusion” that can produce one brick of 10 kg every 40 sec.

Patented and developed by Peter Lewis (New Zealand), it tackles the recycling of the dirty plastics. It recovers the discarded plastics at garbage collection centers, shred, wash, rinse and dry to finally compress and fuse them with super-heated water (steam-based process) in the ByFusion (ByFusion, s.d.).

The density, the shape and the size can be adapted according to needs. The target regions are initially the coastal ones. ((Legrand, 2017), (Circular, 2016), (Engineering For Change, s.d.), (ByFusion, s.d.))

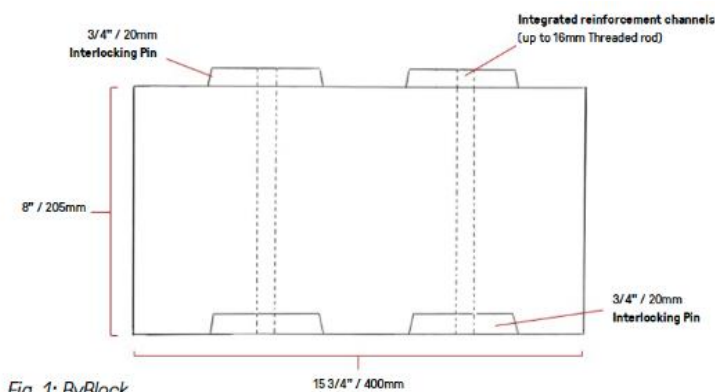


Fig. 1: ByBlock

Figure 35 ByBlock Dimensions (ByFusion, s.d.)

Advantages: lightweight (10 kg), have a good compression and shear strength, easily nested/locked together and can be nailed, screwed, stapled, sawed and drilled, allowing numerous applications (walls, shelters, garages, non-load bearing walls, sound walls, furniture, ...). Good thermal and acoustic isolation, young modulus is 8,4 [GPa] and a load range of 3,4 to 4 [MPa].

Reinforced by threaded rods (and post-tension) to increase the strength and integrate with the rest of the building (wood, concrete, steel). Stable thermal properties and insect resistance. Doesn't crack, fracture or crumble like concrete blocks, no maintenance need, only small surface degradation (sun bleached color) appears if it is directly exposed to the UV. ByBlock brick would emit 41% less GHG than a concrete brick. NB: “ByBlock” walls should not exceed 2,4m without additional structural support.” (ByFusion, s.d.).



Figure 36 Prototype One UNIBRICK and UNIBRICK SAMPLES (Designs, s.d.)

A stackable brick made out of waste plastic and fly ash (100% recycled plastics (HDPE, LDPE, PP and PET)), and easy to process (gather the waste, sort and clean the plastics, shred it into small pieces (9mm) and then process), called “UNIBRICK”, was developed in the Netherlands by the architect Rushabh Chheda (as master thesis) (Delft, s.d.) and the startup venture Conscious Designs, founded in October 2018 (Designs, s.d.). Finds application in developing countries, e.g. in Mexico City, to easily build their houses themselves, making housing construction simpler, cheaper, faster and more sustainable (Clean Energy Challenge, s.d.), as the brick has a self-locking design and integrates local waste (Material District, 2019). As an example, there is 1,5 kg of plastic recycled in one PP-made brick, its compressive strength goes up to 40 [MPa], and its density is 0,9 [g/cm³]. As per Chheda, a 4 adults’ family

house of 55m² can be built in a few weeks, recycling appr. 6 tons of waste plastic and saving 40% of construction costs.

Initially processed in a wooden mold by forcing and shaping the molten plastic inside, the mold was rapidly enhanced by making it into aluminum, thereby having nicer finishes. There is no need of binding agent or mortar, tight together with M8 threaded rods through the holes in the bricks, and attached with standard nuts (Designs, s.d.), can provide a bit of elasticity to the structure (Clean Energy Challenge, s.d.).

Advantages: can connect it in many different ways. Good insulation (3 times more than clay bricks), can resist to high temperatures. UV resistant, low moisture absorption, fungus resistant. Resistant to earthquakes.



Figure 37 Classrooms in Côte d'Ivoire, Plastic blocks made by Conceptos Plásticos (Conceptos Plásticos, s.d.) (UNICEF, 2019)

Plastic blocks out of 100% recycled plastics waste from polluted areas, a recently presented collaboration between UNICEF (the United Nations International Children's Emergency Fund), that “administers programs to aid education and child and maternal health in developing countries” (HarperCollins Publishers, s.d.), and the

Colombian social enterprise Conceptos Plásticos, for a “first-of-its-kind factory” (UNICEF, 2019) to be able to construct 500 classrooms in Côte d'Ivoire. *Advantages: waterproof, well insulated, fire resistant, designed to resist heavy wind, 40% cheaper, and 20% lighter* (UNICEF, 2019).

Similar recycled plastic lego-style bricks for some other classrooms in Côte d'Ivoire and houses in Colombia had already been created by the Colombian startup (Conceptos Plásticos, s.d.), (founded in 2011)). The bricks are made from 100% plastic waste. The process is simple: melt the plastic waste, then pour it into a mold via extrusion (Foggin, 2018). *Advantages: the simple conception of the brick allows them to slot easily and enables anyone to build their houses by themselves*. N.B.: Some more tests need to be performed to prove their capacities as construction materials.

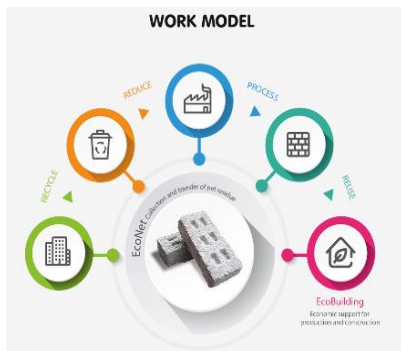


Figure 38 Brick made by Eco Inclusión (Fundación, s.d.)

Blocks made of 100% waste of PET bottles (or any not recyclable plastic). Created by Fundación EcoInclusión, a volunteer foundation founded in 2015 by 3 Argentinians. One brick weights 1,2kg and is made out of 20 bottles of 1,5 liters. The process is similar to the process of concrete bricks: crush the plastic bottles, add sand, cement and water and molded in a mold. Through the whole process, no heat is needed, the brick set itself by contact with the air (Fundación, s.d.). The founders wanted to generate an environmental, economic and social impact to the communities in vulnerable sectors (Faucompré, 2018).



Figure 39 Synergia pavilion made entirely of recycled plastics in Columbus (USA) (Grozdanic, 2017)

Origami pavilion made of recycled plastics on the site of Eero Saarinen's North Christian Church. Thought in Columbus (Indiana, USA). by the students of IU School of Art, Architecture + Design in Bloomington, and led by Professor Jiangmei Wu. Composed of more than 500 bisymmetric polyhedrons hand folded from translucent corrugated recycled plastic sheets, and interlocked together to form a hexagonal shape structure. *Advantages: self-supporting lattice that does not need framing or assemblage* (Grozdanic, 2017).



Figure 40 Pneuhaus Bubble Dome (Grozdanic, 2015)

The Pneuhaus Bubble Dome is a temporary structure made of hundreds of TPU inflated balls and supported by hand-sewn nylon webbing. The construction was made of 2 phases: partially inflate the balls, link them with the webbing and then inflate them to full pressure. There are no external supports or pressure. Three friends graduated from the Rhode Island School of Design designed temporary and inflatable

architecture, with the help of Rihno and modern softwares (Grozdanic, 2015).



Figure 41 Head in the Clouds, New York, 2013
(Brooks, 2014)

STUDIOKCA, an American firm from New York created out of 53 780 recycled plastics bottles a dreamy, cloud-shaped shelter named “Head in the clouds”. Created in 2013 for the City of dreams competition, this 40 feet-tall (12,192 m) shelter can host 50 people. It is not less than 200 volunteers that have assembled bottles and water jugs form

local schools and businesses on the massive structure. Some of them are filled with blue dyed water: “Our practice explores how light and materials tell a story, shape an experience, and create a sense of place” (Brooks, 2014).

Plastics as coarse aggregate for structural concrete

From an article published in the International Journal of Innovative Research in Science, Engineering and Technology (IJIRSET) (Praveen Mathew, 2013), four Indians of the Mar Athanasius college of engineering in Kothamangalam have researched to **use recycled plastics as coarse aggregate for structural concrete**. As plastic loses its strength when recycled many times, they thought it is better to recycle it once and use it as plastic coarse aggregate (PCA) to replace natural coarse aggregate (NCA) in structural concrete. One of the main problems in the concrete is the crushing of the aggregates; PCA has low crushing values and will thus not crush as easily. **They found that it was not possible to replace 100% of NCA by PCA, but possible with 22%, the percentage substitution giving the highest compressive strength (even higher than NCA at 28 days) but decreasing the split tensile strength and the elastic modulus, due to the bonding strength between the matrix and PCA.** Some suitable admixtures could be added to enhance the bond strength, but fire proof coating is then required to compensate the enormous reduction of strength for the PCA when heated. Volumetric substitution of aggregates has been proved more efficient than grade substitution. The PCA concrete is obviously lighter than the NCA. The superior plastic was collected to do the tests. After crushing and washing, it was heated and then extruded in boulders of approximately 100mm that were then crushed down to the size of aggregates.

2.5 Findings

Through this literature review, important conclusions for the pursuit of the thesis can be drawn.

First of all, the structural applications of plastics or recycled plastics always use reinforcement to stabilize the structure. Usually fibers directly incorporated into the material.

Thermoplastics are easily recyclable, not thermosets.

Also, many additives are added in recycling plastics to enhance their properties, increasing the difficulty to recycle them again later.

Rigidity of plastic is very dependent on the temperature and a range of temperature for utilization should be defined to conserve their mechanical properties. Thermoplastics show good mechanical properties, even comparable to wood.

For a mixture of several polymers, the compatibility is very important, and the different studies do not always agree on the compatible mixtures. If a compatible blend is found, the waste are upgraded and the plastic continues its lifecycle, enclosed in the circular economy.

And finally, use recycled plastics or bioplastics drastically decreases the ecological footprint of the material. Moreover, many different recycling processes exist and can be further used to recycle blend of recycled polymers.

As a conclusion we will create and test a new material made of bio and recycled plastics, with no addition of fibers nor any other additives, and then create another new material that is reinforced with a natural material, the bamboo.

2.6 Bamboo

2.6.1 Bamboo characteristics

Bamboo is a natural element belonging to the grass family and comprising many varieties. It adapts easily to the different type of soils and environment, and mainly grows in Latin America, Asia and sub-Saharan Africa.

Bamboo has a tubular structure yielding to a great inertia. The stem, or *straw*, is made of **nodes** connected by **internodes**. It is known as the fastest growing plant, some species are growing up by 25 cm or even up to 1m per day. After 4 to 6 years, the bamboos are ready to use for construction. It is a lot quicker than waiting for wood that takes generally 15 to 25 years and avoid deforestation (Guadua forest is creating 1200 to 1400 stems/HA/Year, very competitive to wood) (Estudia, s.d.)

Mechanical properties depend on several factor: moisture level, age, essence, position on straw, but also direction of solicitation. Moisture content is the most important property governing the mechanical properties of the bamboo (Seema Jain, 1992).

Bamboos present a high percentage of fibers and high silica content on outer face; it confers a high resistance and flexibility, with a smooth appearance.

The stem can be defined in 3 parts: the top part, with a very high fiber content (used for beams and furniture), the middle part, slender, very light and fibrous for an important strength (used for construction) and **the bottom part, with a great wall thickness, short internodes distances and high compressive strength (used for column in construction)** (Estudia, s.d.). Age and position are very important too: top portion shows the maximum strength and modulus of elasticity, thanks to the higher density, and the bamboo seems mature between 3 and 4 years old, because presenting the highest mechanical properties for those ages. Furthermore, the bamboo's age does not affect the modulus of elasticity under compression or bending forces in the elastic domain (Juan Francisco Correal D., 2010).

Bamboo is a natural element, with different characterization for each species and each bamboo. Nevertheless, some general rules for properties can be found: its maximum strength is along its fibers, parallel to the stem (it presents very low properties in transversal direction) (Seema Jain, 1992). Elastic limits for bending, tension and compression parallel to its fibers can even be higher than some woods used in construction (Estudia, s.d.).

Moreover, **bamboos are definitely a green, ecological, sustainable and low carbon footprint material:** it can stock up to 9 tons/HA/Year of CO₂, compare to pine where only 3,5 tons of CO₂/HA/Year is stocked. Even with the transportation from America to Europe, the resulting carbon footprint is negative (Estudia, s.d.). On top of that, it creates 90 tons/HA/Year of biomass, prevent the soil from flooding (by absorbing the excess of water and release it later) and erosion. It is thus an enormous resource that we should investigate to find more structural applications in Europe, as it is still not commonly used, except for decoration.

Above all, the well-known Guadua specie from Columbia, **the Guadua angustifolia is much used in construction thanks to its high mechanical and physical properties.** Its Elastic Modulus E at 12% moisture content reaches in average 17 [GPa] (Estudia, s.d.). **Guadua has a Young Moduls comparable, or even bigger, than wood.**

Guadua stems are generally between 8 and 13 cm diameters (sometimes 25 cm). It is **growing fast (15 cm per day) and reaches its final height (20-30 m) in about 6 months.** The rest of its life, it is developing its woody structure. The wall thickness can reach 3 cm, but is usually between 0,8 and 2 cm (Estudia, s.d.). The Guadua specie can stock up to 12 tons/HA/Year of CO₂ and have a return of 500 to 1300 plants/HA/Year, placing it at the top of all bamboos species (Raison, 2017).

It is important to **treat the bamboos before using it for applications, and to treat it biologically, avoiding harmful chemicals**. One process could be: three cooking cycles in a salted water solution, playing a fungicide role by destroying the fungi and hardening the fibers for a better resistance (Une brique dans le ventre - GreenSteel Concept, 2014). When treated, the Guadua bamboo lifetime increase from less than 2 years to 30 years, before degradation (Cuchet, 2019).

Better use of the bamboo is for structures where it is not too much exposed to weather conditions, because variation of humidity inside can create cracks (Estudia, s.d.).

2.6.2 Bamboo applications

Bamboo is already widely used in many different applications and is a good **green and trendy alternative to wood**.

In construction, it is used to reinforced concrete as a rebar, to create complete load-bearing structures (scaffoldings, framework, ...), or in laminated panels.

Bamboos can also be used as fibers in composite materials: Jain *et al.* developed back in 1992 a bamboo fiber-reinforced plastic (BFRP) composite with 65% volume fraction bamboo fibers and bamboo mats to reinforce epoxy resin, and observed a close to linear elastic behaviour, a perfect bounding between the fibers and the epoxy, and also biaxial strengths (Seema Jain, 1992).

Furthermore, bamboo-reinforced concrete is used for low cost homes (3 times cheaper (Swapnil Dange, 2017)) in developing countries, is developed in many researches: it has to be designed to remain uncracked what results in an increase of the concrete section. Moreover, **the poor bound characteristics between bamboo and concrete is due to the water absorption of bamboo and its thin walls** (Swapnil Dange, 2017). **It is thus not durable at all and needs treatment of its surface with harmful chemicals**. This is thus not a competitive alternative to steel (Hector Archila, 2018).

Researches of PLA matrix reinforced by **bamboo fibers** and made out of pellets (extruded in a twin-screw extruder) through injection molding, teach us that bamboo fibers improve thermal properties and heat resistance; crystallinity has to be improved by adding more bamboo fibers to the PLA and annealing the material (110°C for 5h). **Steam-exploded filaments** have a high interfacial strength with the PLA matrix resulting in the increase of bending strength. Impact strength only increases if **longer bamboo fibers** are added and hot-pressing process is used, avoiding decreasing the fiber length (Ryoko Tokoro, 2018).

PART 3 COMPOSITION OF THE NEW MATERIAL

We want to develop a sustainable blend composition containing recycled plastics (different from the blend of recycled plastics already developed), with a reduced ecological footprint, rigid enough to be used in various structural applications, and recyclable at its end of life.

3.1 Pre-test and early findings

Eco-Oh!, a company based in Houthalen (Belgium) and specialized in sustainable products made of 100% recycled plastics and recyclable at their end of life, provided us with a sitting beam of the Picnic Set Forest Series, that was rejected after production. The composition of the specimen, according to the information received, is a blend made of 60-95% of PE and PP, and the rest is a mix of PVC, PS and PET.

In order to evaluate its flexural characteristics, we performed a 4 points flexural test in the LEMSC laboratories (Louvain-la-Neuve, Belgium) and evaluated the rigidity of the sitting beam (see APPENDIX B). The test has been done under the protocol of standard ISO N408 (NBN, 2012) (evaluation of mechanical properties of timber structures) and the testing device has been installed accordingly (see Figure 43). A potentiometer sensor has been used to measure the deformation at center and a hydraulic jack to apply a continuous increase of force of 0,246mm/s.



Figure 42 Two opposite extremities sections of the specimen

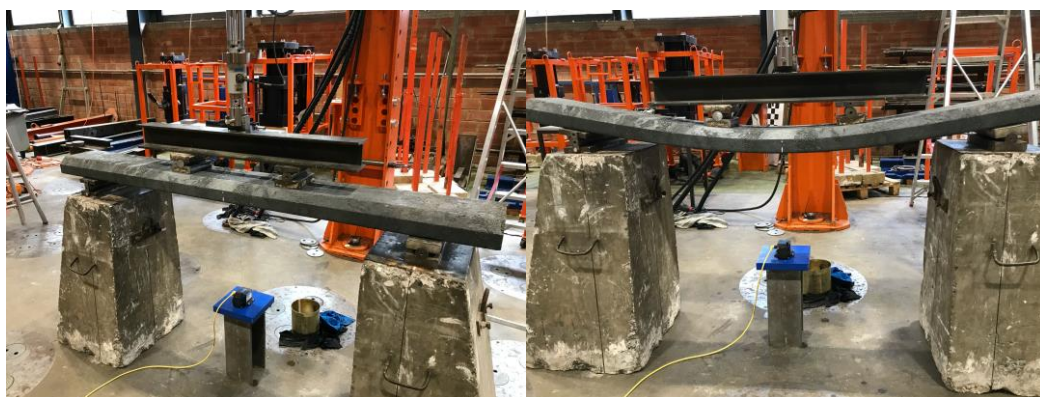


Figure 43 Testing device (left) and behavior of the specimens close to failure (right)

The results of the test showed a global modulus of elasticity of $E_{m,g} = 1009,35 \text{ [MPa]} = 1 \text{ [GPa]}$ and a bending strength $f_m = 12,34 \text{ [MPa]}$ (see APPENDIX B). Those values are very closed to the ones tested by the company (see APPENDIX B).

No cracks were observed during the test, and a brittle failure occurred after 367,86 [s] (see Figure 44) for a maximum force of 9,44 [kN] and a displacement of 99,56 [mm].

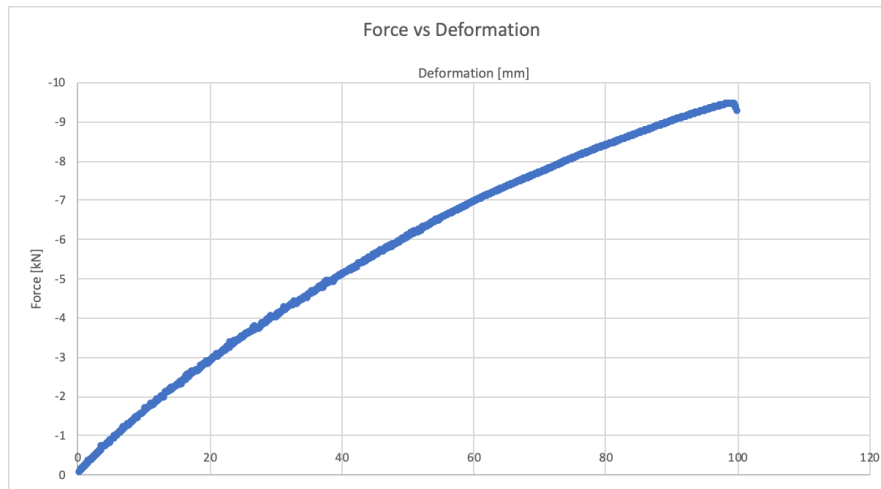


Figure 44 Force vs Deformation - Results of the test

As observed on Figure 42, the rejected beam does include asymmetrical properties, has one extremity section that is quite dense, compared to the other one quite porous (and this is more than probably the reason for the rejection after production). Hence the failure did not appear in the central section of the beam.

As a consequence, this test taught us the importance to find a composition made of miscible polymers, leading to one phase polymer, the importance to choose the right process to avoid porous materials, and the right composition to achieve high modulus of elasticity.

We thus could already exclude the blending of polyethylene PE and polypropylene PP (for the main constituent of the beam), mainly because it leads to a modulus of elasticity around 1 [GPa].

3.2 Challenges

The new composition needs to contain **recycled plastic** and to satisfy the following criteria :

- be rigid enough
- be stable (keep rigidity properties within the range of temperatures for utilization),
- miscibility and compatibility of the components
- be recyclable (circular economy)

3.2.1 Rigidity

The principal characteristic targeted for the new material is its **rigidity**. One of the recurrent problems of plastic is its flexibility, making it difficult to use for high mechanical properties applications.

The rigidity of the material is presented by its elastic modulus [GPa]. “Elastic modulus measures the resistance of the material to elastic [...] deformation” (David R.H. Jones, 2019). The slope (or ratio $\frac{Stress}{Strain}$) of the **elastic** deformation region of the material’s stress-strain curve (linear behavior) gives us its value. The higher modulus, the stiffer.

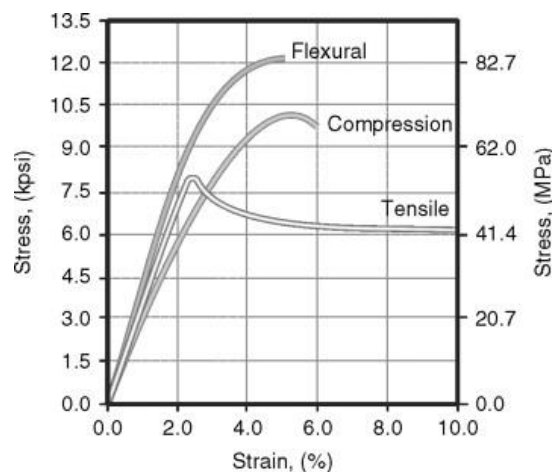


Figure 45 Stress-Strain curves of ABS (rigid) subjected to bending, compression and tension (Campo, 2008)

The Young Modulus is the tensile elastic modulus, evaluated through tensile tests, whereas the **Flexural Modulus** is the elastic modulus in bending, evaluated through a 3 point flexural test. Depending on the material, they can be both very similar, but sometimes present different values. As observed on Figure 45, tensile and flexural modulus of rigid polymers (here ABS) are very close; Flexural Modulus usually slightly bigger than Young Modulus (Campo, 2008).

Even if Young Modulus is often reported by the European design community, it is important to evaluate the dominant loads and use the appropriate elastic modulus (Campo, 2008).

For the purpose of the master thesis, the main loads chosen for the application (modeled in PART 5) are flexural loads and **Flexural Modulus** has thus been evaluated.

Indeed, as long as rigid polymers (like ABS, but also PMMA) undergo small strains, they have an elastic material behavior, and the slope of the initial tangent to the stress-strain curve gives the general *elastic modulus* (De Daniel J. Berry, 2019). Hence, the flexural modulus evaluated through flexural tests (in PART 4) will be comparable to young modulus, as long as the material is used in its elastic domain, **assumption** taken through the entire modelization.

Finally, in order to have a naturally high stiffness without reinforcement, it is important to choose polymers with high naturally elastic modulus.

3.2.2 Stability (keep rigidity properties within the range of temperatures for utilization)

One characteristic of the polymers is that their properties evolve at different temperatures, because their intrinsic structure behaviour evolve with temperature (see 2.1.3 for further explanations).

Consequently, we define a range of temperatures for utilization, from $-20[^\circ\text{C}]$ to $70 [^\circ\text{C}]$, to be sure to enclose the temperature's ranges of western countries.

As seen previously (see Figure 4 in 2.1.3), the Young Modulus E decreases as the temperature increases and reaches the glass transition temperature T_g . Hence the rigidity of the material decreases with the increasing temperature.

It is thus important to carefully choose plastics that has a T_g greater than the range of utilization (here, $70 [^\circ\text{C}]$). For example, PE and PP reach their T_g even before room temperature, between -25 and $-15[^\circ\text{C}]$, preventing them to be used in the target application, as their rigidity have already decreased a lot at room temperature (see 3.1).

3.2.3 Miscibility and compatibility of the components

Many polymers are compatible, but not miscible; that is a challenge.

Miscibility is a very important parameter to increase the thermal properties of the blend, otherwise T_g would stay the ones of the different amorphous phases (Delphine NOTTA-CUVIER, 2018). Several T_g is characteristic of an immiscible blend.

A perfect miscibility will create a new homogeneous polymer matrix characterized by a unique phase and hence a unique glass transition temperature (only one T_g). Many experimental tests exist to evaluate T_g , but the DSC¹⁶ is the most commonly used.

An immiscible but compatible blend would present two phases and inferior mechanical properties (Régis Kovacs Scalice, 2009).

It is thus crucial to find a perfectly miscible blend leading to a homogeneous and unique phase.

3.2.4 Recyclability of the new composition (circular economy)

Existing applications made of recycled plastics are often reinforced with steel (e.g. public benches) in order to support the loads. Polymer blends can also be often reinforced with additives and/or fibers (wood, glass, natural fibers, ...) to increase their mechanical properties. However, these reinforcements and/or additives make the blend impossible to recycle.

The decision was thus made to **avoid additives and fibers**, and hence create an isotropic¹⁷ material that would be recyclable.

3.3 Final composition, manufacturing process and recycling

After many meetings and discussions with researchers in the polymer field, coming either from the academic world, or from the industry world, and analysis of the table showing the main properties of the plastics (see APPENDIX A), it appears that the **Polymethyl methacrylate (PMMA)** from the thermoplastic family is a good candidate, presenting a high Young Modulus ranging from 2,24 to 3,8 [GPa], and a glass transition T_g around 120[°C], higher than the range temperature for utilization (set at max 70 [°C]). Moreover, PMMA has a good tensile and compressive strengths, 80 – 100 [MPa] and 140 [MPa] respectively.

¹⁶ DSC = Differential Scanning Calorimetry : Standard test to realize a thermal analysis of a polymer, based on the measure of differentiation of heat fluxes between a sample and the reference (T_g is found at the inflection point of the curve - change in heat flow rate as function of the temperature – obtain from the test) (NBN, 2020)

¹⁷ Isotropic (Collins, s.d.): having uniform physical properties in all directions.

The PMMA, well-known under the commercial name of PLEXIGLAS, is described above in literature review (2.1.5). Its chemical recycling is a complicated process, which prevents it from being a favorite for recycling; therefore, only 10% of the production is recycled today. There is thus a huge opportunity **to mechanically recycle** all this easily available material and makes it an ideal candidate for our blend.

In addition to this, with the worldwide crisis we are living due to the COVID-19, PLEXIGLAS has been widely installed in shops and companies, used as screen to protect people. All this PMMA will have to be recycled one day to avoid landfilling.

Using recycled PMMA (rPMMA) is not common and match thus the aim to find new solutions for recycling plastic, lowering the ecological footprint of the new material.

Secondly, bioplastics (see 2.2), and more specifically **Polylactic Acid (PLA)** with its very low carbon footprint, are at the heart of many recent researches, mainly for food packaging and automotive applications.

By choosing PLA, we avoid using oil-based plastic, harmful for the environment.

In fact, PLA, with its a strong elastic modulus of 3,45 [GPa] (Ingeo 2003D, NatureWorks), its glass transition temperature at around 60 [°C] and its high miscibility to the PMMA, is the perfect second candidate to meet the objectives.

Blending rPMMA and PLA

Thus, blending recycled PMMA and PLA should enhance each-other properties and create a new material with strong characteristics meeting our objectives.

Finally, and based on our findings (see below), we will check whether a 50/50 weight distribution of PLA/recycled PMMA is appropriate.

3.3.1 Blend rigidity

As per the table of properties (see APPENDIX A), PLA has an elastic modulus of 3,45 [GPa], and PMMA has a young modulus between 2,24-3,8 [GPa].

With a 50/50 mass distribution of rPMMA and PLA, we expect a **flexural modulus** (or elastic modulus) of the blend around **3 [GPa]**, relatively high value for polymers, but realistic with these two high mechanical properties polymers.

3.3.2 Blend Stability

By blending recycled PMMA (T_g around 120[°C]), a high thermal properties polymer, in PLA (T_g around 60 [°C]), it will help increase the global thermal properties and end-up with a single glass transition temperature (thanks to the miscibility of the blend) in between the T_g of PLA and PMMA and depending on the ratio of PMMA (Delphine NOTTA-CUVIER, 2018). Furthermore, T_g also clearly increases with an increase of PMMA content (GARZON, 2018). The researches of the laboratories in Mons (Belgium) have measured a $T_g = 75$ [°C] for a PLLA/PMMA blend with 50%PLLA – 50%PMMA distribution. **This blend thus meets the range of temperature for utilization targeted (-20 – 70[°C]).**

For a unique T_g , please see below in miscibility/process.

A classic prediction of T_g can be made through the Fox equation, assuming similar specific volume for the two components (GARZON, 2018):

$$\frac{1}{T_g} = \frac{w_1}{T_{g1}} + \frac{w_2}{T_{g2}}$$

where w_i represents the weight fraction of the component, and T_{gi} the glass transition temperature of the pure component.

With a 50-50 weight distribution, and T_{gi} equal to 60 and 120[°C] respectively for PLA and PMMA, the predicted T_g is 80 [°C], thus very close to the $T_g = 73$ [°C], found by GARZON in its researches about PLA/PMMA, and the 75°C for the PLLA/PMMA blend (above). Effectively, measured T_g have always been slightly lower than Fox predictions, according to Gonzalez Garzon (GARZON, 2018).

With less than 50% PMMA, the glass transition temperature would be less than 73[°C] (Cedric Samuel, 2013) and not meet the targeted specifications.

3.3.3 Blend miscibility

The **miscibility** of the blend plays an important role on its properties. Many parameters play a role in the miscibility of the blend, among which the manufacturing process.

Samuel, Raquez and Dubois in a research of PLLA(Ingeo 4032D, D-isomer)/PMMA blend in 2013 (Cedric Samuel, 2013), found that if the blend is processed via a **twin-screw extrusion technique** (see 2.1.4) at melt state (min 210 [°C]), the blend is perfectly miscible, generating a **unique glass transition** (temperature in between the two respective T_g).

Indeed, immiscible blends will present several glass transition temperatures. Gonzalez Garzon, through its researches on the PLA/PMMA blend (in Québec, Canada) further found

that to homogenize the blend and create a **single phase material**, the blending parameters were very important and have to be from a relative long time period (GARZON, 2018).

He has also concluded that a single phase and thus a single peak T_g is only observed for **injection molded specimens** if we add a **dwel time of 20 minutes** between the melt-mixing and the injection step. A DMA¹⁸ test to evaluate the change in $\tan \delta$ versus the temperature curves was done on the specimens. $\tan \delta$ reach its maximum in the surroundings of glass transition, so its appears clearly on Figure 46 that for a dwell time of 20 min, there is a single peak and hence a **unique T_g** (GARZON, 2018).

According to Notta-Cuvier *et al.*, injection molding indeed helps to increase the thermal properties of the blend (Delphine NOTTA-CUVIER, 2018).

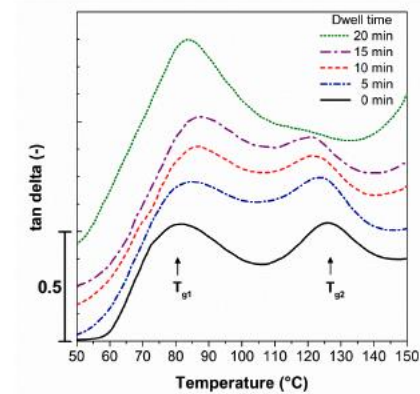


Figure 46 Influence of dwell time on evolution of $\tan \delta$ for injection molded c-PLA (semi-crystalline)/hv-PMMA (high viscosity amorphous) (50/50) blends (GARZON, 2018)

Finally, miscibility of this kind of blends is characterized by the miscibility of the amorphous phase of both polymers. Indeed, Gonzalez Garzon also analyzed the miscibility of the 50/50 PLA/PMMA blend through a DSC test and observed a fully amorphous and unique phase (GARZON, 2018).

3.3.4 Blend recyclability

The newly created blend can be chemically recycled by hydrolysis of PLA and recuperation of rPMMA. The undissolved rPMMA can thus also be recovered for subsequent use. This process enables the lifecycle of both polymers to pursue their routes and is firmly enclosed in circular economy.

This process was found by Coszach *et al.* in 2013 and is further described in the literature review (see 2.3.3).

¹⁸ DMA = Dynamic Mechanical analysis: enables to study the viscoelastic properties in the linear phase. Impose a cyclic deformation and analyze the dephasing δ between the resulting stress and strain. 0° corresponds to a perfectly elastic solid, and 90° corresponds to an entirely viscous fluid (GARZON, 2018).

Conclusion on the blending PLA/rPMMA

Finally, the miscible blend made of recycled PMMA and PLA will lead to a fully amorphous and unique phase **new polymer**, presenting one T_g above temperature of utilization, recyclable at its end of life and good mechanical properties. Indeed, they are both high molecular weight polymers and will thus lead to the highest achievable properties (Cedric Samuel, 2013).

3.4 Reinforce the new material with bamboos

The new material composition as developed hereabove will lead to approximatively an elastic modulus of 3 [GPa], what is high for a plastic, but very low compared to other materials like wood ($E = 6-15$ [GPa]), concrete (E around 30 [GPa]), or steel (E around 200 [GPa]) (see APPENDIX A).

The idea to reinforce the material with bamboos to increase its rigidity, while protecting the bamboo from outdoor weather, led us to develop a beam composed of several **bamboos interlocked** in the polymer and working together as a whole. This material is still green and sustainable and follow the thus the overall objectives.

Bamboos, as replacement for steel rebars, already exist to reinforce concrete.

However, such application has weaknesses: bamboo fibers do strengthen the material but make the material impossible to recycle properly, and bamboo rebars have already been used in some applications but the tendency of bamboos to absorb water, to swell and shrink will result in de-bonding between bamboo and concrete, and cracks in concrete. Moreover, the difference between bamboo and concrete thermal expansion coefficients will also result in de-bonding (Prof. Dirk E. Hebel with Felix Heisel, 2015).

Our goal is thus to fix these problems.

The entire bamboos (adding them still let the blend recyclable) will be encapsulated in the polymer matrix:

Low permeability conferred by the PMMA in PLA¹⁹ will avoid water penetration to the encapsulated bamboos, and thus also avoid shrinking or swelling. Moreover, each node of the

¹⁹ Indeed, it is possible to control the permeability to gases like O_2 , N_2 and CO_2 of the PLLA/PMMA blend by adding PMMA miscible portion to PLLA melt-blending process, that will lower the permeability of the blend and hence increase the resistance to weather (Cedric Samuel, 2013).

bamboo presents an increase in the cross-sectional area compared to the internodes cross area and will thus increase the bounding between the bamboo and the polymer, like the role serrated rebars play in concrete.

Good bounding characteristics are thus predicted between bamboo and polymer and will be verified through the tests (see PART 4).

3.5 Costs and CO₂ footprint

When developing a new green material, it is important to analyze whether it is sustainable and economically viable.

The prime recycled PMMA is (and will also be) widely available and sleeping in hangars of companies. In fact, PMMA is still not much recycled, as the process of chemical recycling can be expensive and is not yet industrialized. Researchers are working on developing that process.

There exists another way to reuse the PMMA at its end of life: the mechanical recycling. This solution is easier and cheaper than the first one and uses an existing manufacturing process. Also, companies definitely want to get rid of PMMA and they could sell it almost for free. Indeed, in the composition created in this thesis, for example, we recycle PMMA coming from roofs which has not been washed, did not specifically go through recycling centers, and was directly crushed, which makes it an almost free component.

Bioplastics like PLA are annually renewable materials of low-cost production and approximatively cost 2,50€/kg bio-based polymer (Florence Aeschelmann (nova-Institute), 2017).

Other sources provide us with the following per unit costs of the materials: PMMA (Ashby, 2011) price of 1,4-2,1 \$/kg (in 2011), about 3€/kg for the PLA, and bamboo (Ashby, 2011) price of 2,6-2,8 \$/kg (in 2011). It is also interesting to know that the purest the outcome of the recycling is (much washing, melting, grinding, ...), the more expensive the material is. Yet, recycled materials may be much cheaper than the virgin plastic (as an example; a ball of recycled HDPE may cost 650 € compared to 3000 € for the virgin HDPE).

In short and for the new polymer created in this thesis, prime materials are very cheap, and as the manufacturing processes are already industrialized, the costs would mainly and only come from creating a new customized injection mold for the application. Again, this is not too expensive, and some molds can be created for 6000€ already (Govaplast, 2020). Obviously, if a larger scale production could be planned, the cost could be further reduced.

Moreover, these materials also present a low carbon footprint, as it is made of bioplastics annually renewable and recycled plastics. The life cycle assessment (LCA) of the

products showed very good impact to reduce CO₂ emissions and hence reduce their carbon footprint.

More precisely, a particular attention has been conveyed to prohibit all additives and fibers, reducing considerably the initial cost, as the additives are very expensive), but also enable the mechanical recycling of the material at its end of life. Indeed, if the materials presents several components, the recycling is not economically viable and the material would end in landfill, the total other way around of the principal objective to be part of the circular economy.

Finally, the bamboos are also a very cheap prime material with a low carbon footprint, even if it has to be transported from far countries from where they come from.

As a conclusion, the new composition could be a very cheap solution to recycle the PMMA. A detailed analysis of its value chain should be done before launching the product.

PART 4 EXPERIMENTAL TESTS

In this part of the thesis, the **mechanical properties** of the new composition PLA/rPMMA, as well as the new composition reinforced with bamboos are analyzed in laboratories through **bending** tests, **traction** on bamboos and **pull-off** test to analyze the adherence between them. The aim is to define the flexural strength and flexural modulus of the material and use these parameters in the next part to design an application. The chapter ends with conclusions on the observations done. A recapitulative table of each test can be found in Appendices (APPENDIX F).

The choice to perform **bending tests** to determine flexural properties was directed by the main solicitation for the modeled applications (see PART 5), the availability of the material, the budget, but also the very limited accessibility of the labs (or closed labs) due to the containments linked to COVID-19 global crisis.

The materials used for the new composition PLA/rPMMA blend are (see technical data sheets at APPENDIX C):

- PLA Ingeo 2003D (4,1% D-isomer, pellets), semi-crystalline structure
Created by NatureWorks LLC (USA) and distributed by RESINEX, it presents an elastic modulus of 3,45 [GPa].
- recycled PMMA from DHK (DHK, 2020) : recycled PLEXIGLAS® Heatstop Cool Blue S5P 32/1230-32 White WZ009 (RÖHM, 2020)

It comes from the deconstruction of greenhouses' roofs in the Netherlands.

It is alveolar plates of 32mm height, initially produced by extrusion, used for the roof of greenhouses, as they reduce the solar thermal radiation, to temperate the heat inside, with their golden/pearly color (Thyssenkrupp, 2020).

They are crushed into flakes, ready to use in the machineries of polymer implementation. Their elastic modulus is between 2,24 and 3,8 [GPa] (see APPENDIX A).

4.1 Test the mechanical properties of new composition PLA/rPMMA

To characterize the new material, it was important to create small specimens according to the standards and test them.

The company INNOLOGIC (Sint-Denijs, Belgium) has first prepared the 4x10x80 [mm³] injected bars according to ISO 294-1 (ISO, 2017) to test them in flexion according to ISO 178 (ISO, 2019). The detailed injection parameters and results can be found in APPENDIX D.



Figure 47 Injected PLA/rPMMA bars tested

As explained in previous part (see PART 3) with a PLA/rPMMA 50-50 weight distribution made of the materials described hereabove, the expected *flexural modulus* was 3 [GPa].

The results showed a **flexural modulus** of **3,243 [GPa]** and meet thus perfectly the objectives.

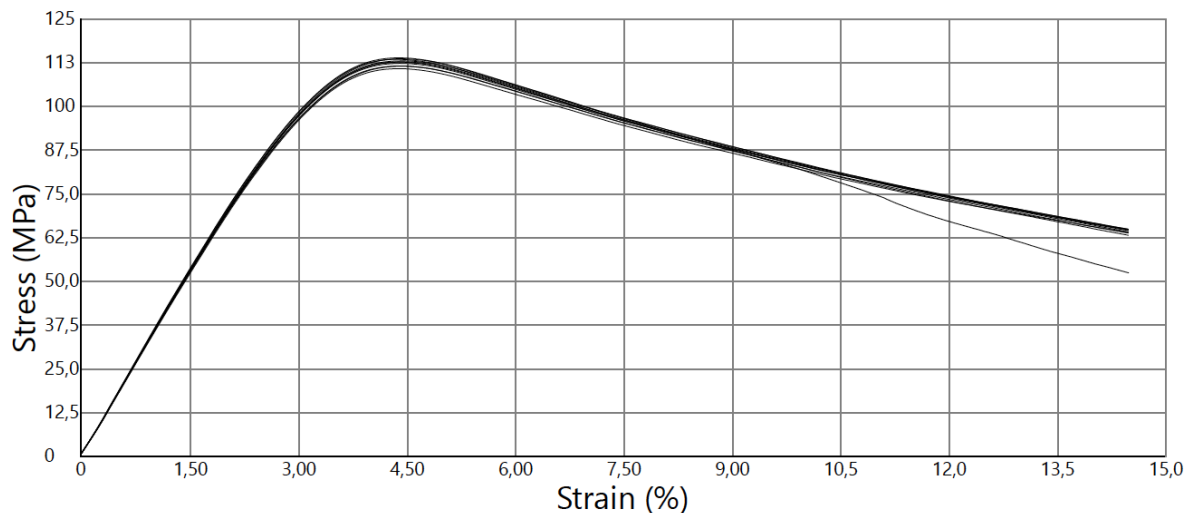


Figure 48 Stress-Strain curve of injected PLA/rPMMA (INNOLOGIC, 2020)

As observed on the diagram (Figure 48), the material presents a high ductility and a smooth transition between elastic and plastic domains. The yield strength is thus approximate at 96,43 [MPa] (at $\epsilon = 0,2\%$). From the curve, we first observed an elastic behavior. After, it reached the highest stress recorded, the flexural strength, at **112,6 [MPa]** for a mean elongation of 4,4 [%]. In the second part of the curve, we observed a relaxation of the material, where the material undergoes plastic deformations: the stresses are concentrated in the necking at middle region of the bar and failure will occur in that zone.

Purely concerning the material created: because of the golden/pearly color the PMMA has, the new material is not transparent (like virgin PLA and PMMA) and has a pearly color (see Figure 47). Each bar weights 4 grams and its density is 1,25 [g/cm³], very close to both PMMA and PLA respective densities (1,2 and 1,25 [g/cm³]).

Finally, the material presents very good and high mechanical properties, close to both the PMMA and PLA properties, showing that the first recycling cycle for PMMA does not decrease a lot the mechanical properties. Moreover, the injection molding process has been shown as very efficient to maintain the high mechanical properties of materials.

4.2 Creation of prototypes bamboos interlocked in PLA/rPMMA

To create bigger elements and test their mechanical properties, we created prototypes in formwork timber.

The formworks for **bending tests** are 50x50x300 [mm³], according to the maximum section dimensions recommended by standard ISO 178. Several dispositions of bamboos have been thought:

- without bamboo (to test the properties of the plastic matrix itself);
- with bamboos : 1 in the middle, 2 (vertical and horizontal) and 4.

The formworks for the **pull-off tests** are 60x60x300 [mm³], with a central bamboo (8-10 [mm] diameter).

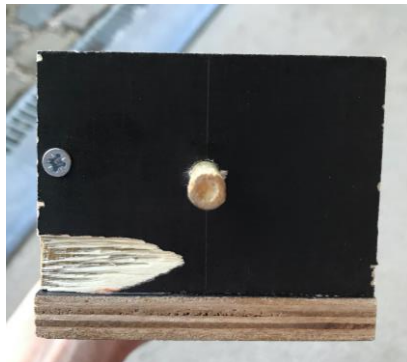


Figure 49 Final configuration of the formworks

All the lengths of molds were thought to be able to **embed 2 nodes** of the bamboo's stem (each node is separated by +/- 20cm). Indeed, the adherence between the materials is greatly enhanced by the protrusion of the stem at the nodes. It is thus very important to put as much as possible nodes inside the matrix to enhance this adherence.

The company GOVAPLAST (Hasselt, Belgium), filled the formworks with the new composition, the PLA/rPMMA 50-50 weight distribution (using exactly the same materials as for the injected molded bars). It was first blended in a blender in order to unify the repartition of the pellets and flakes correctly. Then **extruded** at 200 [°C] (near melting point of PLA) in a single-screw extruder before being taken at the exit (with gloves) and manually compressed in the formworks (thus different from injection). Finally, it cooled down at room temperature.

The **initial idea** was to do all the flexural tests with 4 bamboos inside the plastic matrix. However, when filling the formworks, we experienced **difficulties to evenly distribute** the material between the bamboos because of the congestion. It has thus been decided to insert two bamboos instead of four.



Figure 51 Filled formworks and created elements

4.3 Test the mechanical properties of the real scale elements

All the following tests have been done in the *Laboratoire essais mécaniques, structures et Génie civil (LEMSC)* at university UCLouvain (Louvain-la-Neuve, Belgium).

4.3.1 Traction on bamboos

To characterize the mechanical properties of the bamboos used in the section for the bending tests, we proceeded traction tests on bamboos along their fibers (longitudinal properties) and evaluated their **Young Modulus** and **tensile strength**.

One constraint was to find very thin bamboos to scale their influence in the matrix as much as possible. Guadua species, even though it has very good mechanical properties, does not exist in small diameter; instead, “natural” bamboos (Nortene®) of 90 [cm] long, with diameter 8-10 [mm] were found in the market and used.

Concerning the test devices, to avoid scratching the bamboo’s edges with the clamping jaws, a pink resin was used to fix the bamboos extremities in aluminum tubes (see Figure 53 and Figure 52).



Figure 53 Traction test device at LEMSC

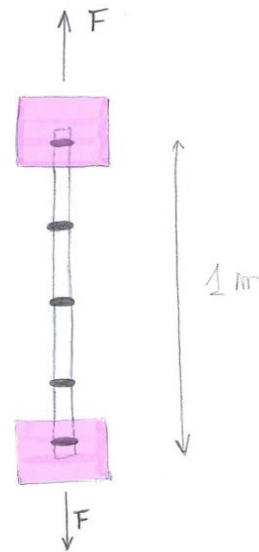


Figure 52 Schematic test device

With the force, displacement of the clamping jaws s_{MAX} , as well as the initial gripping distance $L_{Gripping}$ (between clamping jaws), it was possible to realize a Force-Displacement and a Stress-Strain diagram for all the bamboos tested. The **tensile modulus** E_t was then calculated as the slope of the stress σ /strain ϵ curve, in the strain interval $\epsilon_1 = 0,05$ [%] and $\epsilon_2 = 0,25$ [%], as $E_t = \frac{\sigma_2 - \sigma_1}{\epsilon_2 - \epsilon_1}$ (Standard, 2012).

The **mechanical properties** drawn from results are given in Table 2. It appears that the bamboos are similar and present a high tensile modulus ranging from 22 up to 29 [GPa]. The deficient Bamboo 2 was removed from the mean as it exhibits very low properties compared to the others. Its growth has probably encountered problems, giving it low strength.

	F_{MAX} N	S_{MAX} mm	$\sigma_{\max} = \frac{F}{A_0}$ MPa	L_{Gripping} mm	$\epsilon_{\max}$ /	E_t GPa
Bamboo 1	7222,2744	4,66365585	141,472083	773	0,00603319	23,4595756
Bamboo 2	5438,6577	6,64826776	106,534062	770	0,00863411	12,8637533
Bamboo 3	11516,6915	7,7776494	225,592415	790	0,00972262	25,8697892
Bamboo 4	9029,2129	6,59175469	176,866937	793	0,00831243	25,6243105
Bamboo 5	7647,9795	6,02499652	149,810922	779	0,00773427	22,1779032
Bamboo 6	9818,626	5,52607484	192,330198	796	0,00694231	29,8264664
MEAN	8445,57366	6,20539984	165,434436		0,00789649	23,303633
MEAN _{except2}	8946,72632	6,13158852	175,251165		0,00777355	25,043613

Table 2 Recap mechanical properties of the bamboo tests

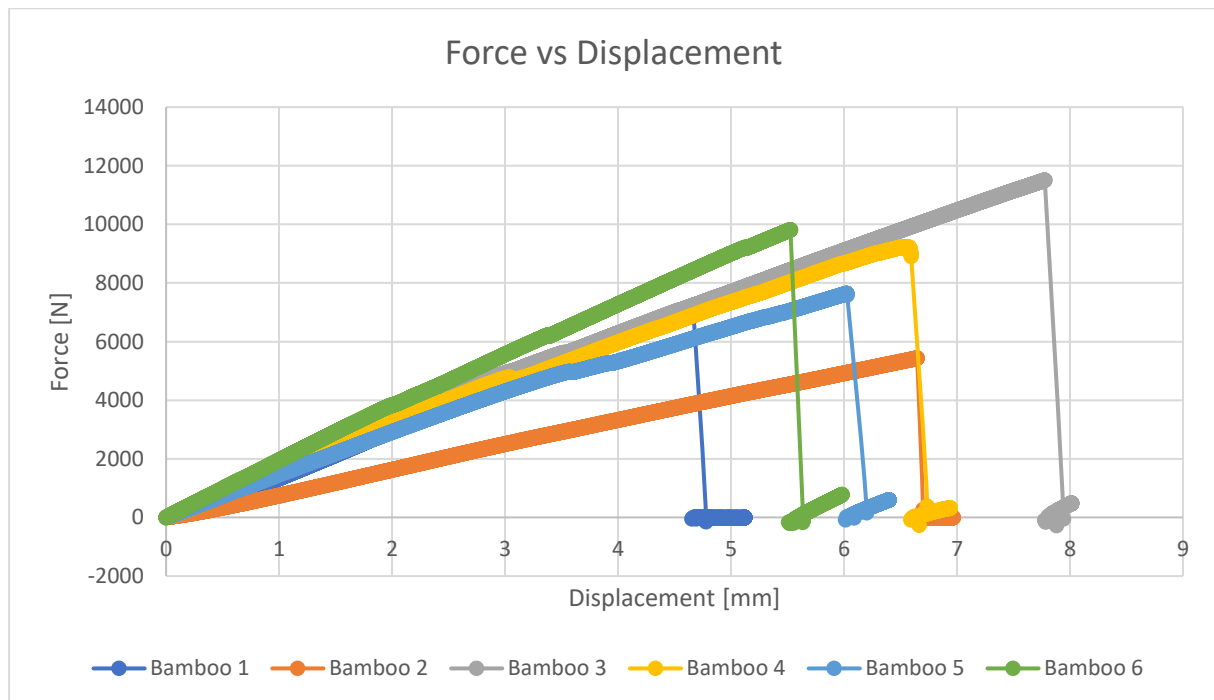


Figure 54 Force vs Displacement of the 6 bamboos

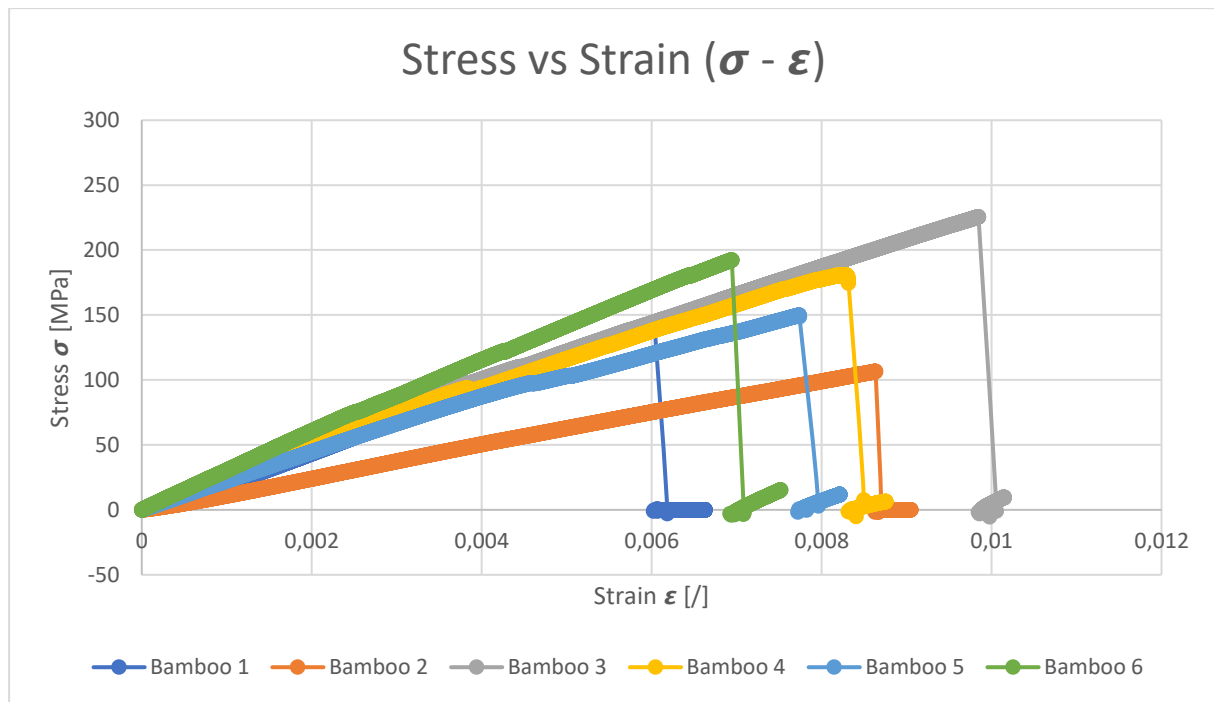


Figure 55 Stress vs Strain of the 6 bamboos

The bamboos are known as brittle material, and the diagrams confirm the assumption. They deform in their elastic region (linear part of the plot) and break without any plastic deformation as the graphs (Figure 54 and Figure 55) show.

The bamboos tested did not present any necking and the failure always occurred at a node. In fact, and as explained before (see 2.6.1), bamboos are weaker at their nodes and present their best properties in the stem of the internodes; the behavior follows the assumption.

Finally, comparing the mean values obtained with other bamboos characteristics (APPENDIX A), these bamboos look very much like the **Moso species**: they have a mean tensile modulus of **24,044 [GPa]** were Moso presents a modulus between 9 and 27,4 [GPa], and a tensile strength of **175,25 [MPa]**, were Moso presents 115,3 [MPa] at 1,3 [m] high of the stem.

Moreover, bamboos are anisotropic²⁰ materials that could be compared to timber; however, timber presents a smaller tensile strength of 30-60 [MPa], 3 to 6 times smaller than bamboo.

As conclusion, bamboo is a **high potential material** gathering excellent longitudinal properties. However, properties can vary a lot from one specie to another, from bottom or top of the bamboo, and from one bamboo to another. It is thus important to choose them carefully and remember they are natural and can sometimes present defaults.

²⁰ Anisotropic (Collins, 2020): not isotropic; having different physical properties in different directions.

4.3.2 Pull-off to characterize the adherence

One of the most important characteristics for the beam of bamboos working together and linked with PLA/rPMMA, is the adherence between both materials. Indeed, to transfer the efforts and enable the section to work as one, adherence is needed.

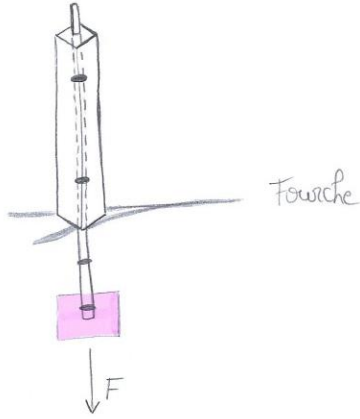


Figure 56 Schematic test device



Figure 57 Pull-Off test device at LEMSC

Thus to characterize the adherence between bamboo and the PLA/rPMMA material, two pull-off tests were realized on bamboo embedded in the material. As shown in Figure 56, the free end of the bamboo underwent traction, while the other end of the bamboo embedded in plastic was retained by a metallic box (see Figure 57). This test did not follow a specific standard and was homemade but gives a first proper approximation of the adherence.

The **shear strength** at the interface was calculated according to the formula used by French researches in their study of the “*Interfacial Characterization by Pull-Out Test of Bamboo Fibers Embedded in Poly(Lactic Acid)*” (Quentin Viel, 2018):

$$\tau_{app} = \frac{F_{deb}}{\pi D_f L_{emb}}$$

where the fiber is replaced by the bamboo, and the PLA by our PLA/rPMMA composition in our case and where :

- τ_{app} is the apparent interfacial shear strength [MPa] (apparent because the diameter and embedded length are parameters, whereas they are normally assumed constant);
- F_{deb} is the force required to debond the bamboo [N];
- πD_f is the perimeter of the bamboo [mm];
- and L_{emb} is the embedded length of the bamboo into the matrix [mm],

and hence $\pi D_f L_{emb}$ is the total lateral surface on which the shear stress applies.

Because there is an increase of +25% of the section diameter at the nodes, we take the **assumption** that the 2 nodes embedded are the only part effectively participating in the overall adherence (they could be compared to the crenulations of the serrated steel).

The values to calculate the shear strength were deducted from the results of the tests.

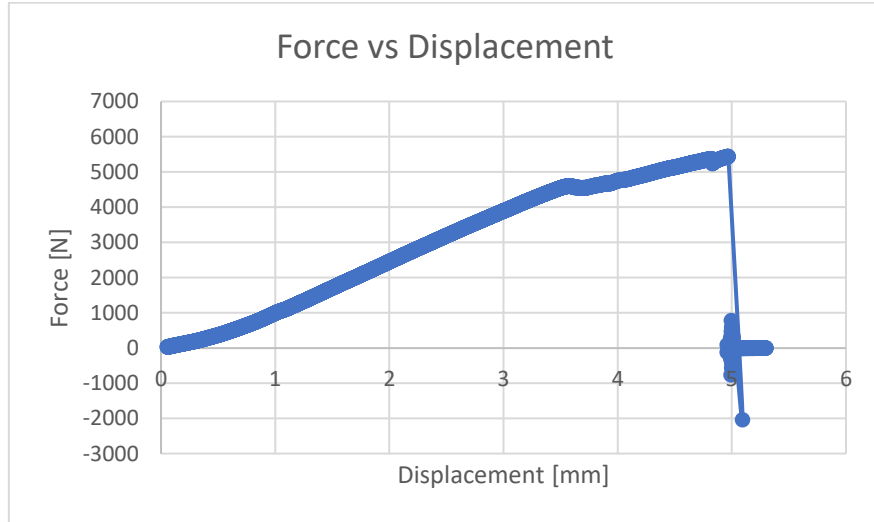


Figure 58 Force vs Displacement Pull-off 1 without loss of adherence

The **pull-off test number 1** (see Figure 58) presents a quasi perfect linear behaviour before failure, and looks very similar to the bamboo tests done before (see 4.3.1.). No loss of adherence was observed, at least till the maximum traction force recorded, before failure of the bamboo at 5445,6284 [N]. This force corresponds to a tensile stress of 1,676 [MPa] applied on the section (bamboo+matrix).

The shear strength was then calculated with the maximum force recorded: τ_{app} reached **14,45 [MPa]**²¹.

²¹ Note that if the bamboo was stronger, failure would have appeared later and we could probably have thus achieved even a greater strength.

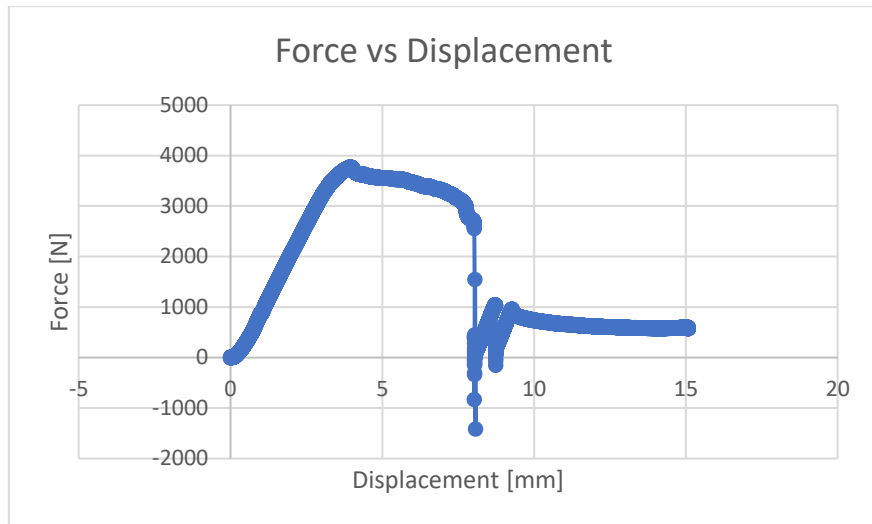


Figure 59 Force vs Displacement Pull-Off 2 with loss of adherence

For the **pull-off test number 2** (see Figure 59), the results were more significant because there is a clear loss of adherence, enabling us to calculate the shear strength more accurately. Indeed, the force reaches a maximum around 3767,06 [N] and then decreases, while the displacement continues to increase, characterizing the loss of adherence.

The tensile stress corresponding to the maximum force reached before debonding was 1,082 [MPa]. Thus, the shear strength τ_{app} calculated is **6,813 [MPa]**, smaller than pull-off test 1.

To conclude, there is effectively an adherence between bamboo and the PLA/rPMMA matrix at the nodes.

4.3.3 Flexion

Finally, to characterize the **flexural strength** and **flexural modulus** of the composition and the composition with bamboos, flexion tests have been done on several specimens to evaluate their behavior under bending.

Flexural 3 points tests were realized following the ISO 178 standard (ISO, 2019) and the test device is pictured in Figure 60. The plastic is a *rigid plastic* according to the definition of the standard, as it presents a modulus of elasticity greater than 700 [MPa] (see first results 4.1) and thus no metallic plates were used between specimens and supports to prevent from indentation. Even, no markings at all were observed on the specimens after the test.

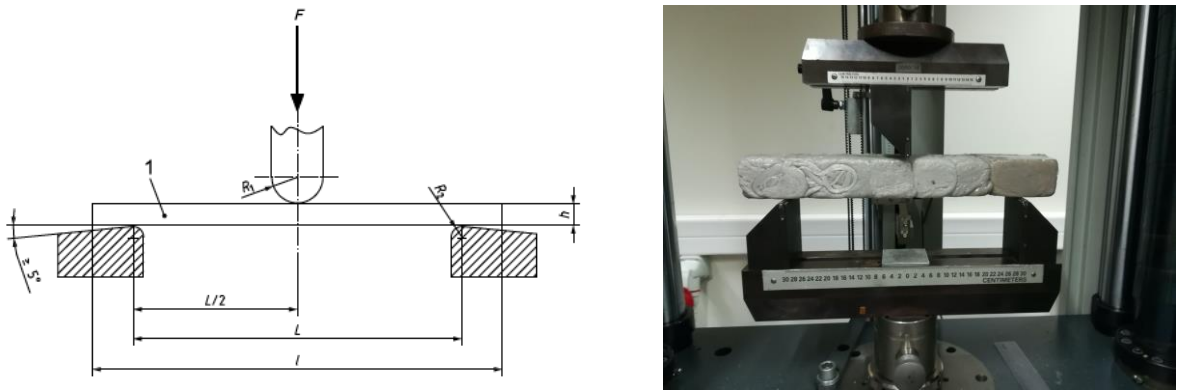


Figure 60 Three points flexural test device according to ISO 178

4.3.3.1 Without bamboo

The aim of this test was to check the correspondence between the results of a bigger element and the small injected bars tested by INNOLOGIC (4.1).

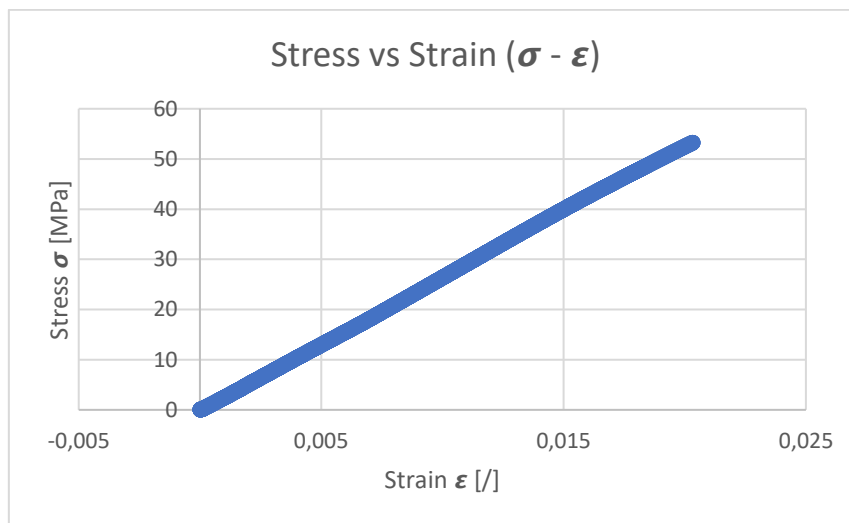


Figure 61 Force vs Displacement PLA/rPMMA without bamboo

The stress-strain diagram (Figure 61) shows a very **brittle material** compared to the graph in Figure 48 where the material showed very ductile properties. Indeed, the flexural

strength σ_{fM} is only 53,2512 [MPa] against 112,6 [MPa] for the injected bars. After analysis of the case, the reason for this difference comes from the manufacturing process.

First, injection is clearly a better process: the material is injected under pressure and cooled down at a certain rate, and leads to better mechanical properties (see 2.1.4). Here, the extruded material was compressed manually into the formworks and cooled down rapidly under ambient temperature. This rapid cool down inhibits the microstructure to settle. Also, the absence of the pressure and degassing phases did not allow the micro air bubbles to come out of the material. Hence a brittle behavior was observed.

Moreover, the comparison between the injected bars and this current test shows a **flexural modulus of only 2,618 [GPa]**, while 3,243 [GPa] should have been found. We can, also observe a brittle failure of the material at 2,033 [%], smaller than the 4,4 [%] ultimate strain recorded for the ductile material. Only elastic deformations occurred, while plastic deformations should have been observed as well.

This test is thus not relevant for characteristics values but is more than important to indicate the **crucial role of the manufacturing process** in the overall properties of a material.

4.3.3.2 Prototype of bamboo interlocked in PLA/rPMMA

The aim of the following tests is to see whether several bamboos could work together and create a beam where they would be interlocked in PLA/rPMMA matrix.

Several configurations of bamboos' layers have been tested: 1 central bamboo, 2 bamboos vertical, 2 central horizontal and 4 bamboos. A recapitulative table of the results presenting the **flexural strength** and **modulus** are detailed in Table 3.

	F_{MAX}	S_{MAX}	σ_{fm}	ε_{fm}	E_f
	kN	mm	MPa	/	GPa
NOBamboos	14,792	6,09960634	53,2512	0,02033202	2,6189838
2VERTBamboos	10,73	7,00514647	44,7548093	0,02148245	2,31451268
2HORBamboos	14,96	5,3247046	48,9629455	0,01774902	2,50755545
4Bamboos	5,625	4,04501411	20,252556	0,01348338	1,42398
1Bamboo	11,076	2,4543	32,4729755	0,00995494	3,09979959

Table 3 Flexural tests results

Knowing the weaknesses of the PLA/rPMMA matrix from the previous test (brittle behaviour), it is not surprising that the flexural strength shows lower strength, ranging between 20 and 50 [MPa], compared with the 112,6 [MPa] found in the first flexural tests on injected bars.

Indeed, as an example the stress-strain diagram of 1 bamboo embedded specimens is shown on Figure 62 and shows a **brittle failure**. All the diagrams for these tests are similar and can be found in Appendix F III. The failure always quickly occurs for a strain between 1 and 2 [%].

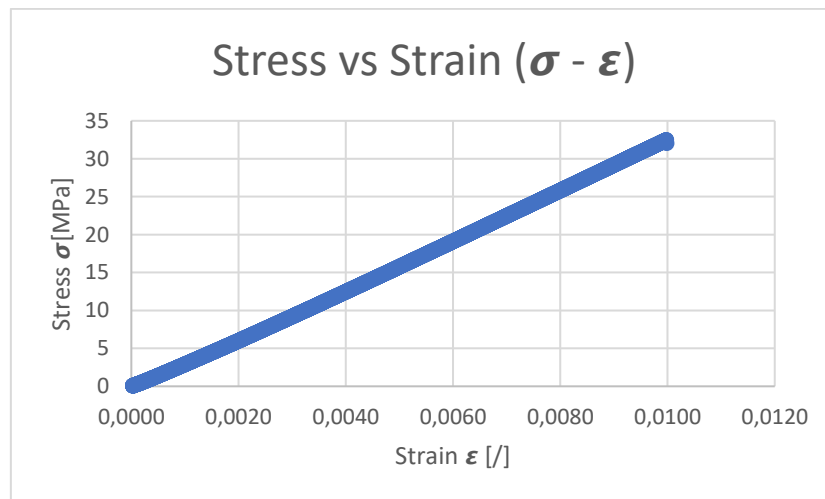


Figure 62 Flexural test on matrix with 1 bamboo embedded

Therefore, we analyze **the influence of the number of bamboos** on the rigidity of the material.

Overall, the **flexural modulus E_f** are lower than 3 [GPa], around 2,5 [GPa] but shows a good rigidity compared to many blends of polymers.

The highest flexural modulus is found for 1 central bamboo configuration, with 3,099 [GPa]. And surprisingly, the lowest flexural modulus was found for 4 bamboos configuration. However, as explained before, this test is rejected because of the difficulties encountered during manufacturing process.

Nevertheless, we see that 1 bamboo does actually increase the flexural modulus compared to no bamboo embedded (3,099 [GPa] compared to 2,62 [GPa]).

In addition, the position of bamboos in the matrix seems also to play an important role: indeed, the 2 horizontal central bamboos showed slightly better flexural modulus than the 2 verticals.

We cannot draw definite conclusions from these flexural tests, but trends are observed and should be further explored in the modelling. However, it still further demonstrates the importance of the manufacturing process on the intrinsic properties of the material.

4.4 Conclusion of the analyzed results

Many tests have been done to characterize the new composition PLA/rPMMA, but also the behavior of bamboos interlocked in this composition.

The first test on the injected composition showed a very ductile material, with very good mechanical properties, and a flexural modulus of 3,243 [GPa] meeting consequently the overall objective. The first cycle of recycling of PMMA does not decrease significantly its mechanical properties.

Further, the traction tests on bamboos showed a very strong material in its longitudinal direction, but also natural material that could present some defaults. The properties are comparable to the Moso specie of bamboos.

Afterwards, pull-off tests highlighted the good adherence between bamboo and PLA/rPMMA matrix, probably highly guided by the bamboo's nodes embedded.

And later, flexural tests showed that the specimens created through the extruded composition present a very brittle material, in contradiction to the first observations done where the material present a ductile behavior. This is due to the manufacturing process and the absence of pressure and degassing phases.

Hence, it was not possible to draw major conclusions on the real effect of bamboos to increase the overall mechanical properties, but the results showed encouraging acknowledgments.

Finally, the properties defined in the first injected molds flexural tests are relevant and will be used for modelling. And to evaluate the strength of the section with bamboos, the flexural tests will be done numerically in the following part.

PART 5 MODELLING FOR APPLICATIONS

This part is divided in three chapters: flexural tests on bamboos interlocked in PLA/rPMMA, design of section for a carport, overall analysis of a carport. The aim of the design is to find a section able to withstand the flexural loads and remain in the first elastic deformation domain of the material.

For the section modelization, we use SeismoStruct software from SEISMOSOFT (enabling to modelize structures under earthquakes (SEISMOSOFT, 2020)), and for the structure modelization, we use ROBOT from AUTODESK a BIM structural analysis software (AUTODESK, 2020).

Even if **SeismoStruct** is more appropriate for seismic analysis, it enables to model reinforced sections with user-defined materials and was therefore chosen. In order to accurately represent the mechanical response of an element under efforts, the behavior of the material has to be appropriate and very similar to its real behavior.

Polymers are non-conventional material in construction: the **elastic behavior** of **PLA/rPMMA** matrix was thus approximate by the first elastic domain of a *Ramberg-Osgood steel model* material, presenting a smooth elastic-plastic transition as observed for our matrix.

The parameters used are the ones from INNOLOGIC test :

- Yield strength : **112 600 [kPa] = 112,6 [MPa]**
- Yield strain : 0,03 [/]
- Fracture/Buckling strain : 0,044 [/]
- Specific weight : 12,26 [kN/m³]

The small injected 4x10x80 [mm³] bars were first analyzed on equal terms to ensure the model was close to reality; what it shown (see Table 4). This user-defined material was thus used for all the simulation.

	σ_{fMAX}	ϵ_{fMAX}	F_{MAX}	S_{MAX}
	MPa	/	kN	mm
INNOLOGIC bars	112,6	0,044	0,18767	7,5093
Numerical bars	108	0,041	0,23	6,6

Table 4 Flexural strength and modulus of PLA/rPMMA

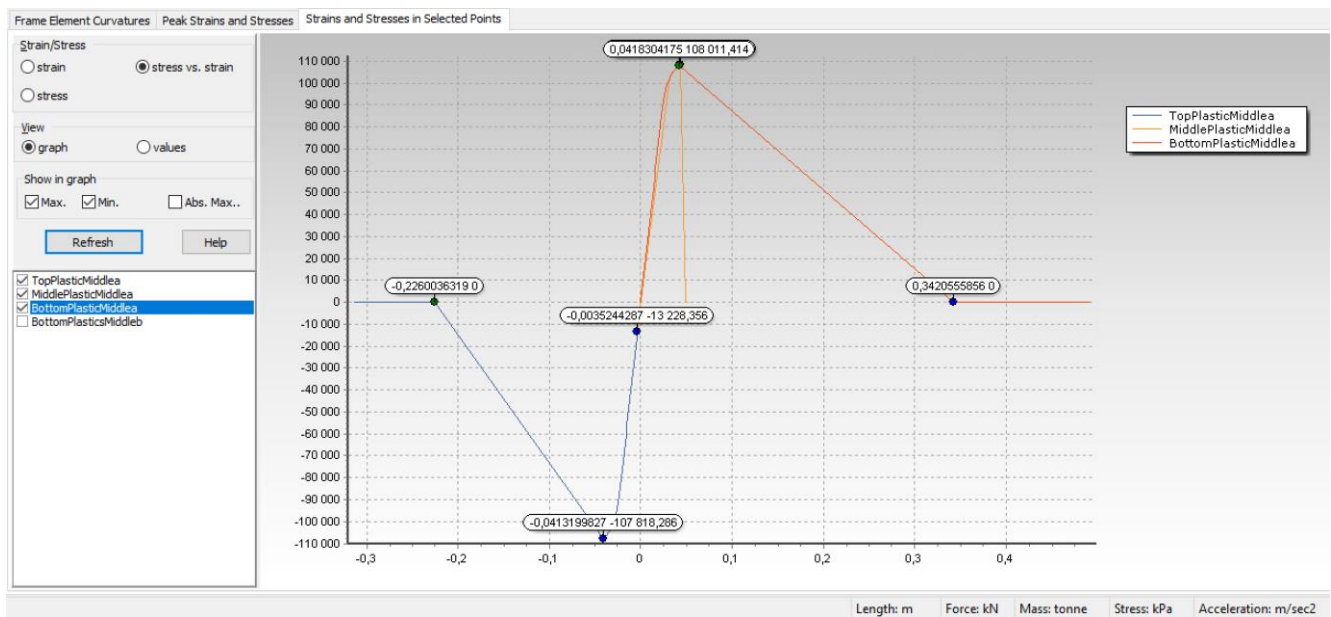


Figure 63 Stress vs Strain plot of the flexural stress on bars (SeismoStruct)

SeismoStruct displays *traction in positive values and compression in negative values*. Indeed, in flexion, the bottom part of the section will take over traction, as we can see on Figure 63 (top part of plot). The linear elastic domain of the numerical model is very similar to the real elastic behavior observed during the lab test (Figure 48). Be aware that Strain scales are different (without units here, and in % before) and Stresses in ordinate axis are displayed in [kPa] (usually expressed in [MPa]). **Numerical model is hence very close to reality.**

Bamboos are neither very common in “modern” structural engineering and hence not present in the soft. As bamboos present a brittle behavior, the first linear elastic part of the steel behavior was used, under the *Bilinear steel model* of the software. Although bamboos tested previously are more than probably Moso specie, here the **Guadua** species was chosen as it presents overall the highest mechanical properties and can be found under large diameters for its use in construction.

The parameters used for bending are the ones found in the literature (see APPENDIX A):

- Modulus of elasticity: 17 900 000 [kPa]
- Yield strength : **90 000 [kPa]**
- Strain hardening parameter : 0 [/]
- Fracture/Buckling strain : 0,005 [/] (approximation towards fail-safe)
- Specific weight : 6,376 [kN/m³]

Finally, several **assumptions** are taken to handle simulation constrains:

- The adherence between materials are assumed by SeismoStruct to be 100%
- The injection manufacturing process is assumed to be used for the creation of the beams to keep the good properties
- The dead load is automatically included by the software.

5.1 Numerical flexural tests

As the real flexural tests on **bamboos interlocked in PLA/rPMMA** matrix were not relevant for the reasons mentioned in 4.3.3.2, they were numerically realized with the help of SeismoStruct.

The **bamboo** model used here is slightly different from the rest, as it uses the values gathered through the tension tests (4.3.1) :

- Modulus of elasticity: 25 040 000 [kPa]
- Yield strength : 175 000 [kPa]
- Strain hardening parameter : 0 [/]
- Fracture/Buckling strain : 0,0077 [/] (approximation towards fail-safe)
- Specific weight : 8,29 [kN/m³]

The sections with **2 bamboos vertical** and the other with **2 bamboos horizontal** (at middle height) were designed to find their flexural properties, according to standard (ISO 178).

The main properties are stated in Table 5.

	σ_{fMAX} MPa	ϵ_{fMAX} /	F_{MAX} kN	S_{MAX} mm	E_f GPa
2 bamboos VERTICAL	86,748	0,01962667	20,80338	6,4	4,58167154
> PLA/rPMMA	108	0,0435			
> Bamboo	168	0,0067			
2 bamboos HORIZONTAL	144,18	0,03733333	40,851	11,2	4,02457235
> PLA/rPMMA	107	0,0408			
> Bamboo	17,302	0,00069			

Table 5 Principal characteristics from numerical flexural tests

Comparing the results of the real tests (Table 3) with the model (Table 5), there is actually an increase in the flexural strength. For the vertical disposition, the bamboos are either taking over compression or traction (top and bottom) and undertake most of the stresses. Therefore, they reach failure before the matrix. The flexural strength is **86,748 [MPa]**.

In the horizontal disposition, the bamboos are placed in the central height of the section, where the stresses are minimum. Hence, it is mainly PLA/rPMMA matrix that takes the stresses and fails before bamboos. Moreover, we can observe that bamboos slightly increase the flexural strength, from 112,6 [MPa] for injected bars without bamboos, to **144,18 [MPa]**.

Comparing the flexural modulus, to the 3,243 [GPa] found for injected bars, we actually observe an increase of the rigidity with bamboos embedded.

Finally, conclusions confirm the trends observed in the real tests. Bamboos increase the strength and the rigidity. However, a good arrangement is essential to solicit both PLA/rPMMA and bamboos within their limits and find the best distribution of stresses within both materials.

5.2 Design the top beam of carport

In this chapter, we will design the roof beam of a carport covering two cars (see below Figure 67).

5.2.1 Theory behind the design

To design and evaluate the load-bearing capacities of an element, three important characteristics are defined: the supporting conditions, the span between those supports and the loads it has to take over. Moreover, the characteristic resistances of the material must be known and the safety coefficient by which it has to be divided.

Indeed, **characteristic resistance** σ_{fM} are drawn from the mechanical tests and coefficient are applied to them in order to secure the overall structure from unforeseen events; in civil engineering, the common global safety coefficient γ_M equals 1,5 : however, as the new material is still not fully determined, the coefficient taken is increased to 2 to manage the uncertainties. The design resistance is thus $\sigma_{adm} = \frac{\sigma_{fM}}{\gamma_M}$.

After defining the loads taken by the beam, the **maximum stresses** can be calculated through:

$$\sigma_{MAX} = \frac{M_{MAX} * y_{MAX}}{I}$$

where the **maximum moment** M_{MAX} of the distributed load, for an isostatic beam, is $\frac{qL^2}{8}$ and of the central point load is $\frac{PL}{4}$, where y_{MAX} is the distance of the farthest fibers of the section from the neutral axis, and I the moment of inertia, equal to $\frac{h^3}{12}$ and $\frac{bh^3}{12}$ respectively, in a rectangular cross-section. The maximum moments, and hence maximum stresses, appear at mid-span between the two supports, as pictured on Figure 64.

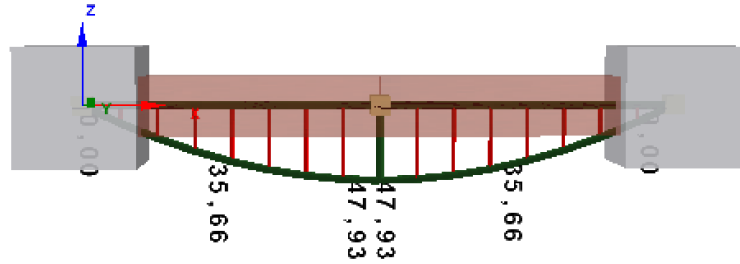


Figure 64 Free body diagram of distributed load (Moments)

Also, the **maximum deflection** f_{MAX} at mid-span of the structure is calculated by $\frac{5 q L^4}{384 E I}$ for distributed load, and $\frac{P L^3}{48 E I}$ for a central point load (F. Frey, 2017). The maximum deflection is a criterion mandated by the parties, and usually taken from the standards as $\frac{L}{500}$ at short term (NBN B 03-003, deformation of structures, (NBN, 2003)).

Furthermore, two limit states are evaluated: the **ultimate limit state (ULS)** to check the resistance of the structure loaded and the **service limit state (SLS)** to check the serviceability of the structure :

- 1) ULS : $\sigma_{MAX} \leq \sigma_{adm} = \frac{\sigma_{fM}}{\gamma_M}$
- 2) SLS, short term : $f \leq f_{MAX} = \frac{L}{500}$

The dimensions of the section are evaluated such that the 2 inequalities are checked. However, a pre-dimensioning can be settled and then check if it satisfied the mentioned obligations.

From the Eurocode 1 (NBN EN 1991-1-1, (NBN, 2002)), all possible **load combinations** must be analyzed, modelling the loads occurring simultaneously. The method of *partial coefficients* defines dominant live loads and accompanying actions.

For the **ULS**, the simplified combination multiplies dead loads by 1,35 and live loads by 1,5 : $q_{ULS} = 1,35 * \Sigma G_{k,i} + 1,5 * \Sigma Q_{k,i}$. Hereafter, all the live loads have been considered as dominant live loads to again consider the non-favorable combination.

For the **SLS**, the characteristic (or unusual) combination used for short term multiplies dead loads and dominant live load by 1, while accompanying live loads are multiplied by $\psi_{0,i}$ (resumed in Table 6) : $q_{SLS,ST} = 1 * \Sigma G_{k,i} + 1 * Q_{k,1} + \psi_{0,i} * \Sigma Q_{k,i}$.

Action	ψ_0	ψ_1	ψ_2
Charges d' exploitation des bâtiments (voir EN 1991-1-1)			
Catégorie A : habitation, zones résidentielles	0,7	0,5	0,3
Catégorie B : bureaux	0,7	0,5	0,3
Catégorie C : lieux de réunion	0,7	0,7	0,6
Catégorie D : commerces	0,7	0,7	0,6
Catégorie E : stockage	1,0	0,9	0,8
Catégorie F : zone de trafic, véhicules de poids $\leq 30\text{kN}$	0,7	0,7	0,6
Catégorie G : zone de trafic, véhicules de poids $> 30\text{kN}$ et $\leq 160\text{kN}$	0,7	0,5	0,3
Catégorie H : toits	0	0	0
Charges dues à la neige sur les bâtiments (voir EN 1991-1-3)	0,5 ⁽⁵⁾	0	0
Charges dues au vent sur les bâtiments (voir EN 1991-1-4)	0,6 ^(5,6)	0,2 ⁽⁶⁾	0
Température (hors incendie) dans les bâtiments (voir EN 1991-1-5)	0,6 ⁽⁵⁾	0,5	0
Tassements (voir EN 1997)	1,0	1,0	1,0
Actions particulières pendant l' exécution (voir EN 1991-1-6) ⁽⁷⁾	1,0	-	0,2

⁽⁵⁾ $\psi_0 = 0,3$ pour une action variable de courte durée (< 1 mois) qui accompagne une action variable principale ou dominante de courte durée

⁽⁶⁾ Pour les états-limites de service, les valeurs de ψ_0 et ψ_1 peuvent dépendre du critère de service

⁽⁷⁾ Les facteurs ψ pour les charges d'exécution sont à déterminer si nécessaire au cas par cas

Table 6 Partial coefficients from EN 1991-1 and according to ANB Belgium annexes (CSTC, 2014)

5.2.2 Modelling the sections

A **rectangular shape** for the section has been chosen to easily insert several bamboos and also increase its inertia (largest dimension is set vertical, and loads are applied parallel to this vertical direction).

Concerning the bamboos, the smallest **Guadua** diameters of 5 cm was used and enables to try several dispositions.

On the basis of regular timber section, the pre-dimension section is $16 \times 24 [\text{cm}^2]$ and enables to evenly dispose 2 bamboos in horizontal direction and up to 3 bamboos in vertical direction (see Figure 65).

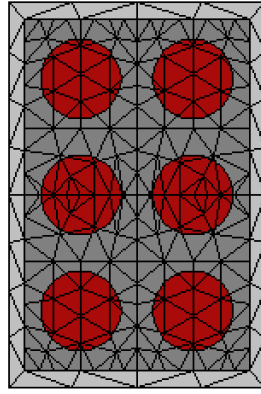


Figure 65 Disposition of the bamboos in section and discretization patterns for SeismoStruct

Several configurations will be analyzed through the model to see whether it can withstand, within their **elastic domain**, the loads applied. The overall dimensions will be adapted if necessary.

The length of the beam has been defined to **3 meters long**, the roof of the carport being divided in 3×3 [m²]. It is modelled as an isostatic beam lying on 2 supports.

In order to evaluate the stresses and deflection, the **applied loads** have to be defined:

- Dead load (intrinsic material properties and depending on the dimensions of the section)
- Live load due to snow : 5 [kPa] gravitational
- Live load due to wind : 1 [kPa] perpendicular to the local surface
- Live load of exploitation : 3 [kPa] gravitational, covering all the live loads
- Live load of maintenance : 1 [kN] in the center, representing a person walking on the roof to fix damages

The exploitation load is taken to maximize the load and represents the most unfavorable situation; but in practical terms, there should be no exploitation on the roof of the carport. Finally, the surface loads are decomposed into linear distributed loads on the most loaded beam, to analyze the most adverse situation, where the beam would have to support **3 meters width** of the roof.

For the purpose of the software, the loads applied have been divided in the distributed loads (distributed live loads) and the point load (maintenance person). Hence, the total values are: **40,5 [kN/m]** for live loads (dead load already calculated by the soft) and **1,5 [kN]** for the person sitting at the middle span of the beam (partial coefficients taken into account).

Following the theory (in 5.2.1), first the **ULS state** is analyzed.

After designing the section and the load actions in the *pre-processor*, several selected points²² are defined in the central section of the beam in order to analyze their behavior in the *post-processor*: typically, points at top, middle and bottom of the plastics, and the bamboos.

The stresses are displayed in the **Stress vs Strain** output and analyzed to see whether failure occurs in plastic and/or bamboos. We can then conclude if the section is able to withstand the loads and verify if it does not exceed $\sigma_{adm} = \frac{\sigma_{fM}}{\gamma_M} = \frac{112,6}{2} = 56,3 [MPa]$.

Secondly, and after potential re-dimensioning of the section, the **SLS state** is analyzed. The values of the distributed loads are changed in the *pre-processor* to **8,904 [kN/m]**. Here, the dominant live load (for SLS) is the maintenance person, whereas the accompanying live loads are snow and wind, short actions with a coefficient $\psi_{0,i} = 0,3$ (short action accompanying short dominant action, see Table 6), reducing drastically the final value of the actions.

After, the graph displaying the Total resultant force (applied at the central node of the beam) vs Displacement in the output is analyzed: the displacement before failure is compared to the limit deflection $f_{MAX} = \frac{L}{500} = \frac{3}{500} = 0,006 [m] = 6 [mm]$, and the section is either kept or increased to satisfy this second condition.

The admissible stresses for bamboos are calculated as follow (Cuchet, 2019):

$$\sigma_{adm} = k_{mod} k_{sys} k_{len} \frac{\sigma_{fM}}{\gamma_m}$$

where

- k_{mod} depends on the service class and the duration of the loads applied (see Table 7).
- k_{sys} represents the resistance factor of the system (1 except in some specific cases where it is 1.1)
- k_{len} is not taken into account because of gap in the researches for a favorable coefficient for small height
- γ_m is the security factor (1.5 for bamboo)

²² The *Selected Points* are triangles from the meshing of the section.

Service class	Permanent	Long term	Medium term	Short term	Instantaneous
1	0.6	0.65	0.75	0.8	1.05
2	0.6	0.65	0.75	0.8	1.05
3	0.4	0.45	0.75	0.6	0.75

Table 7 k_{mod} coefficients for bamboo (Cuchet, 2019)

According to Eurocode 5 (EN 1995 – Wood), the risk of attacks from woodworm organisms is rising through the classes (Latteur, 2019):

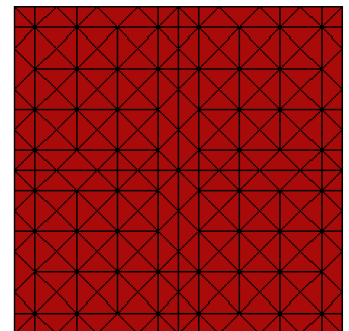
- Service class 1: works protected from bad weather (no water, no steam). Example: internal structure of homes and buildings.
- Service class 2: works partially protected from bad weather (exceptional contacts with water and steam). Examples: open hangers, storage areas, ...
- Service class 3: works exposed to bad weather (contacts with water and steam). Examples: bridges, footbridges, decking, guardrails, ...

Finally, $\sigma_{adm} = 0,8 * 1 * \frac{90}{1,5} = 48 [MPa]$ with the second service class (bamboos are embedded in the matrix and should not be exposed to weather) and short term live loads (snow and wind are defined as short term), thus $k_{mod} = 0,8$.

First section : without bamboo

- 1) ULS : $\sigma_{max} = 34 [MPa] \rightarrow$ condition verified
 $\rightarrow$ no failure observed, elastic deformations (linear stress-strain plot)
- 2) SLS, short term : $f_{max} = 15,5 [mm]$ **exceeding the admissible deflection**

By trial-and-error method, the square section $0,3 \times 0,3 [m^2]$ meets the condition with a deflection of $4,5 [mm]$.



Second section : with 2 bamboos in lower part

1) ULS :

- PLA/rPMMA matrix: -30,78 and 20,389[MPa] (compression and traction respectively) → condition verified
- Bamboos: 51,047 [MPa] **exceeding the admissible value**
→ no failure observed, elastic deformations for bamboos and matrix

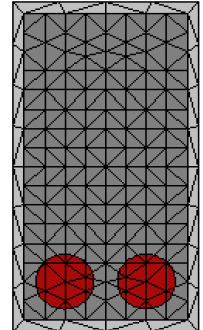
2) SLS, short term : $f_{\max} = 11,4$ [mm] **exceeding the admissible deflection**

By increasing the height to 0,3 [m]:

→ it generates a deflection of 5,6 [mm] at **SLS** → condition verified

→ it reduces the stresses in bamboos at **ULS** to 39 [MPa] → condition verified.

The value of the **traction is here lower than the compression** because the bamboos are taking over an important part of the traction in the lower section. Hence, the deflection decreased.



Third section : with 4 bamboos in lower and middle parts

1) ULS :

- PLA/rPMMA matrix: -28,58 and 20,99 [MPa] → condition verified
- Bamboos: -18,08 and 55,38 [MPa] **exceeding the admissible value**
→ no failure observed, elastic deformations for bamboos and matrix

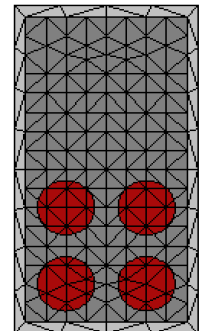
2) SLS, short term : $f_{\max} = 11,035$ [mm] **exceeding the admissible deflection**

By increasing the height to 0,3 [m]:

→ it generates a deflection of 5,66 [mm] at **SLS** → condition verified

→ it reduces the stresses in bamboos at **ULS** to 38,369 [MPa] → condition verified.

The stresses in the lower bamboos have slightly decrease with the increase of the section because the matrix is taking over more stresses.



However, it seems that the entire disposition of the bamboos in the section does not lead to an adequate section, as the deflection did not improved compare to the section with only 2 bamboos. The only advantage is the reduction of the stresses in the bamboos.

Fourth section : with 4 bamboos in lower and upper parts

After the last observations, place 2 bamboos in each part of the section taking over the greater stresses seemed a good idea.

1) ULS :

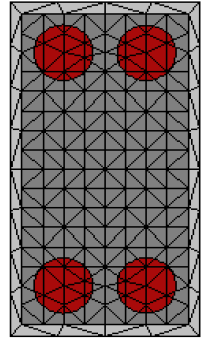
- PLA/rPMMA matrix: -2,416 and 2,42 [MPa] → condition verified
- Bamboos: -89,5 and 89,702[MPa] **exceeding the admissible value**
→ no failure observed, elastic deformations for bamboos and matrix

2) SLS, short term : $f_{\max} = 9,628$ [mm] **exceeding the admissible deflection**

By increasing the height to 0,3 [m]:

→ it generates a deflection of 4,66 [mm] at SLS → condition verified

→ However, stresses in bamboos at ULS are 62,39 [MPa] and still **exceeding the admissible value**



The bamboos still stay in their elastic domain but take over a lot of stresses. Indeed, here the matrix only serves as link between the 4 bamboos at the extremities and does not take over many stresses.

Hence, this section is not appropriate: the bamboos are exceeding their limit values, whereas the matrix is not much solicited. There is thus an unbalanced distribution of the stresses on the 2 materials composing the section.

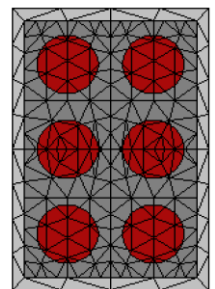
Fifth section : with 6 bamboos and 8 bamboos

After the last observations, the idea is thus to fill the gap between the 2 extreme layers of bamboos by bamboos placed in the middle section.

1) ULS :

- PLA/rPMMA matrix: -16,792 and 16,806 [MPa] → condition verified
- Bamboos: -49,75 and 49,819[MPa] **exceeding the admissible value**

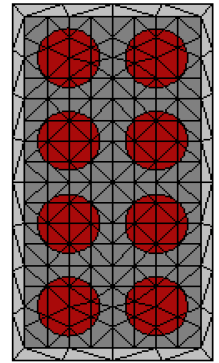
→ no failure observed, elastic deformations for bamboos and matrix



2) SLS, short term : $f_{\max} = 7,46$ [mm] **exceeding the admissible deflection**

By increasing the height to 0,3 [m], and adding an additional layer of bamboos (8 bamboos in total):

- it generates a deflection of 3,504 [mm] at **SLS** → condition verified
- stresses in PLA/rPMMA matrix have decreased : -9,848 and 9,853 [MPa]
- it reduces the stresses in bamboos at **ULS** to maximum 33,644 [MPa] → condition verified.



Finally, this 8 bamboos section presents the lowest values at ULS and SLS, for stresses in matrix and bamboos, as for deflections.

Sixth section : with 4 bamboos in the middle

There is still a problem concerning the bamboos. Indeed, this brittle material are efficient regarding the loads to withstand, but when it comes near failure, bamboos do not elongate much before they fail (maximum strain at 0,005). Consequently, the extreme bamboos (in the 8 bamboos section) taking over the greater stresses will fail relatively rapidly and before the matrix.

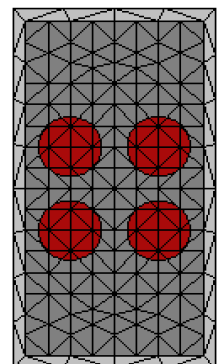
A last section was thus thought, in order to **maximize the utilization of bamboos and of PLA/rPMMA matrix**: place 4 bamboos in the central part of the section will increase the overall flexural modulus and use the bamboos and matrix adequately. Bamboos placed at the center will increase the rigidity and undergo only small elongation, whereas the PLA/rPMMA at extremities will undergo greater but allowable elongation (maximum strain of 0,044).

1) ULS :

- PLA/rPMMA matrix: -19,91 and **19,929** [MPa] → condition verified
- Bamboos: -22,63 and **22,7** [MPa] → condition verified

→ no failure observed, elastic deformations for bamboos and matrix

2) SLS, short term : $f_{\max} = 7,1$ [mm] **exceeding a little the admissible deflection** of 6 [mm], but reasonably acceptable.



Finally, these 4 middle bamboos section presents the **best repartition of the stresses** among all sections and will be used in the design of the carport.

Conclusion

A table resuming all the important values discussed hereabove, for the dimensioning of the section is pictured in APPENDIX G.

What emerges from the analysis is that the full PLA/rPMMA square section ($0,3 \times 0,3 \text{ [m}^2\text{]}$) without bamboos, and the rectangular 4 middle bamboos section ($0,16 \times 0,3 \text{ [m}^2\text{]}$), both presents good capabilities and meet the requirements (ULS and SLS). Indeed, the initial dimensions of the section never met the SLS criteria of deflection, and sections have thus always been changed to bigger dimensions (bamboos have been rearranged accordingly).

Finally, the 2 above mentioned sections will be used in the design of the carport because they present the best characteristics.

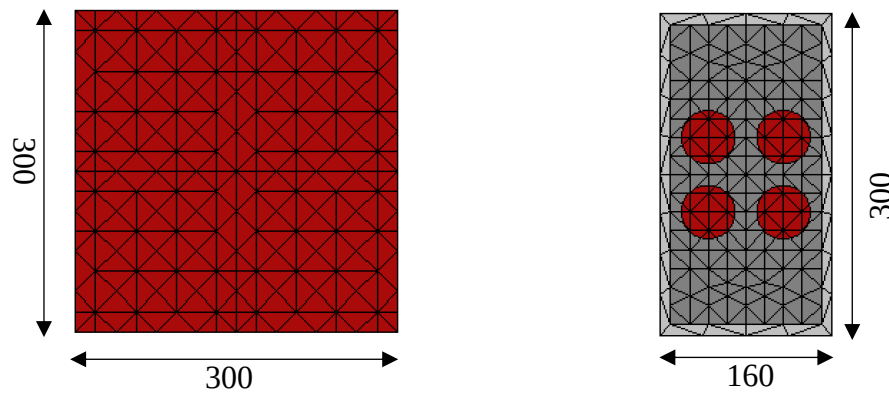


Figure 66 Dimensions of the final sections (dimensions in millimeters)

5.3 Design of a carport

In this chapter, a static linear analysis of the carport with the 2 sections selected previously is done and compared to the same sections made of timber C40:

- square PLA/rPMMA (0,3x0,3 [m²])
- square timber C40 (0,3x0,3 [m²])
- rectangular PLA/rPMMA with 4 bamboos in the center (0,16x0,3 [m²])
- square timber C40 (0,16x0,3 [m²])

The structure is 2,3 m high, 6 m width (able to protect 2 cars) and 6 m long. The 6 x 6 [m²] of the roof are divided in 4 equivalent squares of 3 x 3 [m²] (the beam dividing the roof are called *central beams* further on). The 3D carport has been drawn in the software and is pictured at Figure 67. The longest beam of the roof is thus **3 meters long**.

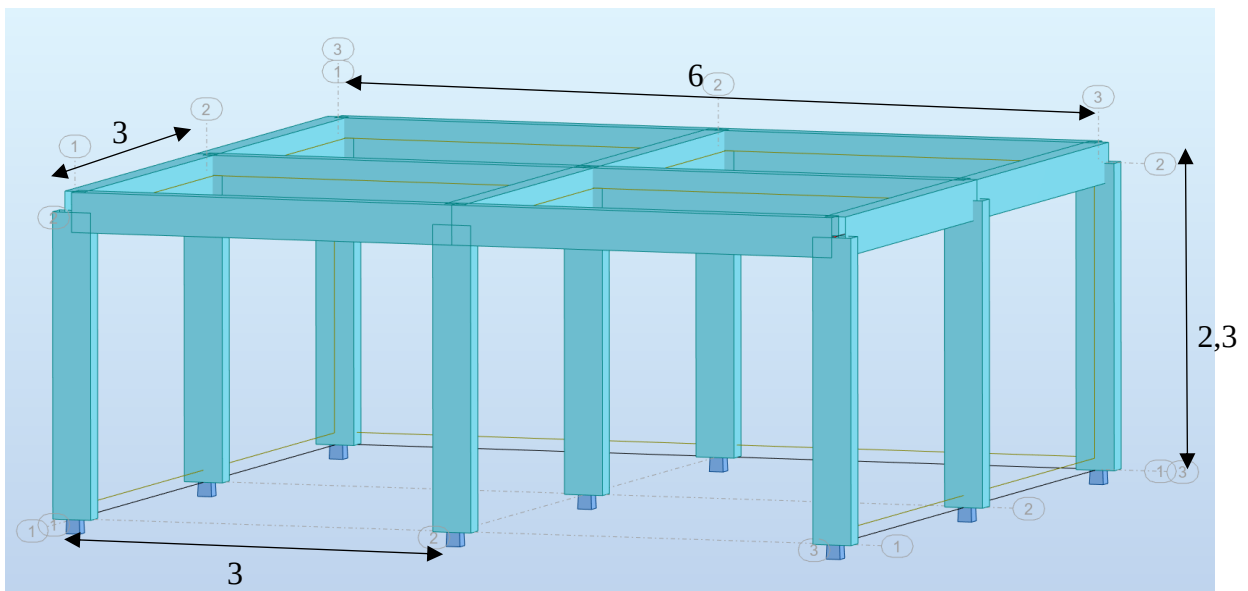


Figure 67 General structure of the carport (dimensions in meters)

The ULS and SLS criteria are checked **for 3 different load combinations** through the software **ROBOT** from Autodesk. Indeed, this BIM modeler enables to create user-defined Materials and analyze the full structure with user-defined Load Combinations.

So first of all, to define the **material properties**, a numerical flexural test have been done (with SeismoStruct) on both sections to determine their flexural strength and modulus (same procedure than 5.1, with formulas according to ISO 178).

	σ_{fMAX}	ϵ_{fMAX}	F_{MAX}	S_{MAX}	E_f
	MPa	/	kN	mm	GPa
SQUARE PLA/rPMMA	136,538183	0,038	819,2291	190	3,73669458
> PLA/rPMMA	108,162189	0,04223374			
RECTANGLE 4 bamboos MIDDLE + PLA/rPMMA	134,506063	0,036	430,4194	0,18	4,22671445
> PLA/rPMMA	107906,832	0,04155179			
> Bamboos Middle TOP	-83,067945	-0,0046407			
> Bamboos Middle LOW	84,074898	0,00469692			

Table 8 Flexural strength and modulus of both model sections

These values (Table 8) allow us to create the new materials in the software and the parameters are described hereafter:

- Young Modulus²³ : 3,736 and 4,226 [GPa] (square PLA/rPMMA and 4 bamboos middle, respectively)
- Poisson ration : 0,4
- Shear Modulus²⁴ : 2050 [MPa]
- Specific Weight : 12,26 [kN/m³]
- Thermal expansion coefficient: $80 \cdot 10^{-6}$ [°C]
- Damping ratio : 0
- Design resistance ($\frac{\sigma_{fM}}{\gamma_M}$) : 68,265 and 67,25 [MPa] (square PLA/rPMMA and 4 bamboos middle, respectively)
- Reduction factor for shear²⁵ : 1,126

²³ NB : flexural modulus is used here because the beams are evaluated under flexural loads (see 3.2.1)

²⁴ (CamJIC, 2015)

²⁵ $R = \frac{\text{elastic strength}}{\text{yield strength}}$ of the PLA/rPMMA matrix

All common timber are already in the software: it was chosen to take timber C40 ($\sigma_{fM} = 40$ [MPa], (Latteur P., 2019)), the best resinous wood, more flexible than deciduous trees and thus more appropriate for comparison:

The admissible design value for timber is calculated through the following formula (Latteur, 2019):

$$\sigma_{adm} = \frac{k_{mod} * \sigma_{fM}}{\gamma_m}$$

where $k_{mod} = 0,3$ for class 3 (outdoor use, permanent load) and $\gamma_m = 1,3$ for solid wood. As timber C40 has a flexural strength $\sigma_{fM} = 40$ [MPa], the admissible stresses should be smaller than 15,38 [MPa].

Three load combinations representing different critical situations have been defined and checked for ULS and SLS criteria:

- 1) The most critical one with several live loads: maintenance persons (2 on edges, 1 in middle of a central beam), snow on entire roof, wind left & back & right & top and exploitation:

$$q_{ULS,1} = 1,35 * [DeadLoad] + 1,5 * [Snow + WindLeft \& Right \& Back \& Top + MaintenancePersons + Exploitation]$$

$$q_{SLS,1} = 1 * [DeadLoad] + 1 * [Snow + WindLeft \& Right \& Back \& Top + MaintenancePersons + Exploitation]$$

- 2) With dominant load snow on front of the roof and accompanying load wind back:

$$q_{ULS,2} = 1,35 * [DeadLoad] + 1,5 * [SnowFront + WindBack]$$

$$q_{SLS,2} = 1 * [DeadLoad] + 1 * [SnowFront] + 0,3 * [WindBack]$$

- 3) With dominant load wind back & right (blowing in 2 directions) and accompanying load snow:

$$q_{ULS,3} = 1,35 * [DeadLoad] + 1,5 * [WindBack \& Right + Snow]$$

$$q_{SLS,3} = 1 * [DeadLoad] + 1 * [WindBack \& Right] + 0,3 * [Snow]$$

The loads, their values, partial coefficients and safety coefficients in use were explained in section 5.2.1.

For the **ULS criteria**, the maximum flexural stresses should not exceed the specific design (admissible) value.

For **SLS criteria**, deflection should not exceed $L/500$ thus 6 [mm].

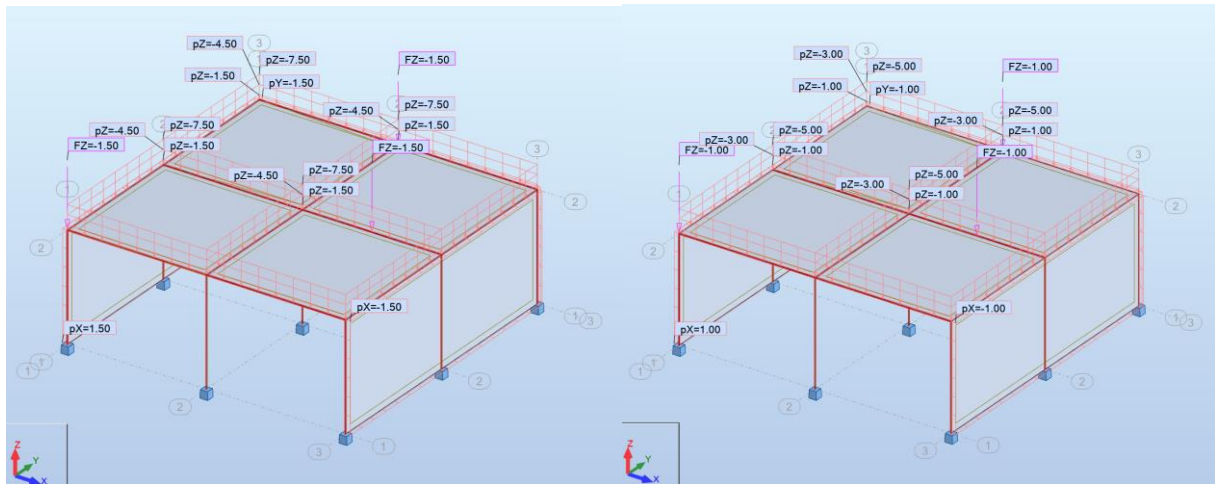


Figure 68 COMB 1 All : ULS (left) and SLS (right)

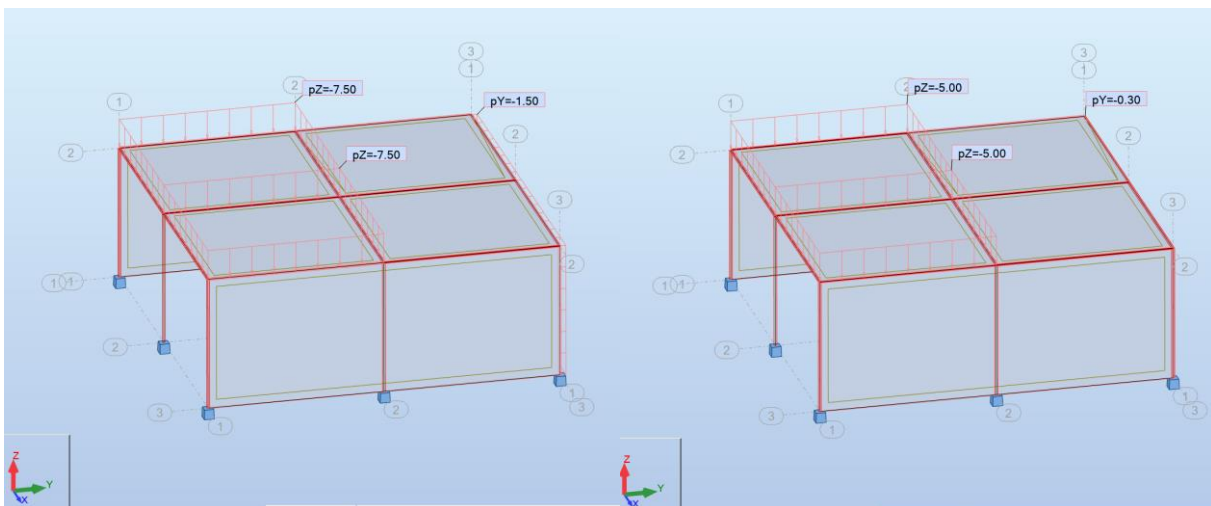


Figure 69 COMB 2 SnowFront+WindBack : ULS (left) and SLS (right)

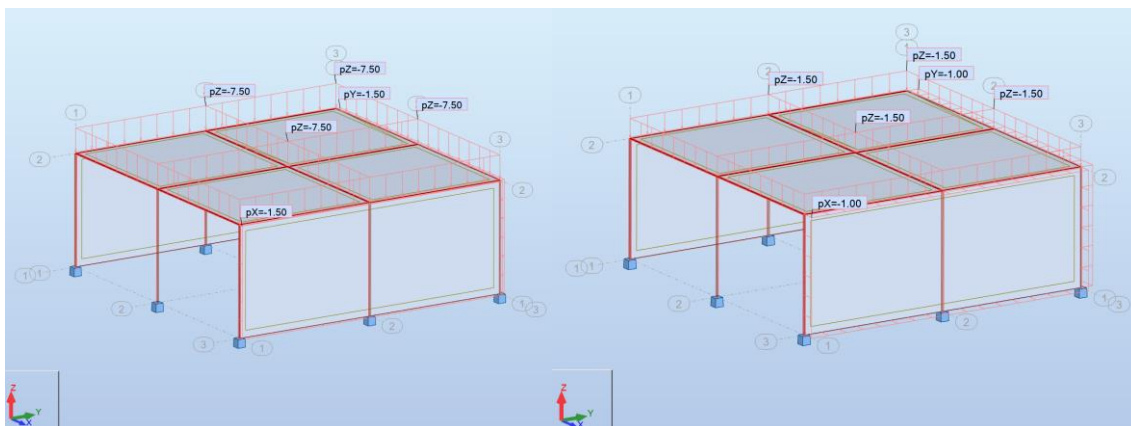


Figure 70 COMB 3 SnowTop+WindBack&Right : ULS (left) and SLS (right)

For the analysis of the carport, the same sections were used for the columns and the roof beams.

However, the compressive properties of the material have not been defined through mechanical tests. Thus, an estimation for the column compressed has been made through SeismoStruct, with the bending characteristics of the material defined before. The biggest normal forces (-Z direction) induced by the actions are in the central column: hence a force of $Z=-62$ [kN] was applied on top (because each beam of the modelization in 5.2.2 have a resultant central force of 124 [kN], leading to a 62 [kN] reaction force at each supports; represented here by the column). It appears that the material can withstand the load without failure. Moreover, the real nodal load in the carport design does not exceed 36,23 [kN], smaller than 62 [kN]. Hence, the sections seem to be good candidate for columns as well.

1 ALL						
ULS	σ_{MAX} in bending M_y [MPa]	σ_{adm} in bending [MPa]	Deflection MAX [mm] Z	SLS	Deflection MAX [mm] Z	Admissible Deflection L/500 = 6 [mm]
Square PLA/rPMMA 30x30 [cm ²]	5,41	68,26	-4		-2	-6
TimberC40 30x30 [cm ²]	5,25	15,38461538	-1		-1	-6
4BamboosMiddle 16x30 [cm ²]	11,06	67,25	-7		-5	-6
TimberC40 16x30 [cm ²]	10,94	15,38461538	-2		-1	-6
2 Snow Front + Wind Back						
ULS	σ_{MAX} in bending M_y [MPa]	σ_{adm} in bending [MPa]	Deflection MAX [mm] Z	SLS	Deflection MAX [mm] Z	Admissible Deflection L/500 = 6 [mm]
Square PLA/rPMMA 30x30 [cm ²]	2,16	68,26	-3		-2	-6
TimberC40 30x30 [cm ²]	1,95	15,38461538	-1		0	-6
4BamboosMiddle 16x30 [cm ²]	3,47	67,25	-5		-4	-6
TimberC40 16x30 [cm ²]	3,22	15,38461538	-2		-1	-6
3 Snow Top + Wind Back & Right						
ULS	σ_{MAX} in bending M_y [MPa]	σ_{adm} in bending [MPa]	Deflection MAX [mm] Z	SLS	Deflection MAX [mm] Z	Admissible Deflection L/500 = 6 [mm]
Square PLA/rPMMA 30x30 [cm ²]	3,21	68,26	-2		-1	-6
TimberC40 30x30 [cm ²]	3,04	15,38461538	-1		0	-6
4BamboosMiddle 16x30 [cm ²]	6,43	67,25	-4		-1	-6
TimberC40 16x30 [cm ²]	6,27	15,38461538	-1		0	-6

Table 9 Section verification of SLS and ULS criteria for three load combinations

We observed from the results that the 4 sections meet both the ULS and SLS criteria for the 3 different combination loads. Moreover, maximum stresses appear in central beams, on top of central column, at the cross of the 4 central beams. The maximum deflection also always appears in one of the central beams.

Analyzing the different load combinations, we observe for the **SLS state**:

- First, for the square PLA/rPMMA ($0,3 \times 0,3$ [cm²]), we see that the deflection is way lower than the 6 mm admissible, and almost in line with the timber. Hence it shows a very good behaviour of our material for a roof beam carport.
- Second, for the rectangle 4 middle bamboos ($0,16 \times 0,3$ [cm²]), the deflection is greater than the timber, but still admissible. So, the smaller section of bamboos meets the criterion as well.
- Overall, we have lower deflection than the one calculated with SeismoStruct in previous chapter, because the repartition of the loads is slightly different: here the loads are distributed on the 4 beams.

Analyzing the different load combinations for the **ULS state**, we observe:

- That the maximum stresses appearing in central beams are far from their admissible values: hence the sections could support larger loads. However, because rigidity of the materials are still low (3,7 for PLA/rPMMA and 4,2 for bamboos interlocked [GPa]), the SLS criterion would probably not be verified, especially for the smaller rectangular bamboos section.

Moreover, the total weight of the structure with square PLA/rPMMA is 3402 kg, whereas with the timber square section, it is only 2143 kg. In that way, the structure made of the new recycled plastic material PLA/rPMMA is heavier and contribute to a better stability of the structure. However, compared to the great density of steel, those structures are still very light and a complete dynamic analysis has to be done to determine if bracing are needed or not.

Looking at the good properties of square PLA/rPMMA section, we have evaluated that material with a smaller section $0,16 \times 0,3$ [cm²], and observed that this section also meets both criteria, with deflection values at SLS very close to the 4 bamboos section. Indeed, the flexural strength and flexural modulus of square PLA/rPMMA and 4 bamboos interlocked are very similar (cfr Table 8).

Thus, for a roof beam of carport, **bamboos are not especially necessary**, and the developed new recycled composition is a good substitute to timber under flexural loads.

Moreover, bamboos present different thermal expansion than the polymers so further investigation on that parameter should be done.

In addition to present a low carbon footprint, the PLA/rPMMA is weatherproof, isotropic, does not need a lot of maintenance, has a greater lifetime, non-sensitive to corrosion or insects and also store CO₂ like wood, by its utilization of PLA bioplastic made of biomass. PLA/rPMMA presents thus many advantages of wood and even more and obliterates the disadvantages.

In this way, PLA/rPMMA seems to appear as a perfect substitute to outdoor wood structures. The PLA/rPMMA used to interlock bamboos together should however not be thrown as it presents very good and similar properties as well.

PART 6 CONCLUSION

From the beginning of plastic production back in the 50ies, only 10% has been recycled, and the rest has terminated mainly in landfills and oceans creating deep environmental issues, both harmful for animals and humans. There is thus a huge need to create new products from recycled plastics and this was the overall objective of this master thesis.

A green sustainable material made of recycled plastics and bioplastics has thus been developed and analyzed to determine applications in structural engineering.

Plastics and polymers encounter many challenges for their use in structural applications. The new blend needed to be rigid, stable through a certain range of temperatures, composed of miscible and compatible polymers. Moreover, the material was thought with the strong willingness to have it recyclable; hence, no fibers nor additives were permitted in the blend although such components would have even further increased its properties.

To achieve all these goals, we came up with a new innovative material made of a blend of high mechanical properties polymers: recycled PMMA (PLEXIGLAS) and bioplastic PLA were blended through extrusion, with a 50/50 weight distribution. The composition proved to be a miscible blend presenting only one amorphous phase and a single glass transition temperature, and it enhanced the components' properties. Earlier researchers had also demonstrated the possibility for such a blend to be recycled through hydrolysis.

Through flexural testing of the material, the flexural modulus showed to be 3,243 [GPa] and its strength reached 112,6 [MPa], which was encouraging values for polymers.

To further enhance its mechanical properties, a third green element was interlocked within the new polymer matrix. Several dispositions of entire bamboo stems in the PLA/rPMMA have been studied. It has been demonstrated that adherence between bamboos and PLA/rPMMA matrix certainly exist.

Through numerical modelizations to evaluate the load-bearing capacities, two sections have been retained for the creation of a carport: a square section of $0,3 \times 0,3$ [m²] of PLA/rPMMA, and a rectangular section of $0,16 \times 0,3$ [m²] of PLA/rPMMA with 4 guadua bamboos interlocked at the center.

Outcomes of the modelization showed that the created composition is a very good substitute to timber for roof beams of a carport under flexural loads. Moreover, interlocked bamboos slightly increased the rigidity of the material, but the gain is not substantial.

Some further researches may be explored in the frame of other master thesis, such as simulating several life cycles of the blend by extruding it more than once before injection,

studying the thermal properties, and producing specific larger scale injection molds able to interlock the bamboos to further analyze the mechanical properties.

Thanks to all the above, we can consider that this sustainable new material meets both the structural engineering constraints and the circular economy objectives: the loop is complete.

TABLE OF FIGURES

Figure 1 Structure of a semi-crystalline polymer (A. Simar, 2017).....	6
Figure 2 Young's Modulus vs Density Plot and performances (Simar, 2019) (Ashby, 2011)...	7
Figure 3 Evolution of rigidity and specific volume of semi-crystalline polymers (left) and amorphous polymers (right) with temperature (Courard, s.d.).....	9
Figure 4 Young Modulus vs Temperature for relevant thermoplastics.....	10
Figure 5 Extruder (A. Simar, 2017)	11
Figure 6 Structure of methyl methacrylate (MMA) (PMMA, 2020)	12
Figure 7 Chemical structure of polymethyl methacrylate (PMMA) (GARZON, 2018).....	12
Figure 8 Market of bio-based and biodegradable plastics (Bioplastics, s.d.).....	15
Figure 9 LCA of different plastics comparing data from America and Europe (PlasticsEurope, APC and NaturWorks Data) (NatureWorks, 2016).....	16
Figure 10 Carbon footprint of Ingeo compare to over common plastics (NatureWorks, s.d.)	16
Figure 11 Synthesis of the lactide (Futero, s.d.)	18
Figure 12 Both ways to create PLA (Futero, s.d.)	18
Figure 13 Chemical structure of lactic acid and lactide, and PLA (GARZON, 2018)	18
Figure 14 Global plastic production from 1950 to 2018 (in millions of matrix tons) (Statista, 2019).....	20
Figure 15 Global production, use and fate of polymer resins, synthetic fibers and additives (1950 to 2015; in millions of metric tons) (Roland Geyer, 2017).....	21
Figure 16 Global Plastic waste by disposal, 1980 to 2015, (Richie & Roser, 2018)	21
Figure 17 Plastic recycling codes (AcmePlastics, 2018)	23
Figure 18 Lifecycle of polymers (Kim Ragaert, 2017)	25
Figure 19 Comparative of various methods of plastic recycling (Régis Kovacs Scalice, 2009)	25
Figure 20 Change of Molecular weight and Elongation at break for PET sample through the number of recycling processes (Kim Ragaert, 2017)	27
Figure 21 First vehicular bridge at Fort Leonard Wood, Missouri (1998) (J. S. KIM, s.d.)....	29

Figure 22 Vehicular bridge at Wharton State Forest, New Jersey (2002) (J. S. KIM, s.d.).....	29
Figure 23 First bridges made of almost 100% recycled plastics at Fort Bragg, North California (2009) (J. S. KIM, s.d.)	29
Figure 24 First railroad bridges made of almost 100% recycled plastics at Fort Eustis, Virginia (2010) (J. S. KIM, s.d.)	30
Figure 25 First highway thermoplastic bridge made of almost 100% of recycled plastics at York, Maine (2011) (J. S. KIM, s.d.)	30
Figure 26 Properties of the thermoplastic obtained by ASTM tests (J. S. KIM, s.d.)	31
Figure 27 Plastic Bridges in Rotterdam (Material Distric, 2016)	31
Figure 28 KLP recycled plastics footbridge near Rickmansworth in Hertfordshire (England) (ECS Engineering Services, 2014).....	32
Figure 29 The Easter Dawyck Bridge (Iberdrola, s.d.)	32
Figure 30 PlasticRoad (Material Distric, 2016)	32
Figure 31 Polli-Bricks used to construct the Pavilion EcoARK in Taipei, Taiwan (2010) (MiniWiz, s.d.).	33
Figure 32 Polli-Ber Bricks (MiniWiz, s.d.).....	33
Figure 33 Structural Insulated Panel (SIP) (Composites, s.d.).....	33
Figure 34 ByBlock by ByFusion (Leclercq, 2016)	34
Figure 35 ByBlock Dimensions (ByFusion, s.d.)	34
Figure 36 Prototype One UNIBRICK and UNIBRICK SAMPLES (Designs, s.d.).....	35
Figure 37 Classrooms in Côte d'Ivoire, Plastic blocks made by Conceptos Plasticos (Conceptos Plásticos, s.d.) (UNICEF, 2019)	35
Figure 38 Brick made by Eco Inclusión (Fundación, s.d.).....	36
Figure 39 Synergia pavilion made entirely of recycled plastics in Columbus (USA) (Grozdanic, 2017).....	36
Figure 40 Pneuhaus Bubble Dome (Grozdanic, 2015).....	36
Figure 41 Head in the Clouds, New York, 2013 (Brooks, 2014).....	37
Figure 42 Two opposite extremities sections of the specimen.....	41

Figure 43 Testing device (left) and behavior of the specimens close to failure (right)	41
Figure 44 Force vs Deformation - Results of the test	42
Figure 45 Stress-Strain curves of ABS (rigid) subjected to bending, compression and tension (Campo, 2008).....	43
Figure 46 Influence of dwell time on evolution of tan for injection molded c-PLA (semi-crystalline)/hv-PMMA (high viscosity amorphous) (50/50) blends (GARZON, 2018)	48
Figure 47 Injected PLA/rPMMA bars tested	53
Figure 48 Stress-Strain curve of injected PLA/rPMMA (INNOLOGIC, 2020)	53
Figure 49 Final configuration of the formworks	54
Figure 50 Creation of formworks.....	54
Figure 51 Filled formworks and created elements	55
Figure 52 Schematic test device.....	56
Figure 53 Traction test device at LEMSC.....	56
Figure 54 Force vs Displacement of the 6 bamboos	57
Figure 55 Stress vs Strain of the 6 bamboos	58
Figure 56 Schematic test device.....	59
Figure 57 Pull-Off test device at LEMSC	59
Figure 58 Force vs Displacement Pull-off 1 without loss of adherence	60
Figure 59 Force vs Displacement Pull-Off 2 with loss of adherence.....	61
Figure 60 Three points flexural test device according to ISO 178.....	62
Figure 61 Force vs Displacement PLA/rPMMA without bamboo	62
Figure 62 Flexural test on matrix with 1 bamboo embedded.....	64
Figure 63 Stress vs Strain plot of the flexural stress on bars (SeismoStruct)	67
Figure 64 Free body diagram of distributed load (Moments)	70
Figure 65 Disposition of the bamboos in section and discretization patterns for SeismoStruct	72
Figure 66 Dimensions of the final sections (dimensions in millimeters)	78

Figure 67 General structure of the carport (dimensions in meters).....	79
Figure 68 COMB 1 All : ULS (left) and SLS (right)	82
Figure 69 COMB 2 SnowFront+WindBack : ULS (left) and SLS (right)	82
Figure 70 COMB 3 SnowTop+WindBack&Right : ULS (left) and SLS (right)	82

TABLE OF TABLES

Table 1 Accuracy of NIR sorting technology (Biolplastics, 2015).....	26
Table 2 Recap mechanical properties of the bamboo tests	57
Table 3 Flexural tests results	64
Table 4 Flexural strength and modulus of PLA/rPMMA	66
Table 5 Principal characteristics from numerical flexural tests	68
Table 6 Partial coefficients from EN 1991-1 and according to ANB Belgium annexes (CSTC, 2014).....	71
Table 7 k_{mod} coefficients for bamboo (Cuchet, 2019).....	74
Table 8 Flexural strength and modulus of both model sections.....	80
Table 9 Section verification of SLS and ULS criteria for three load combinations	83

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APPENDICES

APPENDIX A Table of Properties

Materials used in tests	Density (masse volumique) ρ [g/cm ³]	Glass temperature T_g [°C]	Melting temperature (FUSION) T_m [°C]	Elastic Modulus E [GPa] Young's Modulus = tensile modulus = E_t Compression Modulus = E_c Flexural/Bending Modulus = E_b // = longitudinal ⊥ = tangential	Yield Strength f_y [MPa]	Tensile Strength f_t [MPa] // = longitudinal ⊥ = tangential	Compressive Strength f_c [MPa] // = longitudinal ⊥ = tangential	Flexural/Bending strength f_b [MPa] // = longitudinal ⊥ = tangential	Thermal expansion α_t [1/°C x 10 ⁻⁶]	Impact strength [kJ/m ²]	Elongation at failure [%]	Process of fabrication /Applications (5) (3)	Characteristics (5)	Recyclable
Thermoplastic <i>Free polymer chain</i>														
PMMA (plexiglas/acrylic) = Polymethyl methacrylate	1,19 (13)	85-165 (3)	/ (6)	E_t = 2,24-3,8 (3)	53,8-72,4 (3)	80-100 (5)	140 (5)		82 (5)	20 (CHARPY) (9)	3 (5)	Extrusion: Tablecloth, advertising sign, lighting, road signs, spectacle glass/lens, sink, bathtub, guardrail, safety glass, interior doors, skylight for roofing, aircraft windows, reflectors, compact discs, automobile taillights, electrical insulation Biocompatibility: prostheses, ocular lenses	- High transparency - Can be elongate between 80 and 100% → better mechanical strength - Ductile - Easy machining - Good chemical inertia (except HCl) - Waterproofness and outdoor exposure resistance	YES
	1,18 (5)	120 (19)		E_t = 3,3 (9)		48,3-79,6 (3)			72-162 (3)	1,1 (IZOD) (4)	5 (9)			
	1,16 - 1,22 (3)	116 (9)				77 (9)			90 (20)					
		100 (6)												
Bioplastic														
PLA Polylactic Acid	1,24 (17)	60 (19)	210 (17)	E = 3,45 (17)	60 (TENSILE YIELD) (17)	53,1 (17)	93,8 (12)	106 (23)		Notched IZOD impact: 16 [J/m] (11)	6 (17)	Extrusion: Floors and walls (impact protections) ,carpets, textile fibers in sunscreens, landscape drains, agricultural films, reusable bags, trash and vacuum bags, single-used service ware, electronic cases, food packaging (yogurt pot, infusion bags, coffe capsule, ...), cartons, use in 3D printing (under the form of filament) Biocompatibility: sutures, orthopedic pins	- Bio-based plastic - Biodegradable (under certain strict conditions: compost under 60°C for a long time) - Brittle	YES
	1,252 (23)	55 (23)	180 (19)	E_t = 3,5 (17)		59 (23)		90 (9)			7 (23)			
		60 (9)	165 (23)	E_t = 1,28 (23)	70 (23)	70 (9)		94,7 (12)		2,3 (IZOD) (4)	3 (traction) (9)			
				E_t = 3 (9) E_b = 3,5 (9)		65,7 (12)				2,7 (IZOD) (9)				
Bamboo														YES
Natural	0,802 (22)	77-102 (3)		E_t = 15-20 (3)	35-44 (3)	// 200,5 (22)		// 230,09 (22)	2,6 – 10 (3)	// 63,54 (22)	// 10,2 (22)	Shelters, decoration, event structures, gardens, ...	- Maximum strength along the fibers and minimum strength across the fibers - Good composite: 65% fiber volume fraction (22) - Nodes +/- each 20 cm - Brittle	
	0,6-0,8 (3)					⊥ 8,6 (22) 36-45 (3)		⊥ 9,04 (22)		⊥ 3,02 (22)	⊥ 0,10 [mm] (22)			
Moso (Phyllostachys pubescens)	0,553 (inner layer, at 1,3 [m]) - 1,006 (outer layer, at 4 [m]) (11) 0,58 (inner layer, bottom) - 0,84 (outer layer, top) (16)			$E_{t, //}$ = 9 (inner layer, at 1,3 [m]) - 27,4 (outer layer, at 4 [m]) (11) E = 13,162 (bottom, $\rho=0,75$ [g/cm ³]) (16) $E_{c, //}$ =4,896 (bottom) - 5,185 (top) (16) $E_{c, \perp}$ = 0,553 (bottom) - 0,552 (top) (16) E_c = 9,4 (21) E_t = 8,9 – 27,3 (21) E_b = 13,2 (21)		// 115,3 (at 1,3 [m]) - 309,3 (at 4 [m]) (11) 115 - 309 (21)	// 93,6 (bottom) - 85,8 (top) (16) ⊥ 34,1 (bottom) - 35, 1 (top) (16) 117 (21)	186,2 (bottom, for $\rho=0,75$ [g/cm ³]) (16) 51 (21)					- Comes from Asia - Outer layer the strongest → all mechanical properties assign to that part - Highest section the strongest (except tensile strength (no much difference with height)) - Nodes +/- each 20 cm - Small diameters exist (≥ 2 [cm]) - 5 year-old bamboo, 12% moisture content, bending properties increase a lot with the age of the bamboo, highest Young's Modulus in top portions → Bamboo has directional properties (16) - (Yu & Chung) <5% moisture content (21)	
Guadua angustifolia	0,65 (7) 0,7646 (14)			$E_{t, mean}$ = 13 (7) E_c = 17,9 (14) E = 17,2 (14) E_t = 8-16,25 (2) E_b = 17,9 (21) E_c = 18,4 (21) E_t = 17,9 – 24,1 (21)		40 (7) 162,7 (21)	20 (7) 36,8 (14) 56 (21)	35 (7) 104,1 (14) 74 - 100 (21)					- From Colombia - No small diameters - Comparable to wood C35 (in terms of f_m and E_t) (7) - Values for top of the culm & mean on age 2 to 5 - Maturity at 3 and 4 years old (mechanical properties) - E not really affected by height or age - Top portion of culm better properties (14) - (Eicher) 15% moisture (21)	
Kao Jue (Bambusa pervariabilis) (15)				$E_{c, d}$ = 10,3 $E_{b, d}$ = 22			103	109				Access scaffoldings (South East Asia)	- Moisture content <5% (dry condition) - Excellent mechanical properties in compression and bending	
Mao Jue (Phyllostachya Pubescens) (15)				$E_{c, d}$ = 9,4 $E_{b, d}$ = 13,2			134	85				Access scaffoldings (South East Asia)	- Moisture content <5% (dry condition) - Excellent mechanical properties in compression and bending	

Other Plastics	Density (masse volumique) ρ [g/cm³]	Glass temperature T _g [°C]	Melting temperature (FUSION) T _m [°C]	Elastic Modulus E [GPa] Young's Modulus = tensile modulus = E _t Compression Modulus = E _c Flexural/Bending Modulus = E _b // = longitudinal ⊥ = tangential	Yield Strength f _y [MPa]	Tensile Strength f _t [MPa] // = longitudinal ⊥ = tangential	Compressive Strength f _c [MPa] // = longitudinal ⊥ = tangential	Flexural/Bending strength f _b [MPa] // = longitudinal ⊥ = tangential	Thermal expansion α _t [°C x 10 ⁻⁶]	Impact strength [kJ/m²]	Elongation at failure [%]	Process of fabrication /Applications (5) (3)	Characteristics (5)	Recyclable
Thermoplastics													Free polymer chain	
PET (or PETE) = Polyethylene terephthalate	1,35 (13) 1,29 – 1,4 (3)	60 – 80 (3)		2,76 – 4,14 (3)	56,5 – 62,3 (3)	48,3 – 72,4 (3)			114 – 120 (3)			Blow-molded: bottles, film, audio/video tape, sails	Highly flexible (semi-rigid or rigid depending on the process) Semi-crystalline structure Good gas and moisture barrier	YES
PVC = Polyvinyl chloride	1,3 - 1,58 (13) 1,3 – 1,4 (5) 1,3 – 1,58 (3)	105 (3)	75 (3)	2,14 – 4,14 (3)	35,4 – 52,1 (3)	60 (5) 40,7 – 65,1 (3)		120 (5)	100 – 150 (3)		300 (3)	Special type of leather (skai, ...), packaging (oil bottle), bins, car bumper, tarpaulin, soft carpet, ... CALENDERING: rigid leaves and film, protective canvas, movables partition, plastic tiles for flooring, waterproof sheets for roof, terrace, tunnels, swimming pool coating, inflatable structures and furniture EXTRUSION: continuous profile (Rigid PVC: conveyance and drainage of water, gutters, drainage tube, gas pipeline, window frame & Soft PVC: garden hose, door bottoms, joints, waterproof coasting for terrace, coating for electrical conductors) EXTRUSION BLOW MOULDING: Mostly rigid PVC for bottles (water and wine) INJECTION: pieces of plumbing (connection, pipe bend, ...) EXPANSION: foams for thermal and sound insulation THERMOFORMING: profiles or pieces with a rotational symmetry from the initial plates	High hardness Low price Low heat resistance	FEW
PS = Polystyrene	1,05 (13) (5) 1,04 – 1,05 (3)	74 – 110 (3)		2,28 – 3,34 (3)	28,7 – 56,2 (3)	45 – 50 (5) 35,9 – 56,5 (3)	80 – 100 (5)		90 – 153 (3) 90 – 150 (13)		2 – 3 (5)	One-time use tableware, toys, packaging, cutlery, audio cassette/CD cases	Transparent resin, Soften itself at 100°C Able to withstand temperatures up to 260°C, Dimensional stability is good, Chemical resistance is good, Low fire resistance, Low impact resistance, Non-toxicity, no smell, no taste, excellent optical clarity	YES
ABS = Acrylonitrile butadiene styrene	1,01 – 1,21 (3) 1,05 (5)	88 – 128 (3)		1,1 – 2,9 (3)	18,5 – 51 (3)	27,6 – 55,2 (3) 40 – 65 (5)			84,6 – 234 (3)		10 – 20 (5)	3D printing, electrical appliances	Copolymer of styrene Mixture of SAN and butadiene rubber High impact resistance (40 – 300 [N.cm/cm]) Good chemical resistance except with chlorinated solvents Not transparent Cracks will meet rubber during propagation, rubber blocks that can absorb some energy because of their capacity of elastic deformation	YES
PTFE (Teflon) = Polytetrafluoroethylene	2,17 (13) 2,14 (5) 2,14 – 2,2 (3)	123 (3)	380 (5) 107 (3)	0,35 (5) 0,4 – 0,552 (3)	15 – 25 (3)	35 (5) 20 – 30 (3)			95 (5) 126 – 216 (3)		400 (5)	Sliding supports of bridges (friction coefficient on itself ≈ 0), nonstick coatings, bearings, skis, electrical insulation, tape, pan	Good resistance to heat	
PA = Polyamide (nylon)	1,04 – 1,14 (5) 1,12 – 1,14 (3)	44 – 56 (3)	185 – 250 (5)	1,2 – 3 (5) 2,62 – 3,2 (3)	50 – 94,8 (3)	90 – 165 (3)	At 20°C : 60 -100 (5)		144 – 150 (3) 40 – 100 (5)			INJECTION: hammer head, boat propeller EXTRUSION: coating for electrical wires, elongate, elongated for fibers and textile yarns (greatest application) Textile (underwear), tablecloth, melted on metallic pieces as painting, geotextile, gears, bearings, plumbing, packaging, bottles, fabrics, textiles, ropes	Resin of polycondensation but with a linear chain ➔ characteristics as thermoplastics. Very good mechanical properties (collision, fatigue, abrasion, friction) Very good electrical properties. Very good chemical resistance. High fusion point. Crystalline and amorphous areas due to the intermolecular forces linked to the parallel orientation of the molecules Stretching properties ➔ yarns/threads Adjuvants: colorants/pigments, lubricants, UV protection, self-extinguishing, plasticizers to lower the fusion point	
PC = Polycarbonate	1,20 (13) 1,14 – 1,21 (3)	142 - 205 (3)		2 – 2,44 (3)	59 – 70 (3)	60 – 72,4 (3)			120 – 137 (3)			Safety goggles, shields, helmets, light fittings, medical components	High impact strength, high dimensional stability	YES
PE = Polyethylene	0,939 - 0,96 (3)	-25 - -15 (3)		0,621 – 0,896 (3)	17,9 – 29 (3)	20,7 – 44,8 (3)			126 – 198 (3)			EXTRUSION BLOW MOLDING: film (protect walls from upwellings), concrete joint (roads), protection of roof or site, jerrycans EXTRUSION: cladding for electrical insulation of wires, tubes, profiles and plates Bucket, container, bins, packaging (bottle of milk), grocery bags, squeeze tubes, toys, artificial joints	Same use as PP and PVC! HDPE to withstand cold (< 0°C), PVC for medium temperature (20 – 60 °C) and PP to withstand heat (>120°C).	YES

Other Plastics II	Density (masse volumique) ρ [g/cm³]	Glass temperature T_g [°C]	Melting temperature (FUSION) T_m [°C]	Elastic Modulus E [GPa] Young's Modulus = tensile modulus = E_t Compression Modulus = E_c Flexural/Bending Modulus = E_b // = longitudinal ⊥ = tangential	Yield Strength f_y [MPa]	Tensile Strength f_t [MPa] // = longitudinal ⊥ = tangential	Compressive Strength f_c [MPa] // = longitudinal ⊥ = tangential	Flexural/Bending strength f_b [MPa] // = longitudinal ⊥ = tangential	Thermal expansion α_t [1/°C x 10 ⁻⁶]	Impact strength [kJ/m²]	Elongation at failure [%]	Process of fabrication /Applications (5) (3)	Characteristics (5)	Recyclable
Thermoplastic II													Free polymer chain	
HDPE = High-density polyethylene	0,959 (13) 0,93 – 0,96 (5)		125 – 135 (5)	0,8 – 1,2 (5)		25 – 30 (5)			106 – 198 (13)		1000 – 1200 (5)	INJECTION: garden furniture, taps EXTRUSION: electrical pipes or irrigation pipes, able to convey corrosive liquid, gas and solvent	High-density polyethylene → processing under low pressure with catalyzers. The catalyzers produce products more consistent/regular, hence a higher density. More rigid than LDPE, Fusion point at 130°C, High crystallinity (90%)	YES
LDPE = Low-density polyethylene	0,925 (13) 0,92 (5)		108 – 120 (5)	0,2 (5)		< 15 (5)					800 (5)	EXTRUSION: lamination of LDPE on Kraft paper to waterproof it and use it as packaging	Low-density polyethylene → processing under high pressure (1500 atm.) at 200°C in tank Transparent and opaque solid No smell Smooth for small thickness Great chemical inertia, stable at heat Cold, the LDPE is hard and brittle It oxidizes under UV rays It burns slowly and progressively with no emission of toxic gas	YES
PP = Polypropylene	0,905 (13) 0,9 (5) 0,89 – 0,91 (3)	-25 - -15 (3)	170 (5)	1,1 – 1,3 (5) 0,896 – 1,55 (3)		30 – 35 (5)			122 – 180 (3) 145 – 180 (13)		1000 (5)	INJECTION: same applications as HDPE, knowing that heat resistance is greater for PP but cold resistance is greater for HDPE. EXTRUSION: sheets, films, plates, profiles and tubes (as for HDPE) As for HDPE → processing under low pressure with catalyzers	More resistant against heat compare to HDPE → Softening point : 120°C (against 75°C) → Fusion at 170 °C (against 135°C) More rigid Greater failure load Low UV stability Brittle when cold It burns (as PE)	YES
Thermoset													Bridged polymer chain	NO
EP = Epoxy resin EP	1,2 – 2 (5) 1,11 – 1,4 (3) 1,3 (8)	n/a (3)	n/a (3)	4 (5) 2,35 – 3,075 (3) 3 (8)	36 – 71,7 (3)	80 (5) 45 – 89,6 (3) 100 (8)	120 (5)		58 – 117 (3)			Adhesives, resin to cast, coating, laminate reinforced with glass fibres (usually in Polyester, except with high temperatures), fiber composites, electronic encapsulation	Pre-polymerization (creation of linear chains) + polymerization (bridging between chains to create a 3D network) Good adhesiveness to many materials like concrete, steel, glass Characteristic very dependent on type!	
PEST = Unsaturated polyester PEST	1,1 – 1,2 (5) 1,04 – 1,4 (3)	n/a (3)	n/a (3)	3,5 – 4,5 (5) 2,07 – 4,41 (3)	33 – 40 (3)	50 – 70 (5) 41,4 – 89,6 (3)	150 (5)		99 – 180 (3) 90 – 100 (5)			CONTACT MOULDING: GFRP COMPOUND MOULDING: electrical boxes, garden seats, window unit POLYESTER VARNISH: furniture Clothing, tablecloth, car body element, reconstructed marble with polyester, laminated roof and cladding, tanks, GFRP (80%) , corrugated plate, roof skylight, window frame, suspended ceiling, concrete casing, polyester concrete, exterior benches, furniture, boats, sporting goods	Polycondensation Unsaturated and saturated (double bounds or not) Unsaturated : 3D network by bridging with other products (like the solvent styrene) → thermal irreversibility → thermosetting resin or bridged polymer chain Saturated : long linear chains due to no double bounds → thermoplastic or free polymer chain Polyester resins are largely used as matrix for laminate glass fibers used to reinforce the resin as GFRP (Glass Fiber Reinforced Plastics) → GFRP represents 80% of the utilization of the polyester!	
PU = Polyurethane												Foams: thermal and phonic insulation, within prefabricated partitions (rigid foam) Glues: bound the materials (wood, glass, rubber) together (heat the glue up to 100°C) → usually epoxy glue will rather be used Varnish and painting: electrical insulator, metals coating Coating for buildings: concrete coating, protection of screed, industrial floor, treatment of the roads, reparation of old concrete, interior protection of concrete pipes		

Other materials	Density (masse volumique) ρ [g/cm ³]	Glass temperature T_g [°C]	Melting temperature (FUSION) T_m [°C]	Elastic Modulus E [GPa] Young's Modulus = tensile modulus = E_t Compression Modulus = E_c Flexural/Bending Modulus = E_b // = longitudinal ⊥ = tangential	Yield Strength f_y [MPa]	Tensile Strength f_t [MPa] // = longitudinal ⊥ = tangential	Compressive Strength f_c [MPa] // = longitudinal ⊥ = tangential	Flexural/Bending strength f_b [MPa] // = longitudinal ⊥ = tangential	Thermal expansion α_t [/°C x 10 ⁻⁶]	Impact strength [kJ/m ²]	Elongation at failure [%]	Process of fabrication , Applications ⁽⁵⁾ (3)	Characteristics ⁽⁵⁾	Recyclable
Steel	7,85 ⁽¹³⁾			207 ⁽¹³⁾	180 ⁽¹³⁾ 235-450 (nominal thickness < 16 mm) ⁽¹⁾	500 ⁽⁵⁾	500 ⁽¹³⁾		10 ⁽¹³⁾		25 (in 50 mm) ⁽¹³⁾	General civil engineering construction Primary load-bearing structure Lamination	High strength Ductile Low weight compared to reinforced concrete structures	YES
Steel S275					275 (nominal thickness < 16 mm) ⁽¹⁾	410-560 (nominal thickness 3-100 mm) ⁽¹⁾					23 ⁽¹⁾			
Concrete	2,4 ⁽¹³⁾ 2,2 – 2,6 ⁽⁴⁾	1227 ⁽³⁾	927 ⁽³⁾	14-40 ⁽¹³⁾ 25 – 38 ⁽³⁾		2 – 4 ⁽⁵⁾ 2 – 6 ⁽³⁾	32 – 60 ⁽³⁾		6 – 13 ⁽³⁾ 10 – 13,6 ⁽¹³⁾			General civil engineering construction Mix of cement and aggregates with water (exothermic reaction)	Weak in traction, stronger in compression Usually reinforced with steel rebars Brittle	FEW
Timber				6-15 ⁽¹³⁾		30 – 60 ⁽⁵⁾						General civil engineering construction Carport, playground, benches, outdoor furniture, shelters, ... Processed and treated	Anisotropic material Greater performance parallel to fibers Brittle	YES
Resinous // ⊥	0,32 – 0,4 ⁽¹⁸⁾			6 – 9,4 ⁽¹⁸⁾		10 – 26 ⁽¹⁸⁾ 0,4 ⁽¹⁸⁾	18 – 27 ⁽¹⁸⁾ 2,2 – 2,8 ⁽¹⁸⁾	18 – 40 ⁽¹⁸⁾						
Deciduous // ⊥	0,53 – 0,8 ⁽¹⁸⁾			9,2 – 16,8 ⁽¹⁸⁾		18 – 42 ⁽¹⁸⁾ 0,6 ⁽¹⁸⁾	24 – 36 ⁽¹⁸⁾ 5,3 – 12 ⁽¹⁸⁾	30 – 70 ⁽¹⁸⁾						
Glue-laminated // ⊥	0,34 – 0,44 ⁽¹⁸⁾			7 – 11,8 ⁽¹⁸⁾		16 – 25,6 ⁽¹⁸⁾ 0,5 ⁽¹⁸⁾	20 – 32 ⁽¹⁸⁾ 2,5 ⁽¹⁸⁾	20 – 32 ⁽¹⁸⁾						
Sodalime Glass	2,5 ⁽¹³⁾ 2,44 – 2,49 ⁽³⁾	442 – 592 ⁽³⁾		62 - 70 ⁽¹³⁾ 68 – 72 ⁽³⁾		31 – 35 ⁽³⁾	360 – 420 ⁽³⁾		9,1 – 9,5 ⁽³⁾ 9 ⁽¹³⁾			Windows, bottles, tubing, light bulbs, pottery glazes, structural glass façades, curtain walls	Brittle Strong Transparency Durability Resistance to heat and corrosion	YES
Aluminum	2,5 – 2,9 ⁽³⁾ 2,7 ⁽⁸⁾	677 ⁽³⁾	475 ⁽³⁾	69 - 75 ⁽¹³⁾ 68 – 82 ⁽³⁾ 70 ⁽⁸⁾	35 ⁽¹³⁾ 30 – 500 ⁽³⁾	58 – 550 ⁽³⁾ 300 ⁽⁸⁾			21 – 24 ⁽³⁾ 23,6 ⁽¹³⁾		40 (in 50 mm) ⁽¹³⁾	Plane frame, car body, packaging, aluminium profile, angle iron, ... Lamination process	Resistant Long life Low maintenance Heat conductor	YES
Brick (baked clay)	1,8 ⁽¹³⁾ 1,9 – 2,1 ⁽³⁾	1227 ⁽³⁾	927 ⁽³⁾	10-17 ⁽¹³⁾ 15 – 25 ⁽³⁾		3 ⁽¹³⁾ 7 – 14 ⁽³⁾	25 ⁽¹³⁾ 50 – 140 ⁽³⁾		5 ⁽¹³⁾ 5 – 8 ⁽³⁾			Old buildings Load-bearing and non-load-bearing masonry Weight walls	Brittle material Stronger in compression than traction	YES

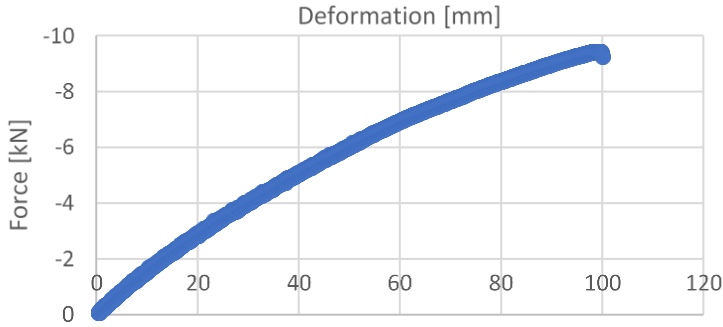
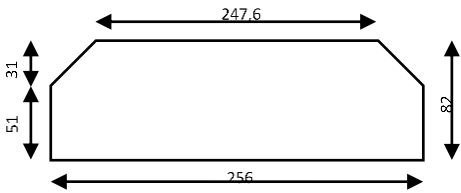
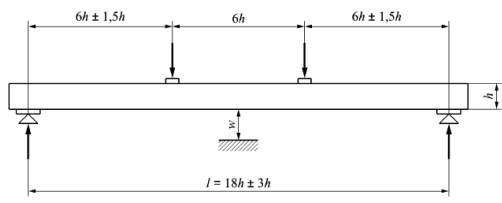
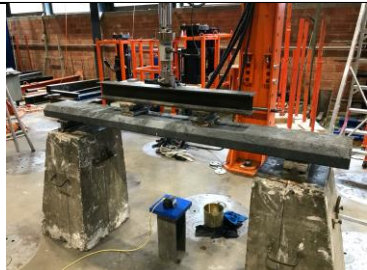
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APPENDIX B

Four points flexural test on Eco-oh! Specimens

Standard	NBN EN 408
A₀ Cross section of matrix	19690 [mm ²]
L Length	190,4 [cm]
F_{MAX} Maximum force	9441,75 [N]
d Deflection at failure	99,56 [mm] (corresponding to F _{MAX})
$\sigma = F/A_0$ Maximum stress	0,48 [MPa]
f_m Bending strength	12,34 [MPa] (rectangular smallest cross section assumed)
E_b Flexural modulus	1,009 [GPa]
Graphs	Force vs Deformation 
Type of rupture	Brittle failure
Pictures	
Test Device	 
Observations	No cracks observed until failure
Test speed	0,246 [mm/s] (0,003h)



GENERAL

DE ECO-OH! PRODUCTS ARE A RESPONSIBLE CHOICE CHARACTERISED BY THE 4 PILLARS WHICH SUPPORT THEM.

Economical - They require little or no maintenance and are resistant to water and moisture, giving them a long life.

Ecological - All the materials are made entirely from recycled plastics without making use of primary raw materials.

Environmentally friendly - Use of BAT (Best Available Technology) results both in a sustainable production process and sustainable products. All ECO-oh! PRODUCTS can be recycled in our installations and converted into new products: the circle is round, it is the perfect cycle.

Quality - ECO-oh! PRODUCTS guarantee optimal quality. Quality control is guaranteed by the huge experience of our employees. Finished products that are showing signs of deterioration are removed and ground back up to be used as raw material.

ADDITIONAL ADVANTAGES OF OUR ECO-OH! PRODUCTS ARE:

- rot-proof, resistant to acids and salts
- resistant to microbial action
- durable
- very weather resistant
- little or no maintenance
- very user friendly
- 100% recyclable



100% recycled
& recyclable



Rot-resistant



Weather-resistant



Easily processed



Maintenance-free



Long-lasting



Harmless

MATERIAL CHARACTERISTICS

Household plastic waste that meets the conditions of adoption as described previously. The vast majority of this waste consists of one-time household plastic packaging. After treatment in the recycling line (reduction in size, washing, separating, drying, etc.), the different plastics are processed into finished end products. Depending on shape, size and use of the end products, the raw material composition of the end products can differ. Roughly speaking, the end products consist of 60-95% polyolefins (PE-PP), supplemented by the required types of plastic, PVC, PS and PET.

1. STRENGTH PROPERTIES

End products with dimensions of 120 mm x 120 mm x 700 mm were tested using a three-point flexural strength test.

120 mm blocks were tested for compressive strength.

The results were as follows:

- flexural strength: 14,5 N/mm²
- compressive strength: 7 N/mm²
- E-modulus: 600 N/mm²

THESE VALUES ARE WELL BELOW THE VALUES SEEN FOR WOOD.

Wood achieves at least double the flexural strength and six times the elasticity modulus. The deflection will be significantly larger when affected by solar radiation. In this case, distortion already occurs without a load being applied. This means that, when using the material as a post, in the event it is placed under a bending load, account must always be taken of the flexural bending behaviour of the applied loads. In one 3-three-point flexural load according to DIN 53452, the temperature dependence was also tested. Measurements showed that, under the influence of solar radiation, the material never reached a temperature greater than 30°C due to the low thermal conductivity. The stability calculations used the following limit value as an assumption:

- flexural tension $\sigma_b = 10 \text{ N/mm}^2$ - bending strain $\epsilon_b = 5\%$

The material qualifies as a replacement for concrete (traffic islands, guiding elements, etc.). The creep behaviour of plastic, meaning its deflection under a constant load, was also investigated. Here it was found that the maximum deflection of a plank under constant load was achieved after 12 weeks and that there was no further creep after this time.

2. THERMAL BEHAVIOUR

The material was exposed to strong sunlight during testing. Due to the low heat conductivity of the material (1.25 kJ/m hK) it was found that the maximum temperature of the material reached 30°C.

2.1 Shrinkage behaviour

The change of dimensions due to shrinkage or expansion can be between 2.5 mm and 5 mm per meter for a temperature difference of 30°C.

This should be taken into account during construction.

Please note that the material is thermally insulated, which can cause distortion in the event of large temperature differences.

2.2 Behaviour in the heat

Determination of penetration depth in accordance with DIN 53460 as a measure of the form stability.

This showed form stability of the material at 30°C.

2.3 Fire performance properties

2.3.1 Flame at horizontal plane

Determination in accordance with DIN 51960. This showed that the material can be classified in class I.

After the flame was extinguished, no shen remained.

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BTW: BE 0630 639 164 | IBAN: BE18 7350 4132 0065 | BIC/SWIFT: KREDBEBB | www.eco-oh.com



2.3.2 Flame at vertical plane

Determination in accordance with DIN 53438. The material can be classified in class I here as well. After the flame was extinguished, no sheen remained either.

2.3.3 Oxygen index O₂

Determined in accordance with ASTM D 2863-1977 volgens $n = O_2/(O_2+N_2)$.

For air $n = 0,21$

The O₂ value was determined in which the samples did not yet burn. The resulting oxygen index was 25,5. From this it can be concluded that the material is extremely difficult to burn in a normal, free atmosphere.

2.3.4 Test UL 94: (US-standard)

- The material can be classified into 94 V-O, this means no sample burned for longer than 10 seconds after the flame was removed.
- When burning, there are no falling droplets from any samples.
- No sample glows in the holder.

2.3.5 Fire performance properties of building materials

Determined in accordance with DIN 4102 T 1

The material can be included in the building material class B2.

This means the material has a certain degree of fire resistance.

2.4 Thermal conductivity

Determined in accordance with DIN 52612 T 1 in function of the temperature. As mentioned above, the material showed little thermal conductivity and little heating when exposed to strong sunlight.

3. CHEMICAL PHYSICAL EFFECTS OF CHEMICAL SUBSTANCES

A very large resistance to normal chemical substances was shown by means of testing in accordance with DIN 51958.

4. WATER ABSORPTION, FROST-THAW BEHAVIOUR

This is important in case of use in marine applications (pontoons, bank reinforcements). Water absorption is minimal, at least 15 times less than wood. In addition, other important factors to be considered about this material are that it does not rot and contains no impregnation materials.

5. SENSITIVITY TO WEATHER INFLUENCES

5.1 Weather-o-meter-test

A simulation of the equivalent UV light and rainfall for a duration of 6 months determines the effect of such influences. After 4 weeks, the affected layer is only 1/100 mm thick. For thick-walled products, there can be no effect on the strength properties expected.

5.2 Temperature and humidity

A natural cycle of 2 years was simulated.

The strength properties were not affected here either.

6. DENSITY

The density of the material is around 1 g/cm³.

7. ECOLOGICAL REQUIREMENTS

7.1 Leaching research in accordance with KTW

Here, the possible use of the material in drinking water applications was assessed.

The following criteria were considered: Migration of carbon compounds, chlorine consumption, lead concentration, phenol and formaldehyde content. The KTW-limit values are classified into four levels:

- | | |
|-------------------------------|--|
| - A : suitable for piping | - C : suitable for capital goods |
| - B : suitable for reservoirs | - D : suitable for elastic sealing materials |

A is the highest level and D the lowest. Again, a comparison was made with wood and concrete. The plastics fulfilled the requirements B and C; concrete fulfilled the requirements B; no type of wood, whether impregnated or not, fulfilled any of the conditions.

From these tests, it can be seen that no adverse environmental impact is to be expected from the use of recycled mixed household plastic waste.

7.2 Microbial contamination

The aim of the tests carried out in accordance with DIN 53739 was to determine the susceptibility to algae and bacterial growth.

Tests showed that damage was negligible. The mixed plastic products were equivalent or superior to conventional materials such as wood and concrete.

7.3 Toys directive

ECO-oh! products comply with the EN 71-2 (Flammability) and EN 71-3 (Specification for migration of certain elements) toy standards.

8. MAINTENANCE AND PROCESSING INSTRUCTIONS

ECO-oh! products require little or no maintenance and are resistant to water and moisture, giving them a long life.

They are best cleaned with lukewarm water and a non-caustic soap.

Cleaning with caustic (solvent-based) agents and/or a high-pressure cleaner is not recommended and can lead to irreversible damage.

It is recommended that ECO-oh! products be processed at a temperature between 10 & 30°C.

APPENDIX C Materials Technical Data Sheets

I. Action Plan PLA-rPMMA

Olivia DEHON (UCL) +32 499 28 91 10 olivia.dehon@student.uclouvain.be <i>Master Thesis – Recycled Plastics</i>		ACTION PLAN		
Composition		PLA + recycled PMMA 50-50 weight distribution Isotropic material, no fibers, no additives		
Production system of specimens		Injection		
Entity name of the laboratories		INNOLOGIC (Sint-Denijs, Belgium)		
Materials		PLA – recycled PMMA		
Target application		Park bench		
Main property to reach		Young's Modulus $E = 3$ [GPa] (2,5 [GPa] min)		
<i>Properties targeted</i>	Mechanical TEST	# speci	Standard	Due date <i>Fill in</i>
E, flexural strength	FLEXION	Min 5	ISO 178	

II. PLA Ingeo 2003D (Resinex, 2020)



Ingeo™ Biopolymer 2003D Technical Data Sheet

For Fresh Food Packaging and Food Serviceware

Ingeo biopolymer 2003D, a NatureWorks LLC product, is a thermoplastic resin derived from annually renewable resources and is specifically designed for use in fresh food packaging and food serviceware applications. Ingeo biopolymer 2003D is a transparent general purpose extrusion grade that is used naturally or as part of a formulated blend. This is a high molecular weight biopolymer grade that processes easily on conventional extrusion equipment. Extruded roll stock is readily thermoformable. See table at right for properties.

Applications

Potential applications for Ingeo biopolymer 2003D include:

- Dairy containers
- Food serviceware
- Transparent food containers
- Hinged-ware
- Cold drink cups

Processing Information

Ingeo biopolymer 2003D is easily processed on conventional extrusion equipment. The material is stable in the molten state, provided that the drying procedures are followed. More detailed recommendations and processing requirements are found in the Ingeo biopolymer sheet extrusion processing guide, the purging technical data sheet, and the drying and crystallizing processing guide, all of which can be found at www.natureworkslc.com.

Machine Configuration

Ingeo biopolymer 2003D will process on conventional extrusion machinery with the following equipment: General purpose screw with L/D ratios from 24:1 to 32:1 and compression ratio of

Typical Material & Application Properties ⁽¹⁾		
Physical Properties	Ingeo 2003D	ASTM Method
Specific Gravity	1.24	D792
MFR, g/10 min (210°C, 2.16kg)	6	D1238
Clarity	Transparent	
Mechanical Properties		
Tensile Strength @ Break, psi (MPa)	7,700 (53)	D882
Tensile Yield Strength, psi (MPa)	8,700 (60)	D882
Tensile Modulus, kpsi (GPa)	500 (3.5)	D882
Tensile Elongation, %	6.0	D882
Notched Izod Impact, ft-lb/in (J/m)	0.3 (16)	D256
Shrinkage is similar to PET ⁽²⁾		
Heat Distortion Temperature (°C)	55	E2092

(1) Typical properties; not to be construed as specifications.

(2) Refer to Ingeo biopolymer Sheet Extrusion Processing Guide

2.5:1 to 3:1. Smooth barrels are recommended.

Process Details

Startup and Shutdown

Ingeo biopolymer 2003D is not compatible with a wide variety of commodity resins, and special purging sequences should be followed:

1. Clean extruder and bring temperatures to steady state with low viscosity, general purpose polystyrene or polypropylene.
2. Vacuum out hopper system to avoid contamination.
3. Introduce Ingeo biopolymers into the extruder at the operating conditions used in Step 1.
4. Once Ingeo biopolymer has purged, reduce barrel temperatures to desired set points.
5. At shutdown, purge machine with high viscosity polystyrene or polypropylene.

Drying

In-line drying may be required. A moisture content of less than 0.025%

Processing Temperature Profile ⁽¹⁾		
Melt Temperature	410°F	210°C
Feed Throat	113°F	45°C
Feed Temperature	355°F	180°C
Compression Section	375°F	190°C
Metering Section	390°F	200°C
Adapter	390°F	200°C
Die	375°F	190°C
Screw Speed	20-100 rpm	

(1) These are starting points and may need to be optimized.

(250 ppm) is recommended to prevent viscosity degradation. Typical drying conditions for crystallized granules are 2 hours at 195°F (90°C) or to a dew point of -40°F (-40°C), airflow rate of greater than 0.5 cfm/lbs per hour of resin throughput. The resin should not be exposed to atmospheric conditions after drying. Keep the package sealed until ready to use and promptly reseal any unused material. Pellets that have been exposed to the atmosphere for extended time periods will require additional drying time. Amorphous regrind must be crystallized prior to drying, to assure efficient and effective drying.

Ingeo Biopolymer 2003D Technical Data Sheet

Compostability

Composting is a method of waste disposal that allows organic materials to be recycled into a product that can be used as a valuable soil amendment. Ingeo biopolymer is made of polylactic acid, a repeating chain of lactic acid, which undergoes a 2-step degradation process. First, the moisture and heat in the compost pile attack the polymer chains and split them apart, creating smaller polymers, and finally, lactic acid. Microorganisms in compost and soil consume the smaller polymer fragments and lactic acid as nutrients. Since lactic acid is widely found in nature, a large number of organisms metabolize lactic acid. At a minimum, fungi and bacteria participate in this degradation process. The end result of the process is carbon dioxide, water and also humus, a soil nutrient. This degradation process is temperature and humidity dependent. Regulatory guidelines and standards for composting revolve around four basic criteria: Material Characteristics, Biodegradation, Disintegration, and Ecotoxicity. Description of the requirements of these testing can be found in the appropriate geographical area: DIN V 54900-1 (Germany), EN 13432 (EU), ASTM D 6400 (USA), GreenPla (Japan). This grade of Ingeo biopolymer meets the requirements of these four standards with limitation of maximum thickness 3.2mm.

Food Packaging Status

U.S. Status

On January 3, 2002 FCN 000178 submitted by NatureWorks LLC to FDA became effective. This effective notification is part of list currently maintained on FDA's website at

<http://www.fda.gov/food/ingredient/spackaginglabeling/packagingfcs/notifications/default.htm>

This grade of Ingeo biopolymer may therefore be used in food packaging materials and, as such, is a permitted

component of such materials pursuant to section 201(s) of the Federal, Drug, and Cosmetic Act, and Parts 182, 184, and 186 of the Food Additive Regulations. All additives and adjuncts contained in the referenced Ingeo biopolymer formulation meet the applicable sections of the Federal Food, Drug, and Cosmetic Act. The finished polymer is approved for all food types and B-H use conditions. We urge all of our customers to perform GMP (Good Manufacturing Procedures) when constructing a package so that it is suitable for the end use. Again, for any application, should you need further clarification, please do not hesitate to contact NatureWorks LLC.

European Status

This grade of Ingeo biopolymer complies with Plastics Regulation 10/2011 as amended by 1282/2011. No SML's for the above referenced grade exist in Plastics Regulation 10/2011 as amended by 1282/2011. NatureWorks LLC would like to draw your attention to the fact that the EU-Plastics Regulation 10/2011, which applies to all EU-Member States, includes a limit of 10 mg/dm² of the overall migration from finished plastic articles into food. In accordance with Plastics Regulation 10/2011 the migration should be measured on finished articles placed into contact with the foodstuff or appropriate food simulants for a period and at a temperature which are chosen by reference to the contact conditions in actual use, according to the rules laid down in Plastics Regulation 10/2011.

Please note that it is the responsibility of both the manufacturers of finished food contact articles as well as the industrial food packers to make sure that these articles in their actual use are in compliance with the imposed specific and overall migration requirements.

This grade as supplied meets European Parliament and Council Directive 94/62/EC of 20 December

1994 on packaging and packaging waste heavy metal content as described in Article 11. It is recoverable in the form of material recycling, energy recovery, composting, and biodegradable per Annex II point 3, subject to the standards of the local community. Again, for any application, should you need further clarification, please do not hesitate to contact NatureWorks LLC.

Bulk Storage Recommendations

The resin silos recommended and used by NatureWorks LLC are designed to maintain dry air in the silo and to be isolated from the outside air. This design would be in contrast to an open, vented to atmosphere system that we understand to be a typical polystyrene resin silo. Key features that are added to a typical (example: polystyrene) resin silo to achieve this objective include a cyclone and rotary valve loading system and some pressure vessel relief valves. The dry air put to the system is sized to the resin flow rate out of the silo. Not too much dry air would be needed and there may be excess instrument air (-30°F dew point) available in the plant to meet the needs for dry air. Our estimate is 10 scfm for a 20,000 lb/hr rate resin usage. Typically, resin manufacturers specify aluminum or stainless steel silos for their own use and avoid epoxy-lined steel

Ingeo Biopolymer 2003D Technical Data Sheet

Safety and Handling Considerations

Material Safety Data (MSD) sheets for Ingeo biopolymers are available from NatureWorks LLC. MSD sheets are provided to help customers satisfy their own handling, safety, and disposal needs, and those that may be required by locally applicable health and safety regulations, such as OSHA (U.S.A.), MAK (Germany), or WHMIS (Canada). MSD sheets are updated regularly; therefore, please request and review the most current MSD sheets before handling or using any product.

The following comments apply only to Ingeo biopolymers; additives and processing aids used in fabrication and other materials used in finishing steps have their own safe-use profile and must be investigated separately.

Hazards and Handling Precautions

Ingeo biopolymers have a very low degree of toxicity and, under normal conditions of use, should pose no unusual problems from incidental ingestion, or eye and skin contact. However, caution is advised when handling, storing, using, or disposing of these resins, and good housekeeping and controlling of dusts are necessary for safe handling of product. Workers should be protected from the possibility of contact with molten resin during fabrication. Handling and fabrication of resins can result in the generation of vapors and dusts that may cause irritation to eyes and the upper respiratory tract. In dusty atmospheres, use an approved dust respirator. Pellets or beads may present a slipping hazard. Good general ventilation of the polymer processing area is recommended. At temperatures exceeding the polymer melt temperature (typically 170°C), polymer can release fumes, which may contain fragments of the polymer, creating a potential to irritate eyes and mucous membranes. Good general ventilation should be sufficient for most conditions.

Local exhaust ventilation is recommended for melt operations. Use safety glasses if there is a potential for exposure to particles which could cause mechanical injury to the eye. If vapor exposure causes eye discomfort, use a full-face respirator. No other precautions other than clean, body-covering clothing should be needed for handling Ingeo biopolymers. Use gloves with insulation for thermal protection when exposure to the melt is localized.

Combustibility

Ingeo biopolymers will burn. Clear to white smoke is produced when product burns. Toxic fumes are released under conditions of incomplete combustion. Do not permit dust to accumulate. Dust layers can be ignited by spontaneous combustion or other ignition sources. When suspended in air, dust can pose an explosion hazard. Firefighters should wear positive-pressure, self-contained breathing apparatuses and full protective equipment. Water or water fog is the preferred extinguishing medium. Foam, alcohol-resistant foam, carbon dioxide or dry chemicals may also be used. Soak thoroughly with water to cool and prevent re-ignition.

Disposal

DO NOT DUMP INTO ANY SEWERS, ON THE GROUND, OR INTO ANY BODY OF WATER. For unused or uncontaminated material, the preferred options include recycling into the process or sending to an industrial composting facility, if available; otherwise, send to an incinerator or other thermal destruction device. For used or contaminated material, the disposal options remain the same, although additional evaluation is required. (For example, in the U.S.A., see 40 CFR, Part 261, "Identification and Listing of Hazardous Waste.") All disposal methods must be in compliance with Federal, State/Provincial, and local laws and regulations.

Environmental Concerns

Generally speaking, lost pellets are not a problem in the environment except under unusual circumstances when they enter the marine environment. They are benign in terms of their physical environmental impact, but if ingested by waterfowl or aquatic life, they may mechanically cause adverse effects. Spills should be minimized, and they should be cleaned up when they happen. Plastics should not be discarded into the ocean or any other body of water.

Product Stewardship

NatureWorks LLC has a fundamental duty to all those that make and use our products, and for the environment in which we live. This duty is the basis for our Product Stewardship philosophy, by which we assess the health and environmental information on our products and their intended use, then take appropriate steps to protect the environment and the health of our employees and the public.

Customer Notice

NatureWorks LLC encourages its customers and potential users of its products to review their applications for such products from the standpoint of human health and environmental quality. To help ensure our products are not used in ways for which they were not intended or tested, our personnel will assist customers in dealing with ecological and product safety considerations. Your sales representative can arrange the proper contacts. NatureWorks LLC literature, including Material Safety Data sheets, should be consulted prior to the use of the company's products. These are available from your NatureWorks LLC representative.

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For additional information please contact NatureWorks via our [website](#) on the tab called [FAQ's](#) or by clicking [here](#).

 NatureWorks LLC
15305 Minnetonka Blvd., Minnetonka, MN 55345

Ingeo™ 2003D

NatureWorks® LLC - Polylactic Acid

Thursday, May 7, 2020

General Information**Product Description**

Ingeo biopolymer 2003D, a NatureWorks LLC product, is a thermoplastic resin derived from annually renewable resources and is specifically designed for use in fresh food packaging and food service ware applications. Ingeo biopolymer 2003D is a transparent general purpose extrusion grade that is used naturally or as part of a formulated blend. This is a high molecular weight biopolymer grade that processes easily on conventional extrusion equipment. Extruded roll stock is readily thermoformable.

Applications

Potential applications for Ingeo biopolymer 2003D include:

- Dairy containers
- Food service ware
- Transparent food containers
- Hinged-ware
- Cold drink cups

General

Material Status	• Commercial: Active		
Availability	• Africa & Middle East • Asia Pacific	• Europe • Latin America	• North America
Features	• Compostable • Food Contact Acceptable	• High Clarity • High Molecular Weight	• Renewable Resource Content
Uses	• Containers • Cups	• Food Containers • Food Packaging	• Food Service Applications • General Purpose
Agency Ratings	• ASTM D6400 • EN 13432	• EU 10/2011 • FDA Food Contact, Unspecified Rating	
Appearance	• Clear/Transparent		
Forms	• Pellets		
Processing Method	• Extrusion	• Thermoforming	

ASTM & ISO Properties¹

Physical	Nominal Value	Unit	Test Method
Density / Specific Gravity	1.24	g/cm ³	ASTM D792
Melt Mass-Flow Rate (MFR) (210°C/2.16 kg)	6.0	g/10 min	ASTM D1238
Films	Nominal Value	Unit	Test Method
Elastic Modulus - MD	3450	MPa	ASTM D882
Tensile Strength - MD (Yield)	60.0	MPa	ASTM D882
Tensile Strength - MD (Break)	53.1	MPa	ASTM D882
Tensile Elongation - MD (Break)	6.0	%	ASTM D882
Impact	Nominal Value	Unit	Test Method
Notched Izod Impact	16	J/m	ASTM D256
Optical	Nominal Value	Unit	
Clarity	Transparent		

Processing Information

Extrusion	Nominal Value	Unit
Drying Temperature	91	°C
Drying Time	2.0	hr
Suggested Max Moisture	< 0.025	%

Customer is responsible for determining whether products and the information in this document are appropriate for customer's use and for ensuring that customer's workplace and disposal practices are in compliance with applicable laws and other governmental enactments. Seller assumes no obligation or liability for the information in this document. No warranties are given; all implied warranties of merchantability or fitness for a particular purpose are expressly excluded.

Ingeo™ 2003D

NatureWorks® LLC - Polylactic Acid

Extrusion	Nominal Value	Unit
Hopper Temperature	45	°C
Cylinder Zone 1 Temp.	179	°C
Cylinder Zone 2 Temp.	191	°C
Cylinder Zone 3 Temp.	199	°C
Adapter Temperature	199	°C
Melt Temperature	210	°C
Die Temperature	191	°C
Extrusion Notes		
Screw Speed: 20-100 rpm		

Notes

¹ Typical properties: these are not to be construed as specifications.

Certificate of Analysis

Order number. : 30766

Material : NatureWorks® Biopolymer 2003D
Batch : IA0328B131
Quantity : 26 cartons

This material meets the requirements of the specification.

Feature	Units	Results	Minimum	Limits
		IA0328B131		Maximum
Residual Monomer	%	0,22	0,00	0,30
Relative Viscosity	-	3.92	3,90	4,10
Color, Yellowness Index	-	37.3	0,0	38,0
D Isomer	%	4.1	3,7	4,8

Business Quality Leader
NatureWorks Quality Assurance

**Trademark of NatureWorks LLC.

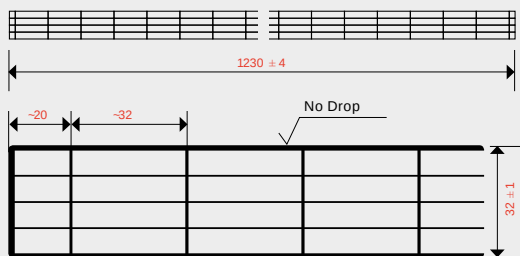
III. PMMA PLEXIGLAS Heatstop (Röhm GmbH, 2020)

TECHNICAL INFORMATION

PLEXIGLAS® Multi-skin sheet

PLEXIGLAS®
THE ORIGINAL BY RÖHM

PLEXIGLAS® Heat stop Cool Blue S5P 32/1230 - 32 WZ009



Cross-section of PLEXIGLAS®Heat stop Cool Blue S5P 32
(dimension in mm)



Product

PLEXIGLAS®Heat stop Cool Blue S5P 32 is an infrared (IR)- reflecting, highly heat- insulating and extremely weather- resistant quintuple- skin sheet made of impact- modified acrylic (polymethyl methacrylate, PMMA). The Heat stop coating is uniformly and permanently fused with the sheet material and is equally effective on the upper and lower side of the sheet.

Properties

Besides the general properties of PLEXIGLAS®like

- Excellent light transmission and brilliance
- Outstanding weather resistance
- 100% recycling ability
- Easy to fabricate
- High surface hardness

PLEXIGLAS®Heat stop Cool Blue S5P 32 possesses the following properties:

- Incident solar energy is reduced by as much as 78 %.
- The color impression beneath the glazing is very pleasant and cool.
- The sheets offer excellent protection against an excess of harmful UV radiation.
- They are impact- resistant during transport, handling and installation.
- They are highly heat- insulating.
- They help to save energy and minimize CO₂ emissions.
- They are hail- resistant (to hailstones with an impact energy up to 1 joule).
- This comes with a 10- year guarantee.

Applications

Due to these properties PLEXIGLAS® Heatstop Cool Blue S5P 32 is suitable for the following applications:

- Carports
- Conservatories
- Façades
- Greenhouses
- Patio roofs
- Porches
- Skylights
- Verandas
- etc.

Processing

For PLEXIGLAS® Heatstop Cool Blue S5P 32 the following processing guideline is available:

- Instructions for Installing PLEXIGLAS® Multi-Skin, Corrugated and Solid Sheets (Ref-No. 311-8)

Product range

PLEXIGLAS® Heatstop Cool Blue S5P 32 is available in the following grades and sizes:

- Length: 2000 bis 7000 mm
- Width: 1230 mm
- Colors: White (bluish-golden)

For details please refer to the PLEXIGLAS® sales handbook.

Heatstop Cool Blue Effect

The PLEXIGLAS® Heatstop Cool Blue multi-skin sheet very effectively reduces solar heat radiation by means of special technology. This effect is supported by its specific color, which also has a favorable influence on the perceived temperature, a factor that is very important for human wellbeing. The Heatstop Cool Blue coating gives the sheets an attractive golden surface gloss. Seen from below, the sheets have a cool, bluish look, as befits their function. This color has an iridescent effect. The color impression varies depending on the viewing angle and lighting conditions.

Heat insulation

With their further improved U-value, these sheets meet all requirements of the German Energy Saving Ordinance (EnEV). This makes them suitable as highly heat-insulating glazing materials for private construction as well as for factory units and sports halls.

NO DROP coating

The water-dispersing NO DROP¹ coating applied to one side of the sheet causes any surface water to flow off as a thin, continuous film. When the sheet is installed with the NO DROP coating on the outside of the roof, it supports natural cleaning by rainwater. Installed on the inside of the roof, the coating helps to prevent dripping from condensation and the damage this may cause. The NO DROP coating is covered with a protective layer applied during the manufacturing process. This protective layer can be washed off with water and a sponge, or by hosing down the sheet. This activates the NO DROP coating.

Load-bearing capacity Support spacing

Thanks to their high rigidity, these sheets allow large spans, which reduce shadows inside the room and cuts construction costs. Supported on all four sides, the PLEXIGLAS® Heatstop Cool Blue S5P 32/1230 quintuple skin sheet requires no additional cross-members at a load of up to 1,000 N/m². The spacing stated in the table applies to greater loads. The loadbearing capacity of PLEXIGLAS® Heatstop Cool Blue S5P 32/1230 is determined in line with ETAG 010 (Guideline for European Technical Approval for Self-supporting, Translucent Roof Kits), assuming a rebate depth of 20 mm for the multiskin sheets in the glazing system. The support spacing should be reduced correspondingly for smaller rebate depths.

¹ Europ. Patent 149 182

Support spacing

Load [N/m ²]	Support spacing [m]
750	no cross members
1000	no cross members
1250	5,7
1500	4,2
1750	3,7
2000	3,3
2250	3,1
2500	2,9
2750	2,7
3000	2,6

Brandverhalten

- Im Brandverhalten ist PLEXIGLAS® in die europäische Klasse E nach DIN EN 13501 eingestuft.
- PLEXIGLAS® brennt nahezu rauchfrei nach DIN 4102 und ist leicht zu löschen.
- Die Rauchgase von PLEXIGLAS® sind nicht akut giftig nach DIN 53436 und nicht korrosiv nach DIN VDE 0482-267.
- Lichtflächen aus PLEXIGLAS® im Dach können im Brandfall aufschmelzen und als Rauch- und Wärmeabzug wirken.

Technical data (Typical values)	
Available length	2000 to 7000 mm
Light transmittance $\tau_{0.65}$	
White WZ009	18%
Total energy transmittance g	
White WZ009	15%
Heat transfer coefficient k	1,5 W/m ² K
Coefficient of linear thermal expansion α	0,09 mm/m ² K
Possible expansion due to heat and moisture	approx. 6 mm/m
Max. service temperature without load	70 °C
Weighted sound reduction index	24 dB
Area weight	approx. 5,8 kg/m ²

Garantie

Garantiebedingungen zu diesem und weiteren Produkten finden Sie unter www.plexiglas.de.

Röhm GmbH
Acrylic Products

Riedbahnstraße 70
64331 Weiterstadt
Germany

www.plexiglas.de
www.roehm.com

® = registered trademark

PLEXIGLAS is a registered trademark of Röhm GmbH, Darmstadt, Germany.
Certified to DIN EN ISO 9001 (Quality) and DIN EN ISO 14001 (Environment)

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The customer is not released from the obligation to conduct careful inspection and testing of incoming goods. Performance of the product described herein should be verified by testing, which should be carried out only by qualified experts in the sole responsibility of a customer. Reference to trade names used by other companies is neither a recommendation, nor does it imply that similar products could not be used.



ISO 178: 2010 - Plastics Flexural Properties

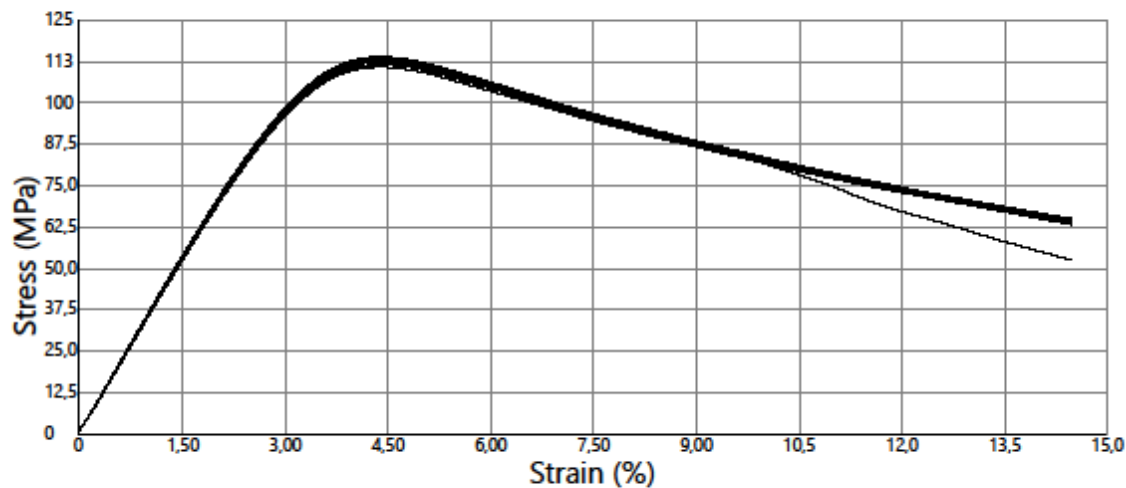
INNOLOGIC BVBA
Jolainstraat 44 - B-8554 Sint-Denijs

Ref Batch: 520000150
Material: 50/50 PLA PMMA
Operator Name: Thibault

Support Span: 64,0 mm

	Width mm	Thickness mm	Flexural Stress MPa	Ultimate Strain %	Flexural Modulus MPa	Flex Stress at sc MPa	Flex Stress at break MPa	Total Elongation %
	10,00	4,00	113,7	4,42	3224	107	52,5	14,5
	10,00	4,00	111,6	4,38	3206	105	63,9	14,5
	10,00	4,00	111,5	4,43	3253	105	63,2	14,5
	10,00	4,00	112,7	4,39	3244	106	64,2	14,5
	10,00	4,00	113,9	4,39	3305	108	64,7	14,5
	10,00	4,00	113,0	4,42	3256	107	64,9	14,5
	10,00	4,00	113,5	4,37	3328	108	64,5	14,5
	10,00	4,00	110,8	4,41	3179	105	64,0	14,5
	10,00	4,00	112,8	4,40	3222	106	64,9	14,5
	10,00	4,00	112,3	4,41	3213	106	64,8	14,5
Average	10,00	4,00	112,6	4,40	3243	106	63,2	14,5
SD	0,00	0,00	1,015	0,0184	45,21	0,925	3,79	0,00140
CoV			0,9016	0,418	1,394	0,869	6,00	0,00967

Comment:



Method: ISO 178: 2010 Plastics - Flexural properties, (rev. 74)
v10.2.5.0 - 80114/08 - Innologic BVBA

- Page 1 of 1 -

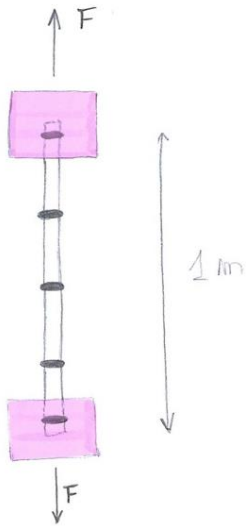
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Injection moulding parameters					
Mould	Arburg 420 M1000-350				
Material description	50/50 PLA PMMA				
Material number	520000150				
Pre-drying (hr / °C)	/		/		
Injection moulding date + operator	12/05/2020 TD				
Barrel temperature (set) (°C) (T801 to T805)	Zone 1	Zone 2	Zone 3	Zone 4	Nozzle
	195	200	205	210	215
Mould temperature (set) (°C)	20				
Injection speed (ccm/sec) (Q301)	35				
Injection pressure (set) (bar) (P301)	700				
Holding pressure (P321)	700				
Holding pressure time (sec) (t321)	12				
Switchover to holding pressure (ccm) (V311)	30				
Cooling time (sec) (t400)	25				
Dosing volume (ccm) (V403)	67				
Dosing speed (m/min) (V401) - Backpressure (bar) (P401)	35			10	
Decompression speed (ccm/s) (V411)	20				
Decompression volume (ccm) (V412)	5				
Cycle time (sec)					
Clamping force (kN)					
Remarks					

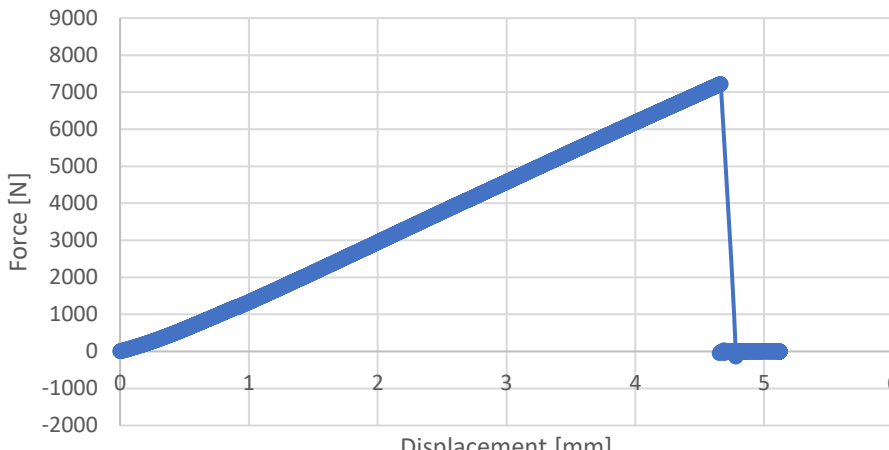
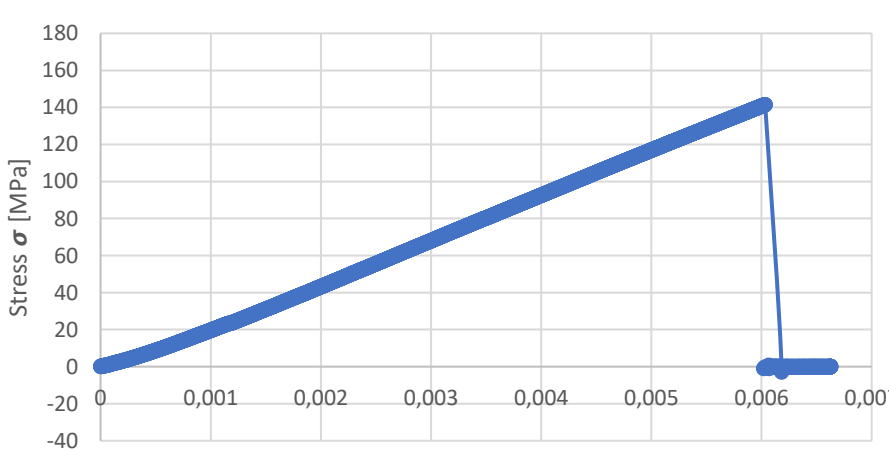
Olivia DEHON (UCL) +32 499 28 91 10 olivia.dehon@student.uclouvain.be <i>Master Thesis – Recycled Plastics</i>	Filling Formworks At GovaPlast (Alken, Belgium)
Elements	3 parallelepiped rectangles with 2 or 4 bamboos inside the plastic matrix (5 x 5 x 40 [cm]) 1 parallelepiped rectangle without bamboo inside (5 x 5 x 40 [cm]) 3 parallelepiped rectangles with 1 bamboo inside the plastic matrix (6 x 6 x 30 [cm]) Composition of plastic: 50% PLA + 50% recycled PMMA weight distribution (anisotropic material, no fibers, no additives) Bamboos : 0,8 - 1 [cm] diameter, nodes +/- each 20 [cm]
Machinery needed	Extruder + gloves
Explanations	
Extrude the 50-50 weight distribution PLA-rPMMA blend in the extruder (NO additives, NO fibers). Try to have a high density, not porous, material by pressing it as much as possible by hands inside the molds. Keep the material in the molds, I will remove them later on. If possible, take a few pictures of the molds filled.	

APPENDIX F Recapitulative Tables of each test

I. Traction on Bamboos

Olivia DEHON (UCL) +32 499 28 91 10 olivia.dehon@student.uclouvain.be <i>Master Thesis – Recycled Plastics</i>				TRACTION on BAMBOO TESTS laboratory LEMSC (UCLouvain)
Element(s)				5 Natural Bamboos
Dimensions				1 [m] long, 0,8 - 1 [cm] diameter, nodes +/- each 20 [cm]
Machinery needed				Machine + résine rose
<i>Properties targeted</i>	TEST	# speci	Standard	Explanations
E, ductility, elongation at break, tensile strength, yield strength	TRACTION	Min 5	/	Propriétés caractérisants le bambou utilisé dans les deux autres tests. Couler les 2 extrémités de chaque bambou testé dans la résine « rose » (cfr P. Latteur). Essai de traction sur chaque bambou, jusqu'à la rupture. Photo du montage.
DRAWINGS 				

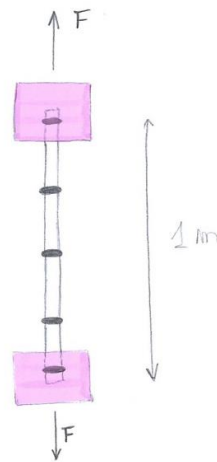
Traction test Bamboo – Test 1

Standard	Based on ISO 527
A₀ Cross section of stem	51,05 [mm ²]
F_{MAX} Maximum force	7222,27 [N]
d_{MAX} Maximum displacement	4,66 [mm] (corresponding to F _{MAX})
$\sigma = F/A_0$ Maximum stress	141,47 [MPa]
L Gripping Distance	773 [mm]
E_t Tensile Modulus	23,46 [GPa]
Graphs	Force vs Displacement  The graph shows Force [N] on the y-axis (ranging from -2000 to 9000) and Displacement [mm] on the x-axis (ranging from 0 to 6). The curve starts at (0,0), rises linearly to a peak of approximately 7200 N at a displacement of 4.66 mm, and then drops sharply to zero force at approximately 4.8 mm. Stress vs Strain ($\sigma - \epsilon$)  The graph shows Stress σ [MPa] on the y-axis (ranging from -40 to 180) and Strain ϵ [/] on the x-axis (ranging from 0 to 0.007). The curve starts at (0,0), rises linearly to a peak of approximately 141 MPa at a strain of 0.006, and then drops sharply to zero stress at approximately 0.0062.
Type of rupture	Brittle

Pictures



Test Device



The ends of the bamboo have been sanded before inserting them in aluminium tubes and bonding them with pink resin. This system avoid squashing bamboos' ends with the clamping jaws of the machine.

Observations

Brittle Failure at node
No necking in the bamboo
"Filament" failure (see pictures)

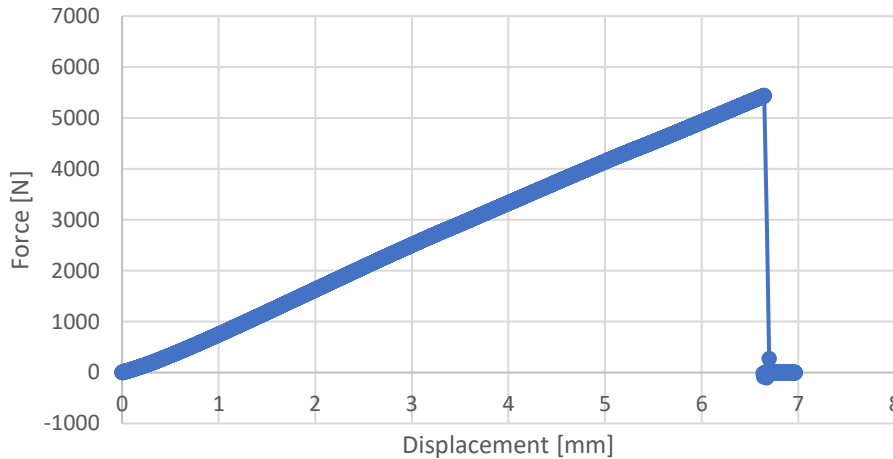
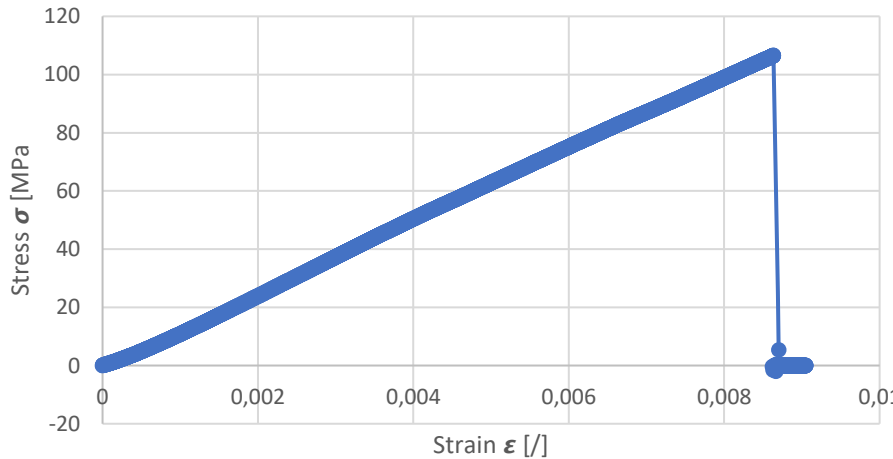
Machineries

MTS 100kN Machine servo-hydraulique universelle

Test speed

10 [mm/min]

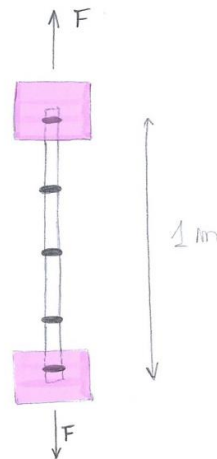
Traction test Bamboo – Test 2

Standard	Based on ISO 527
A₀ Cross section of stem	51,05 [mm ²]
F_{MAX} Maximum force	5438,66 [N]
d_{MAX} Maximum displacement	6,65 [mm] (corresponding to F _{MAX})
$\sigma = F/A_0$ Maximum stress	106,53 [MPa]
L Gripping Distance	770 [mm]
E_t Tensile Modulus	12,86 [GPa]
Graphs	Force vs Displacement  Stress vs Strain ($\sigma - \epsilon$) 
Type of rupture	Brittle

Pictures



Test Device



The ends of the bamboo have been sanded before inserting them in aluminium tubes and bonding them with pink resin. This system avoid squashing bamboos' ends with the clamping jaws of the machine.

Observations

Brittle Failure at node
No necking in the bamboo
"Filament" failure (see pictures)
Strange increase and decrease of the force during the whole test → results to exclude

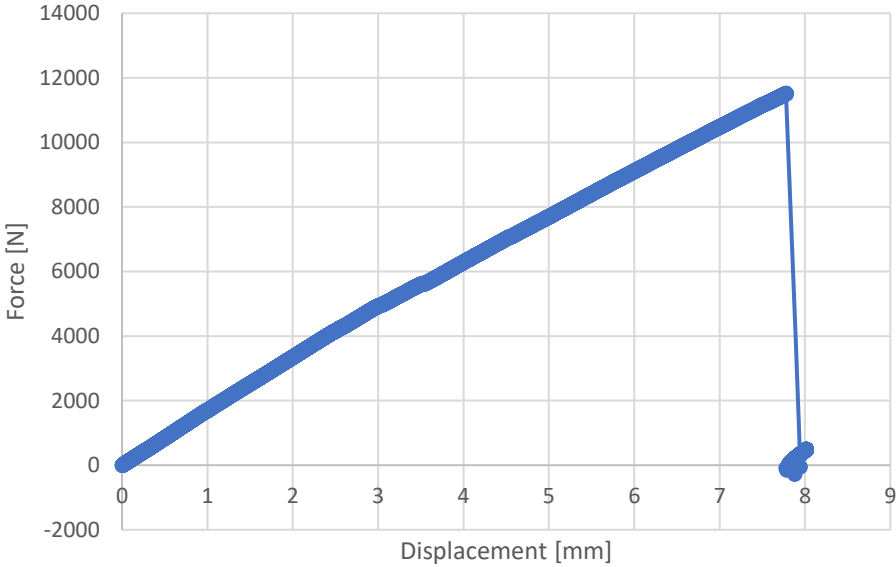
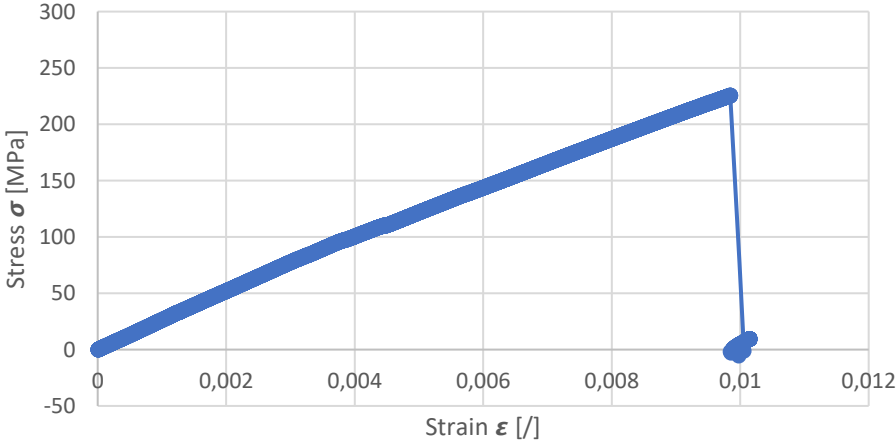
Machineries

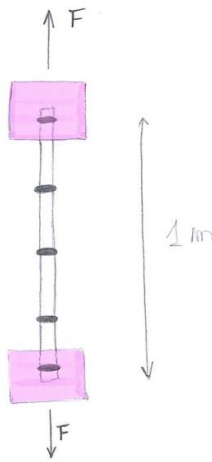
MTS 100kN Machine servo-hydraulique universelle

Test speed

5 [mm/min]

Traction test Bamboo – Test 3

Standard	Based on ISO 527
A₀ Cross section of stem	51,05 [mm ²]
F_{MAX} Maximum force	11516,69[N]
d_{MAX} Maximum displacement	7,77 [mm] (corresponding to F _{MAX})
$\sigma = F/A_0$ Maximum stress	225,59 [MPa]
L Gripping Distance	790 [mm]
E_t Tensile Modulus	25,87 [GPa] (22,75 [GPa] if linear approximation)
Graphs	Force vs Displacement  The graph shows Force [N] on the y-axis (ranging from -2000 to 14000) and Displacement [mm] on the x-axis (ranging from 0 to 9). The curve is linear from (0,0) to approximately (7.77, 11516.69) and then drops sharply to zero at approximately 8 mm. Stress vs Strain ($\sigma - \epsilon$)  The graph shows Stress σ [MPa] on the y-axis (ranging from -50 to 300) and Strain ϵ [/] on the x-axis (ranging from 0 to 0.012). The curve is linear from (0,0) to approximately (0.01, 225.59) and then drops sharply to zero at approximately 0.011.
Type of rupture	Brittle

Pictures**Test Device**

The ends of the bamboo have been sanded before inserting them in aluminium tubes and bonding them with pink resin. This system avoid squashing bamboos' ends with the clamping jaws of the machine.

Observations

Brittle Failure at node
No necking in the bamboo

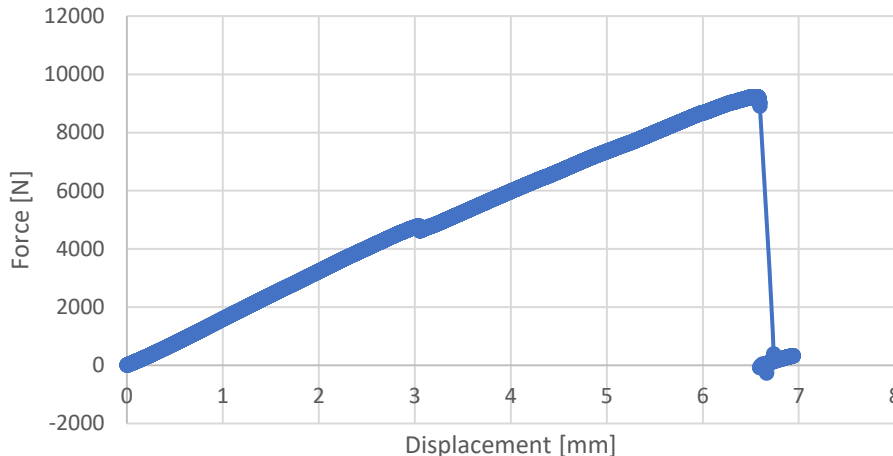
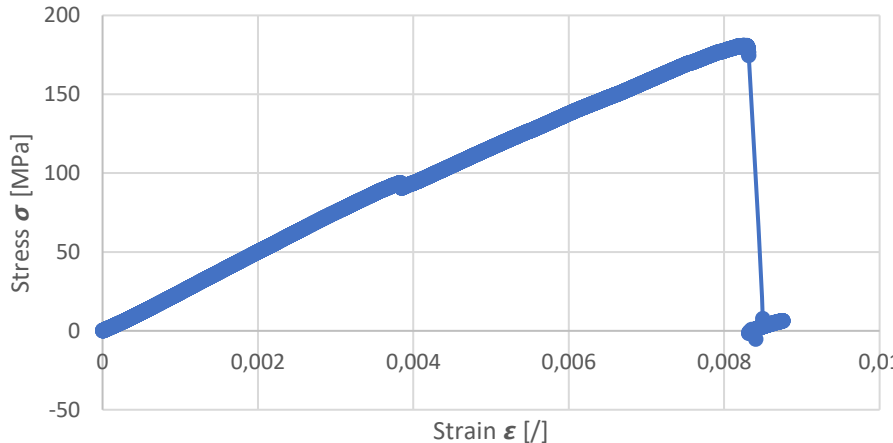
Machineries

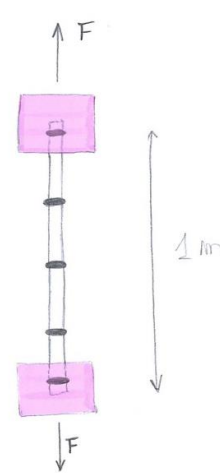
MTS 100kN Machine servo-hydraulique universelle

Test speed

5 [mm/min]

Traction test Bamboo – Test 4

Standard	Based on ISO 527
A₀ Cross section of stem	51,05 [mm ²]
F_{MAX} Maximum force	9029,22 [N]
d_{MAX} Maximum displacement	6,59 [mm] (corresponding to F _{MAX})
$\sigma = F/A_0$ Maximum stress	176,87 [MPa]
L Gripping Distance	793 [mm]
E_t Tensile Modulus	25,62 [GPa] (21,17 [GPa] if linear approximation)
Graphs	Force vs Displacement  Stress vs Strain ($\sigma - \epsilon$) 
Type of rupture	Brittle

Pictures**Test Device**

The ends of the bamboo have been sanded before inserting them in aluminium tubes and bonding them with pink resin. This system avoid squashing bamboos' ends with the clamping jaws of the machine.

Observations

Brittle Failure at node
No necking in the bamboo
"Filament" failure (see pictures)

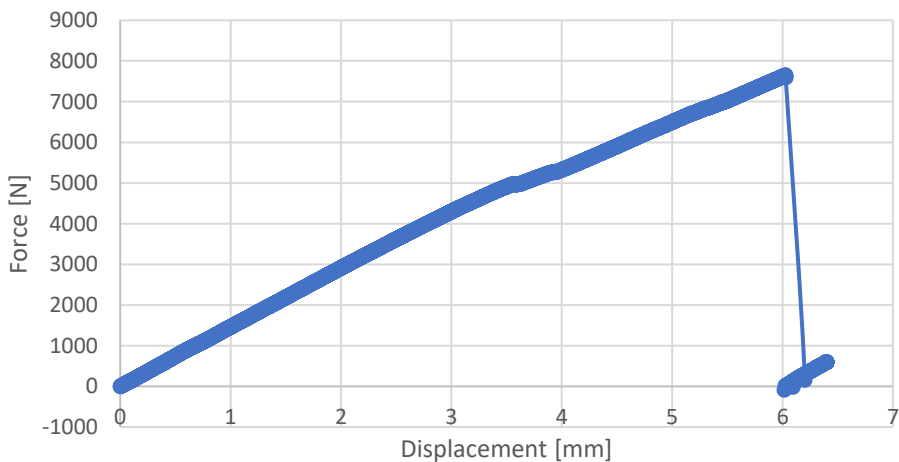
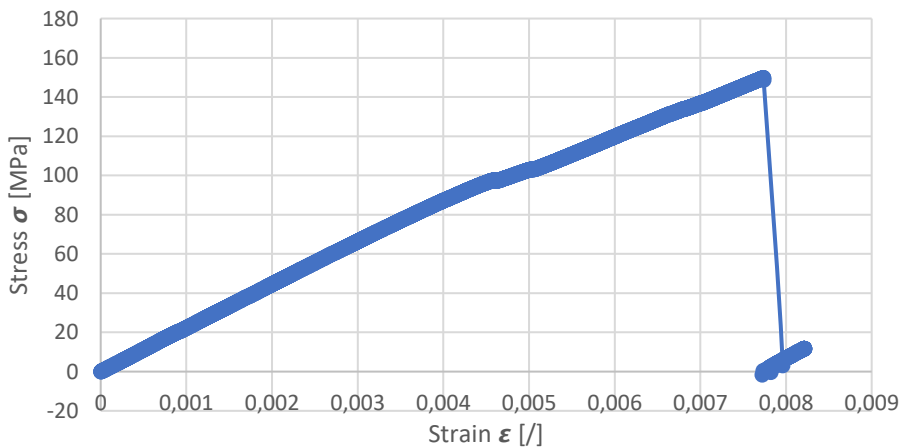
Machineries

MTS 100kN Machine servo-hydraulique universelle

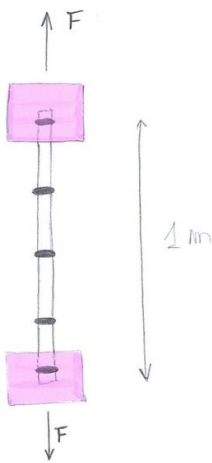
Test speed

5 [mm/min]

Traction test Bamboo – Test 5

Standard	Based on ISO 527
A₀ Cross section of stem	51,05 [mm ²]
F_{MAX} Maximum force	7647,98 [N]
d_{MAX} Maximum displacement	6,025 [mm] (corresponding to F _{MAX})
$\sigma = F/A_0$ Maximum stress	149,81 [MPa]
L Gripping Distance	779 [mm]
E_t Tensile Modulus	22,18 [GPa] (19,15 [GPa] if linear approximation)
Graphs	Force vs Displacement  Stress vs Strain ($\sigma - \epsilon$) 
Type of rupture	Brittle
Pictures	

Test Device



The ends of the bamboo have been sanded before inserting them in aluminium tubes and bonding them with pink resin. This system avoid squashing bamboos' ends with the clamping jaws of the machine.

Observations

Brittle Failure at node
No necking in the bamboo

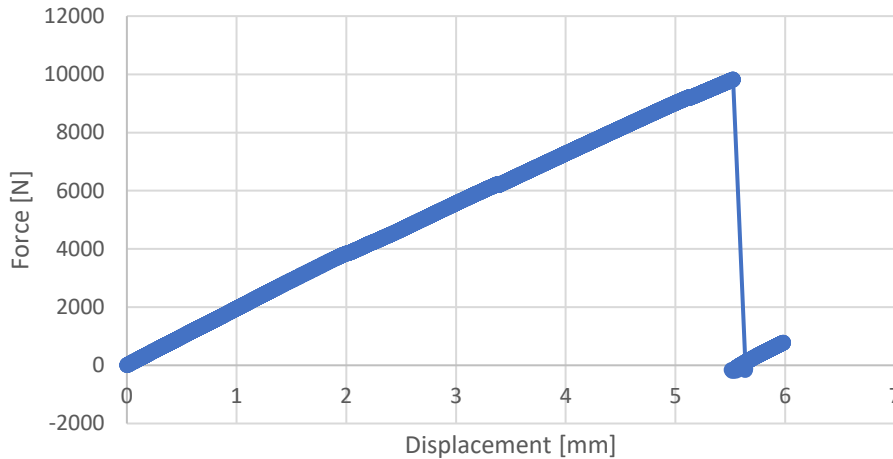
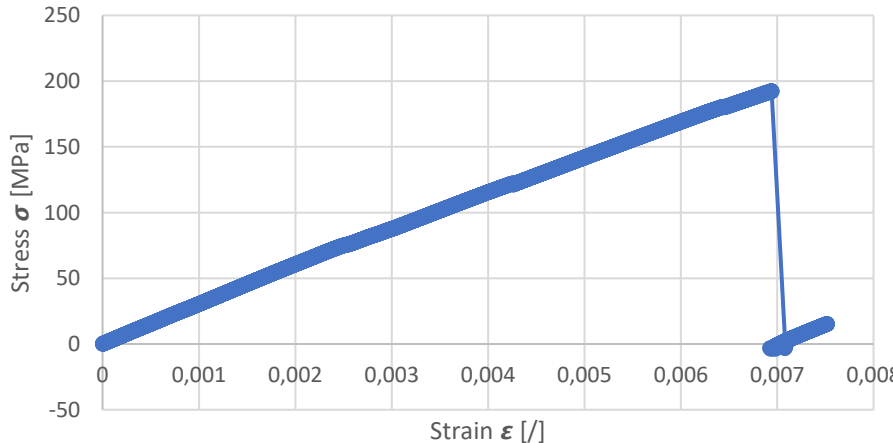
Machineries

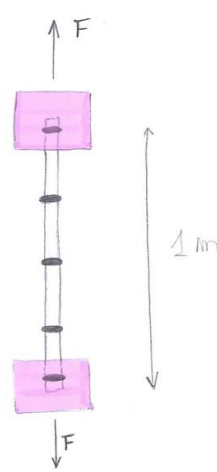
MTS 100kN Machine servo-hydraulique universelle

Test speed

5 [mm/min]

Traction test Bamboo – Test 6

Standard	Based on ISO 527
A₀ Cross section of stem	51,05 [mm ²]
F_{MAX} Maximum force	9818,63 [N]
d_{MAX} Maximum displacement	5,53 [mm] (corresponding to F _{MAX})
$\sigma = F/A_0$ Maximum stress	192,33 [MPa]
L Gripping Distance	796 [mm]
E_t Tensile Modulus	29,83 [GPa] (27,49 [GPa] if linear approximation)
Graphs	Force vs Displacement  The graph shows Force [N] on the y-axis (ranging from -2000 to 12000) and Displacement [mm] on the x-axis (ranging from 0 to 7). The data points form a nearly straight line from (0,0) to (5.53, 9818.63), after which the force drops sharply to zero at approximately 5.5 mm. Stress vs Strain ($\sigma - \epsilon$)  The graph shows Stress σ [MPa] on the y-axis (ranging from -50 to 250) and Strain ϵ [/] on the x-axis (ranging from 0 to 0.008). The data points form a nearly straight line from (0,0) to (0.007, 192.33), after which the stress drops sharply to zero at approximately 0.007.
Type of rupture	Brittle

Pictures**Test Device**

The ends of the bamboo have been sanded before inserting them in aluminium tubes and bonding them with pink resin. This system avoid squashing bamboos' ends with the clamping jaws of the machine.

Observations

Brittle Failure at node
No necking in the bamboo
"Filament" failure (see pictures)

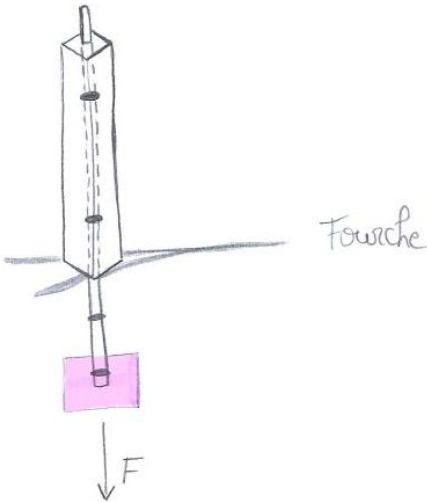
Machineries

MTS 100kN Machine servo-hydraulique universelle

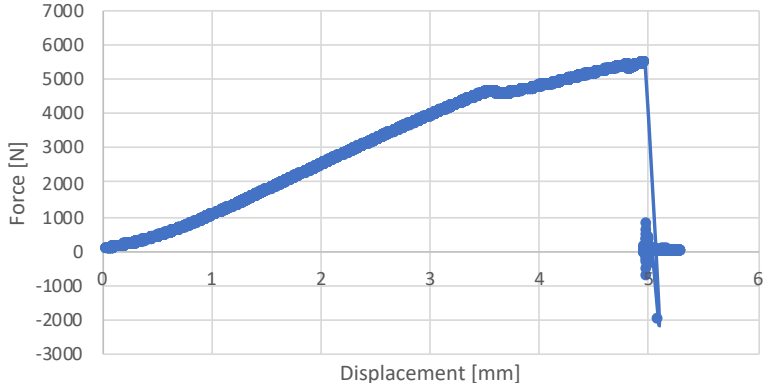
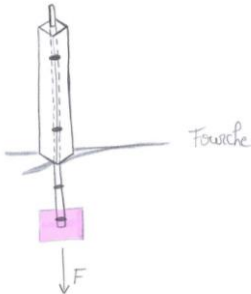
Test speed

5 [mm/min]

II. Pull-off

Olivia DEHON (UCL) +32 499 28 91 10 olivia.dehon@student.uclouvain.be <i>Master Thesis – Recycled Plastics</i>				PULL-Off on element with bamboo TESTS laboratory LEMSC (UCLouvain)
Element(s)				2 elements of bamboo embedded in plastic Composition of plastic: PLA + recycled PMMA (anisotropic material, no fibers, no additives)
Dimensions				Plastic : 6 x 6 x 30 [cm] (2 nodes embedded) Bamboo : 0,9 [m] long, 0,8 - 1 [cm] diameter, nodes +/- each 20 [cm]
Machinery needed				Fourche + machine + résine rose
<i>Properties targeted</i>	TEST	# speci	Standard	Explanations
Adherence	PULL-OFF	2	/	Adhérence entre bambou et matrice plastique. Placer l'élément à travers la fourche : - matrice plastique retenue par la fourche - couler l'extrémité du bambou dans la résine « rose » (cfr P. Latteur). Tirer sur le bambou (jusqu'à atteindre la rupture d'adhérence entre le bambou et le plastique). Documenter (description/photos) le rupture d'adhérence.
DRAWINGS 				

PULL-OFF test Bamboo embedded in PLA/rPMMA – Test 1

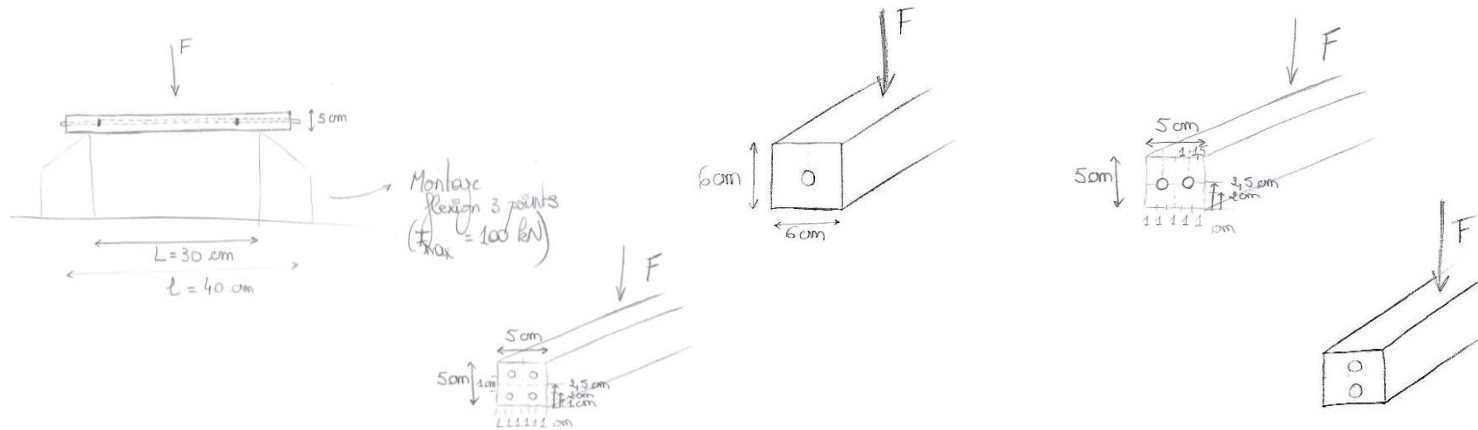
A₀ Cross section of matrix	3249 [mm ²]
πD_f L_{deb} Lateral surface	8482,3[mm ²]
F_{MAX} Maximum force	5445,63[N]
d_{MAX} Maximum displacement	4,969[mm] (corresponding to F _{MAX})
τ_{app} Apparent shear strength	0,642[MPa] (surface is the stem of the bamboo) 14,45 [MPa] (surface are the two nodes embedded)
σ = F/A₀ Maximum stress	1,676 [MPa]
Graphs	Force vs Displacement 
Type of rupture	Bamboo brittle failure
Pictures	
Test Device	 
Observations	Bamboo brittle failure at node (out of matrix) No loss of adherence between bamboo and matrix
Machineries	MTS 100kN Machine servo-hydraulique universelle
Test speed	5 [mm/min]

PULL-OFF test Bamboo embedded in PLA/rPMMA – Test 2

A₀ Cross section of matrix	3481 [mm ²]
πD_f L_{deb} Lateral surface	7539,82 [mm ²]
F_{MAX} Maximum force	3767,06 [N] (reached before debonding)
d_{MAX} Maximum displacement	3,935 [mm] (corresponding to F _{MAX})
τ_{app} Apparent shear strength	0,49 [MPa] (surface is the stem of the bamboo) 6,813 [MPa] (surface are the two nodes embedded)
σ = F/A₀ Maximum stress	1,082 [MPa] (before failure)
Graphs	Force vs Displacement
Type of rupture	Adhesive failure at the interface
Pictures	
Observations	Loss of adherence Later, brittle failure of bamboo inside the matrix
Machineries	MTS 100kN Machine servo-hydraulique universelle
Test speed	5 [mm/min]

III. Flexural tests

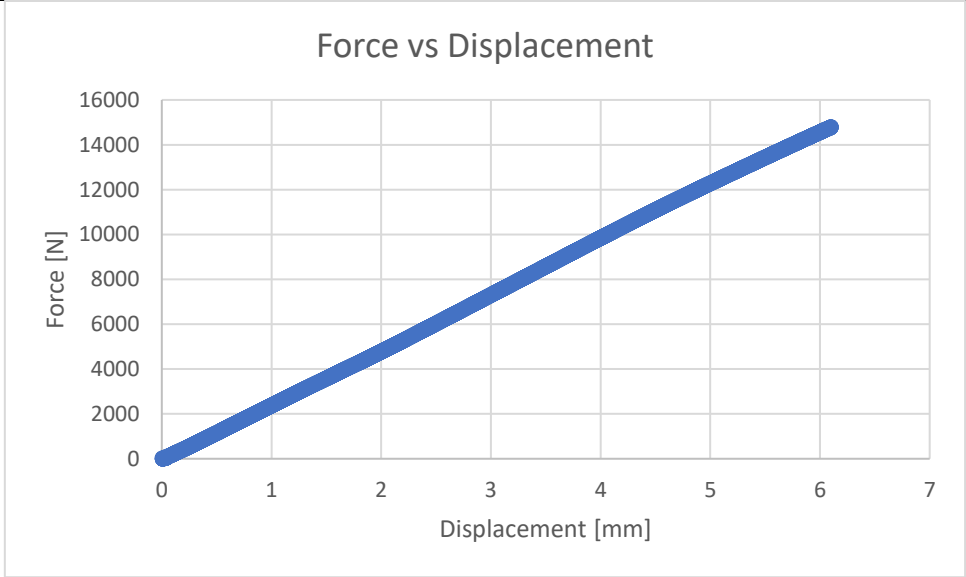
Olivia DEHON (UCL) +32 499 28 91 10 olivia.dehon@student.uclouvain.be <i>Master Thesis – Recycled Plastics</i>				3 points BENDING test on element reinforced with bamboo TESTS laboratory LEMSC (UCLouvain)
Element(s)				2 parallelepiped rectangles with 2 bamboos inside the plastic matrix 1 parallelepiped rectangles with 4 bamboos inside the plastic matrix 1 parallelepiped rectangle with 1 bamboo inside (6x6x30 [cm]) 1 parallelepiped rectangle without bamboo Composition of plastic: PLA + recycled PMMA (anisotropic material, no fibers, no additives)
Dimensions				5 x 5 x 40 [cm] Bamboo : 0,8 - 1 [cm] diameter, nodes +/- each 20 [cm]
Machinery needed				ZWICK + Montage flexion 3 points ($F_{\max} = 100$ [kN]) + capteur
Properties targeted	TEST	# speci	Standard	Explanations
E, flexural strength, overall behavior of the element	FLEXION	4	ISO 178	- Propriétés caractérisants la section de bambous entourée de PLA+rPMMA. Entraxe traverse inférieure de 30 [cm]. Essai de flexion 3 points (avec capteur) jusqu'à la rupture du matériau. Un essai avec 2 bambous à la verticale, un essai avec 2 bambous à l'horizontale, un essai avec 4 bambous, un essai avec 1 bambou. Photo du montage. - Propriétés caractérisants la section de PLA+rPMMA sans bambou Entraxe traverse inférieure de 30 [cm]. Essai de flexion 3 points (avec capteur) jusqu'à la rupture du matériau. Photo du montage.
DRAWINGS				

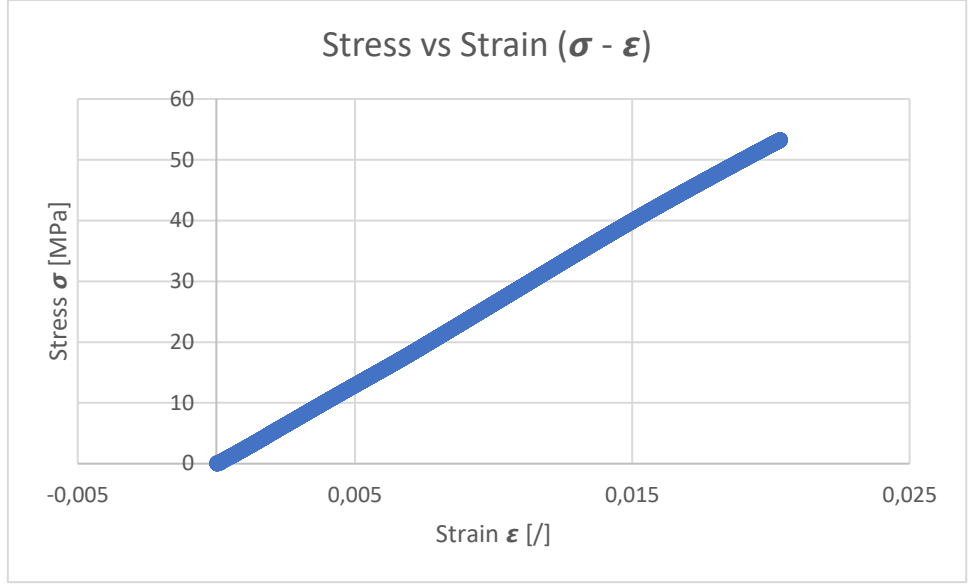


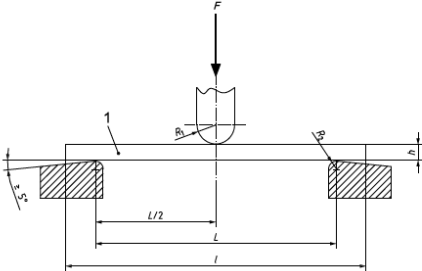
3 points flexural test – PLA/rPMMA without bamboo

Standard	ISO 178
A₀ Cross section of matrix	2500 [mm ²]
B Width	50 [mm]
H Thickness	50 [mm]
L Span	300 [mm]
F_{MAX} Maximum force	14792 [N]
d_{MAX} Maximum displacement	6,099 [mm] (corresponding to F _{MAX})
σ_{fM} Flexural strength	53,2512 [MPa]
ε_{fM} Flexural strain at flexural strength	0,0203 [/]
E_f Flexural modulus	2,62 [GPa]

Graphs

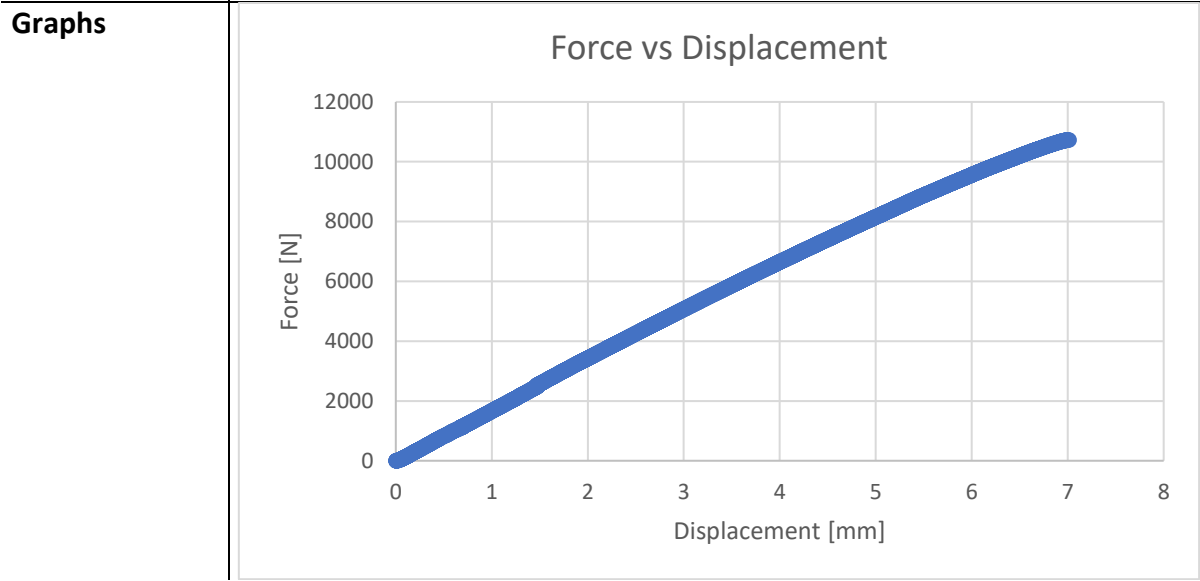




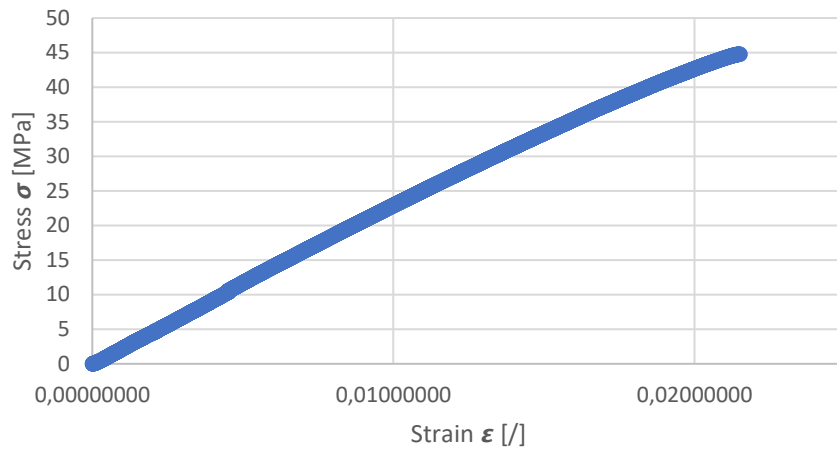
Type of rupture	Brittle rupture	
Pictures		
Test Device		
Observations	Brittle rupture of the material, no plastic deformation	
Machineries	ZWICK 100kN + Montage de flexion 3 ou 4 points (F_{MAX} 100kN)	
Test speed	5 [mm/min]	

3 points flexural test – PLA/rPMMA with 2 vertical bamboos

Standard	ISO 178
A₀ Cross section of matrix	2346 [mm ²]
B Width	51 [mm]
H Thickness	46 [mm]
L Span	300 [mm]
F_{MAX} Maximum force	10732,8 [N]
d_{MAX} Maximum displacement	7,0052 [mm] (corresponding to F _{MAX})
σ_{fm} Flexural strength	44,75 [MPa]
ε_{fm} Flexural strain at flexural strength	0,0215 [/]
E_f Flexural modulus	2,3145 [GPa]



Stress vs Strain ($\sigma - \epsilon$)



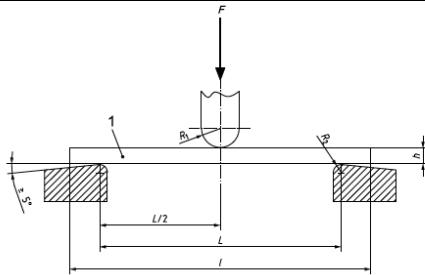
Type of rupture

Brittle failure

Pictures



Test Device



Observations

Brittle failure of the matrix

Machineries

ZWICK 100kN + Montage de flexion 3 ou 4 points (F_{MAX} 100kN)

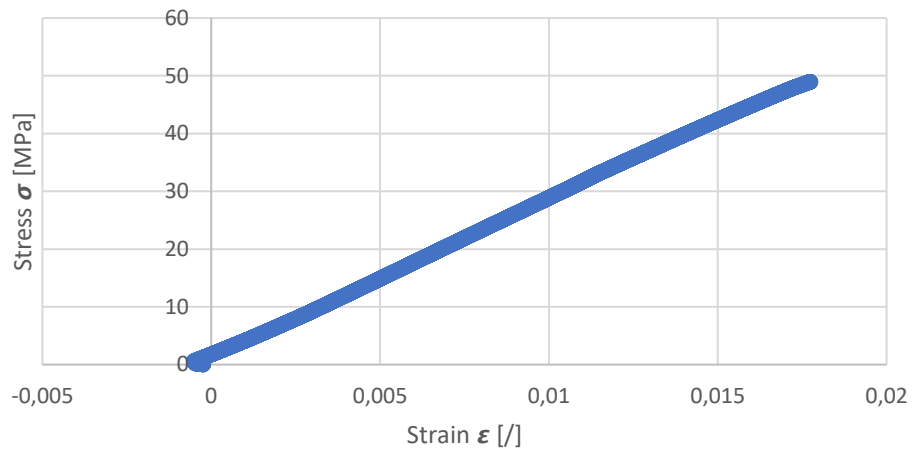
Test speed

5 [mm/min]

3 points flexural test – PLA/rPMMA with 2 horizontal bamboos

Standard	ISO 178														
A₀ Cross section of matrix	2750 [mm ²]														
B Width	55 [mm]														
H Thickness	50 [mm]														
L Span	300 [mm]														
F_{MAX} Maximum force	14960,9 [N]														
d_{MAX} Maximum displacement	5,325 [mm] (corresponding to F _{MAX})														
σ_{fm} Flexural strength	48,96 [MPa]														
ε_{fm} Flexural strain at flexural strength	0,0177 [/]														
E_f Flexural modulus	2,507555455 [GPa]														
Graphs	Force vs Displacement <table border="1"><caption>Data points for Force vs Displacement</caption><thead><tr><th>Displacement [mm]</th><th>Force [N]</th></tr></thead><tbody><tr><td>0,0000</td><td>0</td></tr><tr><td>1,0000</td><td>2992,18</td></tr><tr><td>2,0000</td><td>5984,36</td></tr><tr><td>3,0000</td><td>8976,54</td></tr><tr><td>4,0000</td><td>11968,72</td></tr><tr><td>5,0000</td><td>14960,90</td></tr></tbody></table>	Displacement [mm]	Force [N]	0,0000	0	1,0000	2992,18	2,0000	5984,36	3,0000	8976,54	4,0000	11968,72	5,0000	14960,90
Displacement [mm]	Force [N]														
0,0000	0														
1,0000	2992,18														
2,0000	5984,36														
3,0000	8976,54														
4,0000	11968,72														
5,0000	14960,90														

Stress vs Strain ($\sigma - \epsilon$)



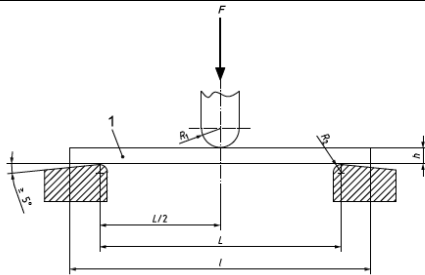
Type of rupture

Brittle

Pictures



Test Device



Observations

Brittle failure of the matrix, no plastic deformation

Machineries

ZWICK 100kN + Montage de flexion 3 ou 4 points (F_{MAX} 100kN)

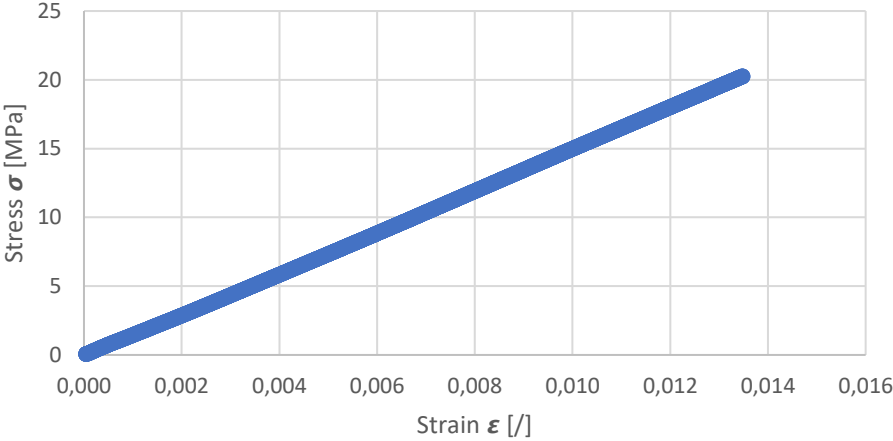
Test speed

5 [mm/min]

3 points flexural test – PLA/rPMMA with 4 bamboos

Standard	ISO 178																						
A ₀ Cross section of matrix	2500 [mm ²]																						
B Width	50 [mm]																						
H Thickness	50 [mm]																						
L Span	300 [mm]																						
F _{MAX} Maximum force	5625,71 [N]																						
d _{MAX} Maximum displacement	4,045 [mm] (corresponding to F _{MAX})																						
σ _{fM} Flexural strength	20,25 [MPa]																						
ε _{fM} Flexural strain at flexural strength	0,0135 [/]																						
E _f Flexural modulus	1,42398 [GPa]																						
Graphs	Force vs Displacement <table border="1"><caption>Data points for Force vs Displacement</caption><thead><tr><th>Displacement [mm]</th><th>Force [N]</th></tr></thead><tbody><tr><td>0,0000</td><td>0</td></tr><tr><td>0,5000</td><td>1250</td></tr><tr><td>1,0000</td><td>2500</td></tr><tr><td>1,5000</td><td>3750</td></tr><tr><td>2,0000</td><td>5000</td></tr><tr><td>2,5000</td><td>6250</td></tr><tr><td>3,0000</td><td>7500</td></tr><tr><td>3,5000</td><td>8750</td></tr><tr><td>4,0000</td><td>10000</td></tr><tr><td>4,045</td><td>5625,71</td></tr></tbody></table>	Displacement [mm]	Force [N]	0,0000	0	0,5000	1250	1,0000	2500	1,5000	3750	2,0000	5000	2,5000	6250	3,0000	7500	3,5000	8750	4,0000	10000	4,045	5625,71
Displacement [mm]	Force [N]																						
0,0000	0																						
0,5000	1250																						
1,0000	2500																						
1,5000	3750																						
2,0000	5000																						
2,5000	6250																						
3,0000	7500																						
3,5000	8750																						
4,0000	10000																						
4,045	5625,71																						

Stress vs Strain ($\sigma - \epsilon$)



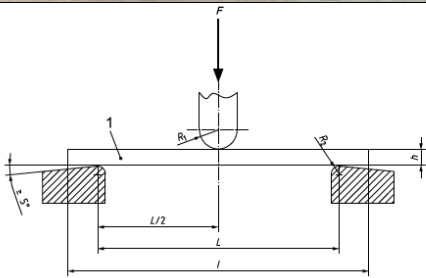
Type of rupture

Brittle

Pictures



Test Device



Observations

Quick and brittle failure

Machineries

ZWICK 100kN + Montage de flexion 3 ou 4 points (F_{MAX} 100kN)

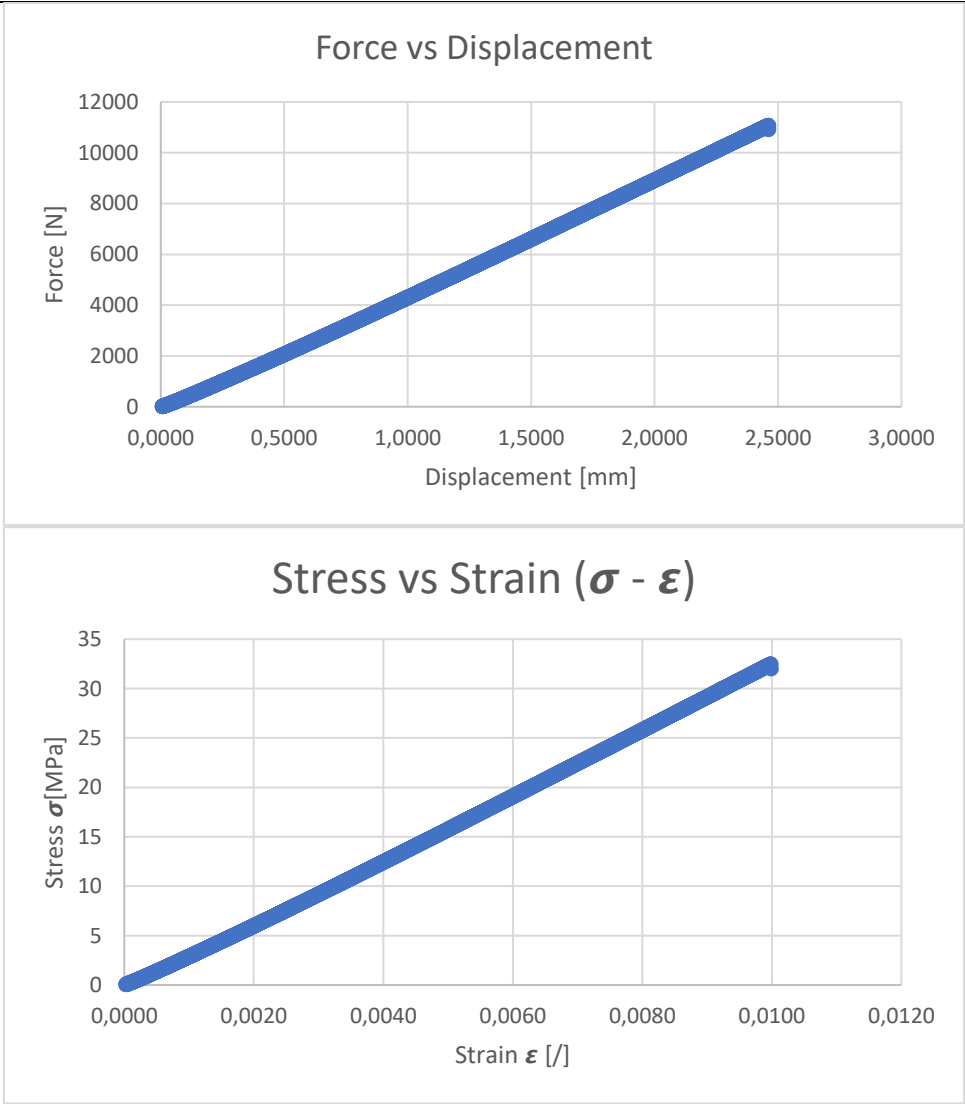
Test speed

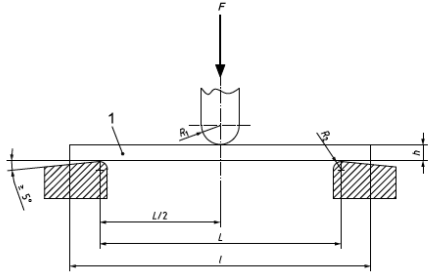
5 [mm/min]

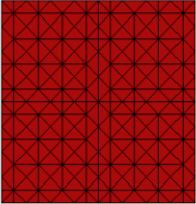
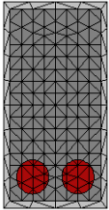
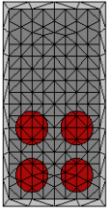
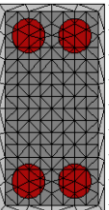
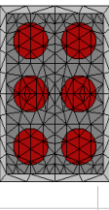
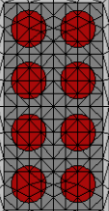
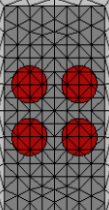
3 points flexural test – PLA/rPMMA with one central bamboo

Standard	ISO 178
A ₀ Cross section of matrix	2703 [mm ²]
B Width	51 [mm]
H Thickness	53 [mm]
L Span	280 [mm]
F _{MAX} Maximum force	11076,3 [N]
d _{MAX} Maximum displacement	2,4543 [mm] (corresponding to F _{MAX})
σ _{fm} Flexural strength	32,473 [MPa]
ε _{fm} Flexural strain at flexural strength	0,0099 [/]
E _f Flexural modulus	3,099 [GPa]

Graphs



Type of rupture	Brittle
Pictures	
Test Device	
Observations	Brittle failure in the matrix, no plastic deformation
Machineries	ZWICK 100kN + Montage de flexion 3 ou 4 points (F_{MAX} 100kN)
Test speed	5 [mm/min]

LENGTH: 3 [m]	PLA/rPMMA		Displacement	Resultant Force	SLS		Comments	SECTIONS
	ULS							
Sections	ϵ_{MAX} /	σ_{MAX} MPa	s_center m	F_center kN	s_center m	F_center kN		
Without bamboo 0,16x0,24 [m²]	0,00915828	34,374093	-0,0638271	124,4124	-0,0155621	29,62435	The SLS state is not verified --> change the section	
section 0,3x0,3 [m²]	0,00317826	11,929064			-0,0045208	31,5222	4,5 [mm] is lower than 6 and thus acceptable	
2 lower bamboos 0,16x0,24 [m²]			-0,0468037	124,343	-0,0114112	29,55501	The SLS state is not verified --> change the section	
PLA/rPMMA								
>> Top	-0,0082013	-30,782263						
>> Bottom	0,0054325	20,389976						
Bamboos								
>> Bottom	0,00285181	51,047438					ULS in bamboos is not verified	
section 0,16x0,3 [m²]					-0,0056842	29,9081	5,6 [mm] is lower than 6 and thus acceptable	
Bamboos								
>> Bottom	0,00218208	39,059305						
4 lower bamboos 0,16x0,24 [m²]			-0,0453669	124,2737	-0,0110352	29,48568	The SLS state is not verified --> change the section	
PLA/rPMMA								
>> Top	-0,0076147	-28,580393						
>> Bottom	0,00559448	20,997952						
Bamboos								
>> Middle	-0,0010101	-18,080686					ULS in bamboos is not verified	
>> Bottom	0,00309418	55,385777						
section 0,16x0,3 [m²]					-0,0056663	29,83877	5,6 [mm] is lower than 6 and thus acceptable	
Bamboos								
>> Middle	1,26E-04	2,252896						
>> Bottom	0,00214357	38,369963						
4 bamboos at extremities 0,16x0,24 [m²]			-0,039605	124,3188	-0,0096283	29,53079	The SLS state is not verified --> change the section	
PLA/rPMMA								
>> Top	-0,0057546	-2,416909						
>> Bottom	0,00576235	2,420187						
Bamboos								
>> Top	-0,0035746	-89,507019					ULS in bamboos is not verified	
>> Bottom	0,00358237	89,70243						
section 0,16x0,3 [m²]					-0,0046658	29,88388	4,6 [mm] is lower than 6 and thus acceptable	
Bamboos								
>> Top	-0,0024883	-62,307247					ULS in bamboos is not verified	
>> Bottom	0,002492	62,399659						
6 bamboos 0,16x0,24 [m²]			-0,0307846	124,2043	-0,0074616	29,41634	The SLS state is not verified --> change the section	
PLA/rPMMA								
>> Top	-0,004474	-16,792517						
>> Middle	-0,000174	-0,6531555						
>> Bottom	0,00447766	16,806152						
Bamboos								
>> Top	-0,0027796	-49,754854					ULS in bamboos is not verified	
>> Middle	1,82E-06	0,03251484						
>> Bottom	0,00278323	49,819883						
8 bamboos section 0,16x0,3 [m²]			-0,0143596	124,4881	-0,0035045	29,70009	3,5 [mm] is lower than 6 and thus acceptable	
PLA/rPMMA								
>> Top	-0,0026239	-9,848187						
>> Middle	-0,0002081	-0,781121						
>> Bottom	0,00262516	9,853092						
Bamboos								
>> Top	-0,0018783	-33,620728						
>> Top Middle	-0,0006257	-11,199111						
>> Bottom Middle	0,00062696	11,222506						
>> Bottom	0,00187956	33,644122						
4 bamboos MIDDLE section 0,16x0,3 [m²]			-0,02904	124,6268	-0,0071126	29,83877	7,1 [mm] is acceptable as the worst case as been u	
PLA/rPMMA								
>> Top	-0,0053059	-19,914901						
>> Middle	-0,0004203	-1,577566						
>> Bottom	0,00530973	19,929186						
Bamboos								
>> Top Middle	-0,0012647	-22,6388					ULS in bamboos is verified	
>> Bottom Middle	0,00126854	22,706928						

COMPANY / ENTITY I (Location) <i>via company/entity</i>	Contact person (Title/Resp.)	Relationship through:	Comments	EEmail Web site
SUEZ (Étalle, BE)	Christine Levêque Angèle Abou'ou Denis Lacave (Head of Transformation Unit Plastics)	Meeting and calls	Meeting with Prof. Latteur and Prof. Almeida and Innovateurs wallons. Connections with other companies to get materials. Specialists in recycling	christine.leveque@suez.com; angele.abouou@suez.com; denis.lacave@suez.com
Novares (Lens, FR)	Luc Dornier (Group Product Dev. - Senior Vice President) Gregory Spingler Nicolas Dargere	Mails, call, mails and calls	Product specialists No possibilities to create specimens directly in LENS. > contact recycling companies : Cimap (UMons), Galloo, Technocoumpound, Recylex, Ravago > contact companies for specimens : Certech, VKC/Centexbel, VITO. « À ma connaissance, les PLA et PS ne sont pas utilisés dans le domaine automobile par rapport à leur propriétés thermo-mécaniques. Les PC sont employés, principalement pour des pièces d'aspect (brillantes, résistantes à la rayure). Je ne suis pas spécialiste du sujet, mais je crois que les seuls PC recyclés employés dans l'automobile sont des mélanges PC+ABS recyclés. Cependant, je ne serai pas surpris qu'il y ait déjà eu beaucoup de travaux sur les PS et PC recyclés. »	ldornier@novaresteam.com
Eco-oh! (Houthalen, BE)	Karel Janssen Luc Schepers	Mails, mails and meeting	Provided me with mixed plastics granules, Provided me with different rejected elements, among others the beam for pre-test	karel@eco-oh.com; luc.schepers@eco-oh.com
UMons CIRMAP <i>Centre of Innovation and Research in Materials & Polymers</i> (Mons, BE) <i>via Novares</i>	Jean-Marie Raquez, Professor Michel Voue	Mails, calls and meetings	Help to elaborate the composition , specimens and tests in their laboratories at UMons possible but laboratories unavailable to students	jean-marie.raquez@umons.ac.be
CSTC - Centre Scientifique et Technique de la Construction (Ottignies, BE) <i>via Prof. Jean-Marie Raquez</i>	Emmanuel Cailleux	Mails, calls and meetings	To validate the scientific approach and application in construction. Conclusion: protocol to develop a new material is good.	emmanuel.cailleux@bbri.be
UCLouvain LEMSC Laboratoire essais mécaniques, structures et Génie civil	Catherine Doneux (Head of LEMSC) Alex Bertholet, Christophe Bayar Quentin Mestrez, Vincent Destoop	Mails and meetings	Pre-tests: cutting of the beam, flexion test on beam. Tests on the two new materials.	catherine.doneux@uclouvain.be; alex.bertholet@uclouvain.be; christophe.bayart@uclouvain.be quentin.mestrez@uclouvain.be;
UltraPolymers (Arendonk & Lommel, BE) <i>via SUEZ</i>	Stef Van Camfort	Mails and meeting	Raw Recyled Materials : provided us with some recycled PS regrind (oxidised) and some PMMA prime material. La société Ultrpolymers distribue les plastiques recyclés, fabriqués entre autres dans l'usine de QCP à Gelen.	stef.vancamfort@ultrapolymers.com
RESINEX (Arendonk & Lommel, BE) <i>via UltraPolymers</i>	Mireille Snoeckx, Claire Borgmans	Mails and calls	Provided us with PLA, PLA NatureWorks 2003D (bag 25 kg)	mireille.snoeckx@resinex.be; Claire.Borgmans@resinex.com; https://www.resinex.be/fr/industries/bioplastics-current-important-trend.html?full
DHK (Châtelineau, BE) <i>via Philippe De Groote (Certech)</i>	Philippe Dubois	Call + mails	They recycle Plexiglass → provided us recycled PMMA rPMMA et rPC et PC issus de la déconstruction des serres (écailles = flakes → directement utilisables dans les machines de mise en œuvre des matériels polymères) rPMMA flakes (crushing the panels of roofs of greenhouses coming from the Netherlands) --> 5 + 25 kg	chatelineau@dhk.be; p.dubois@dhk.be
GOVAPLAST (Alken (Hasselt), BE)	Axel Martin (General Sales manager), Hans De Bruycker (Chemical Engineer)	Mails, calls and meetings	Can provide me with large elements (ask from the list) but cannot create small specimens. Injection Moulding of larger elements (beams, ...) if I provide 200-500kg of material Provided them with the formworks. Able to cast my formworks with the composition PLA/rPMMA through the extruder of their lab. They have raw recycled materials or can have some from their suppliers (but problems of delay due to Covid19).	axel.martin@govaplast.com; hans.debruycker@govaplast.com
BEOLOGIC / INNOLOGIC (Zwevegem, BE) <i>via UltraPolymers</i>	Niels Everaert (Product Development Engineer Jippe Holvoet	Mails and calls, injection	Injection for the small samples ; rPMMA and PLA provided by us. Can help to do the tests in labs, even during lockdown --> have done test ISO 178 Flexural test on small injected specimens with composition 50- 50 weight distribution	evie@beologic.com niels@innologic.be

COMPANY / ENTITY II (Location) <i>via company/entity</i>	Contact person (Title/Resp.)	Relationship through:	Comments	EEmail Web site
Van Werven Recycling Plastics (Lanaken, BE) <i>via Fast-Plus</i>	Raoul Troisfontaine, Willem van de Wetering, Peter Brughmans (Consultant)	Mails, samples collected	Received granules of PVC regrind, PVC micronized, and HDPE. Recycled ABS/PS & PC regrind, but NO PMMA : this is a product we can't process because recycled material will never be clear enough to produce a clear PMMA again. PAS besoin des échantillons finalement (prévenus)	r.troisfontaine@vanwerven.nl; w.vandewetering@vanwerven.nl sales.plasticrecycling@vanwerven.nl peter.brughmans@inter-solution.be;
Heathland (Utrecht, NL) <i>Suppliers of Govaplast</i>	Simon van der Heijden	Mails	PMMA regranulaat (=regranulé) of PMMA maalgoed (glitter = paillettes) (=rebroyé) ==> PMMA extrusiekwaliteit = qualité d'extrusion (kleur : smoke transparant = fumée transparente) WILL SEND BY POST, eventually did not want to send during confinement	simon@heathland.com http://www.heathland.com/?page_id=8&lang=en
Bamboo Concept/ Green Steel Concept (Seraing, BE)	Marc Raison	Call + Mail	Bamboo 2 and 8 cm diameter --> has to look for in stock Variété : la Guadua Angustifolia, ou "acier végétal", la plus résistante au monde! Traité de manière complètement biologique → 3 cuissons dans bain d'eau chaude salée (en Colombie directement) Cela sert de fongicide et permet de raffermir les fibres → solidité à toutes épreuves.	admin@bamboo-concept.com
Certech (Seneffe, BE)	Catherine Henneuse Philippe De Groote (Materials Technology Coordinator) Clément Lemenu (in charge of project MMAtwo)	Mails and calls	Possible collaboration to create specimens, ... BUT have to PAY Projet MMAtwo avec notamment le Certech Recyclage des PMMA en fin de vie pour en faire un nouveau matériau: matière première de haute qualité	catherine.henneuse@certech.be; Philippe.DeGroote@certech.be; http://www.innovatech.be/plexi-glas-pmma-recyclage-dechets/Clement.Lemenu@certech.be;
UCLouvain BSMA Bio- and Soft Matter	Margaux Benoit Vincent Destoop (Research Engineer) Pascal Van Velthem (in charge of the extruder) Martial Kuete (Researcher on PET)	Mails / Meetings		margaux.benoit@uclouvain.be vincent.destoop@uclouvain.be pascal.vanvelthem@uclouvain.be naima.salle@uclouvain.be wael.ballout@uclouvain.be martial.kuete@uclouvain.be
EPBP European PET Bottle Platform	Manon Marlier	Mails	Flakes, pellets and micronisats (powder) of PET; PMMA = plastique technique → difficile d'en trouver car pas bcp recycleur qui en produisent en grande quantité; rPS → difficile à trouver Peuvent fournir du rPET, rPP et rHDPE	mmarlier@plarebel.be Philippe.Alen@FostPlus.be Arn.Malef@FostPlus.be
RAVAGO - parent company of UltraPolymers (Arendonk & Lommel, BE) <i>via Novares</i>			Call Lio from Laboratories → no needs because they just have lab to verify their plastics, they are just recycling (info from UltraPolymers) Pas de PLA → see with Resinex	
Innovateurs Wallons <i>via SUEZ</i>	Patrick Verheyden Frédéric Stachura Panayotis Kytidis	Meetings	Develop lumbers in polyolefins. Were present in our meeting with Suez.	decorativefloors2@gmail.com fred_stachura@yahoo.fr pkexpert@pkexpert.org
Galloo (Halluin, FR (Lille)) <i>via Novares</i>	Helène Dhordain (Responsible R&D + laboratories) Vincent Hauspied (Directeur des ventes)		No possibilities to help more than equipments at UCL (dumb-bell specimens) > contact : Ecole des Mines de Douai (super equipped + researches)	Helene.Dhordain@galloo.com Vincent.Hauspied@galloo.com
TOTAL (linked to Galactic for PLA) <i>via Margaux Benoit</i>	Denis Mignon (Professor)	Mails	Professor at UCLouvain & Head of Polymers Control, Modelling & Simulation Group at TOTAL (Feluy)	denis.mignon@total.com; denis.mignon@uclouvain.be
Galactic (Celles, BE)	Luna Aslan (Co-founder Start-up NOOSA (fibre textile PLA))	Mails	No similar compositions	luna.aslan25@gmail.com https://www.lactic.com/en-us/home.aspx
VKC Centexbel (Gand, BE) <i>via Novares</i>	Isabel De Schrijver	Mails + call	Researches on wood fibers reinforced plastic (not relevant for construction) (Fibers reinforced → not a lot in literature) They have some raw materials if I need. Researches on Polyolefins + PA/PS/PET > contact : wood.be they have a project on developing a method to analyze the long-term behavior/effects	ids@centexbel.be evw@vkc.be

COMPANY / ENTITY III (Location) <i>via company/entity</i>	Contact person (Title/Resp.)	Relationship through:	Comments	EEmail Web site
Materia Nova UMONS Innovation Center (Mons, BE)			BIOMAT Issue: no link with my thesis. MACOBIO Issue: no link with my thesis.	Audrey.tanghe@materianova.be Jevgenij.lazko@materianova.be http://www.materianova.be/index.php/biomat/ http://www.materianova.be/index.php/macobio/ http://www.materianova.be/?lang=fr
Cirsee (Paris, FR) <i>via SUEZ</i>	Marie-Lise Sablayrolles (Project Manager R&D Waste Recovery)	Mails	Will tell her teams and come back. No similar researches.	marie-lise.sablayrolles@suez.com
REPROCOVER (Verviers, BE) <i>via Peter Brughmans</i>		Call	Recyclage de thermdurcissables (bakélite, polyester, epoxy) pour canivaux, chambre de visite, ... TOUT le préfab des voiries. Collaboration possible si on veut développer dans les thermdurcissables. Recherches sur dalles de parking mais rien de structurel.	
Plas Eco (Verson, FR)		Call	Mobilier de jardin (bancs, passerelles, carports, ...) RENFORCÉS (structure acier, ...) https://plaseco.fr/plastique-recycle/?cn-reloaded=1	
European Bioplastics (Berlin, GER) <i>via BiNa</i>		Mails	European bioplastics : STAR-ProBio (Horizon 2020, ...), BiNa (base de données) STAR-ProBio Issue: The analysis of selected case studies on construction materials BiNa Issue: At IKK we conduct various tests on plastics and fiber-reinforced plastic composites. Nothing heard about the compositions. IfBB Issue: no compositions like mine.	info@european-bioplastics.org Madina Shamsuyeva shamsuyeva@ikk.uni-hannover.de; sebastian.spierling@hs-hannover.de; hannah.behnsen@hs-hannover.de; Florian Bittner bittner@ikk.uni-hannover.de Lisa.Mundzeck@hs-hannover.de; info@ifbb-hannover.de https://www.ifbb-hannover.de/en/about-us.html
Plastiqua (Verviers, BE)	Jean-Claude Moreau (Directeur Général)	Call	Envoyer email pour aller chercher BACS en plastiques recyclés.	

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École polytechnique de Louvain

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