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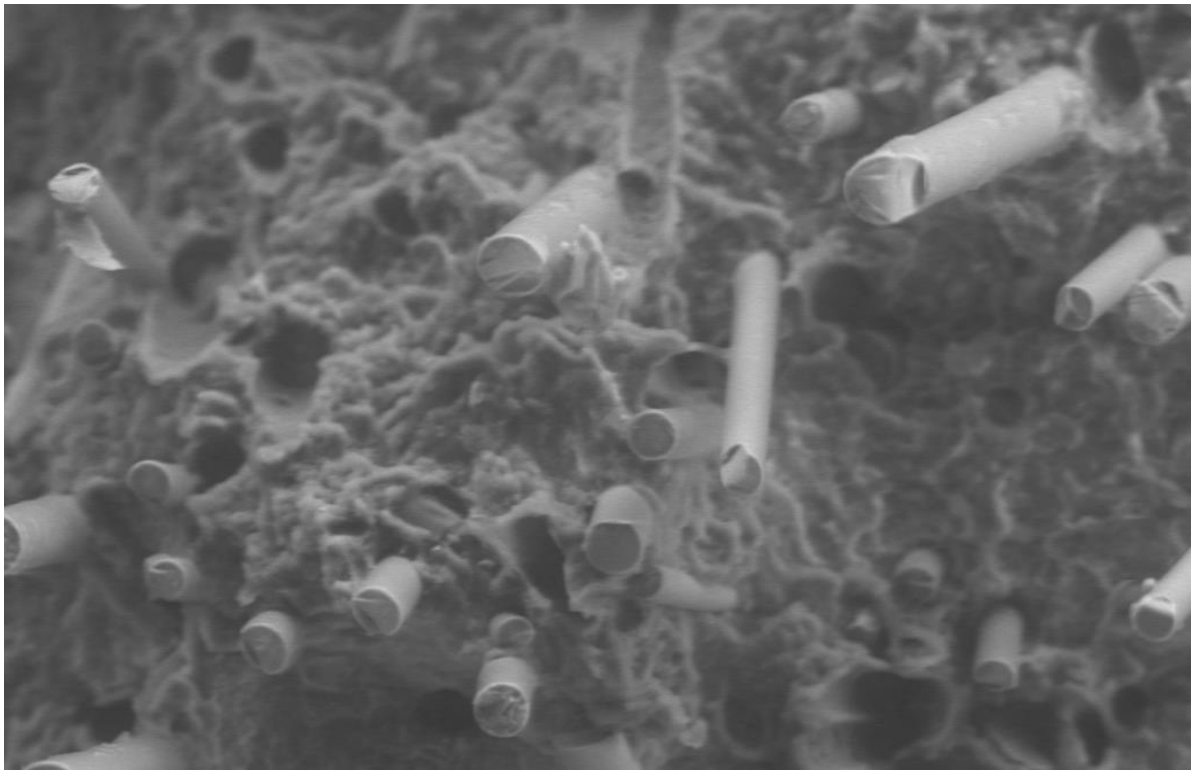

Recycling and upgrading of glass fiber reinforced polypropylene composites

Studying the impact of recycling and potential for upgrading automotive instrument panel carriers

Master's thesis in Materials Engineering

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Recycling and upgrading of glass fiber reinforced polypropylene from automotive instrument panel carriers

Studying the impact of recycling on material properties and the potential for upgrading

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Cover:

SEM micrograph of the fracture surface on a glass fiber-reinforced polymer composite.

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SUMMARY

With increased societal awareness, an emphasis has been created over the need for sustainable, circular solutions. The automotive industry has tried to address these concerns with an increased focus on the end-of-life of vehicles. Mechanical recycling of components has been one of the routes of interest that has been highlighted in this work where newly produced instrument panel carriers produced by Volvo Cars, made of 20 % glass fiber-reinforced polypropylene composites, were recycled three times to study the effect of the processing on mechanical properties. The instrument panels were mechanically recycled by milling, compounding and subsequently injection moulding into test bars. Fiber lengths were measured after each processing step, and the mechanical properties were evaluated. The length of the glass fibers reduced after each processing step, especially after compounding, along with a reduction in all mechanical properties. To restore some of the properties lost during recycling, an upgrading step was investigated. In this step, the recycled instrument panels were upgraded in separate batches by adding three types of additional glass fibers: virgin fibers, post-industrial residual glass fibers, and post-consumer residual glass fibers, respectively. Two different types of impact modifiers were also tested.

In addition, an instrument panel carrier from an end-of-life vehicle was also recycled once to observe its mechanical properties and compare it to the newly produced instrument panel carrier processed in a similar manner. The results showed similar mechanical properties, except that the end-of-life panel had a lower strain at break. An oxidative-induction time (OIT) measurement also showed a lower level of antioxidants, and an oxidative-induction temperature measurement showed a higher degree of matrix degradation in the end-of-life panel.

The study found that recycled glass fiber-reinforced polypropylene can be re-used and made into new useful products with small additions of new material, such as virgin glass fiber or impact modifiers. Further research into the subject should study the effects of the interface between recycled glass fibers and the polymer matrix, as these results were below expectations in this study.

Keywords: Glass fiber, Polypropylene, Recycling, Upgrading, Impact modifier

Table of Contents

List of Abbreviations

Abbreviations	Explanations
PP	Polypropylene
GF	Glass fiber
PPGF	Glass fiber-reinforced polypropylene
PMC	Polymer matrix composite
PIR	Post-industrial residue
PCR	Post-consumer residue
MFI	Melt Flow Index
SEBS	Styrene-Ethylene-butylene-Styrene
AzPPGF	Arizona panel PPGF
IP	Instrument panel
MAPP	Maleic anhydride-grafted Polypropylene
SEM	Scanning electron microscopy
POE	Polyolefin elastomers
IM (IM1, IM2, IM3)	Injection molding cycle #
C (C1, C2, C3)	Compounding cycle #
M (M1, M2, M3)	Milled instrument panel carrier cycle #
Virgin GF	Virgin glass fiber
PIGF	Post-industrial glass fiber
PCGF	Post-consumer glass fiber
OIT	Oxidative-induction time
TGA	Thermal gravimetric analysis
ELV	End-of-life vehicle

1 Introduction

Out of all plastics produced worldwide, only about one tenth is recycled. The rest is either incinerated or ends up in landfills (Parker, 2018). However, there are more laws and initiatives being put in place to make the use of plastic more sustainable by decreasing unnecessary usage and increasing recyclability. As an example, the European Union launched a directive in 2019 which bans single-use plastics entirely where other alternatives are available (European Parliament, 2019). These initiatives have led more companies to start switching towards a circular approach with a strong focus on sustainability and recycling, and Volvo Cars is one of these companies. Volvo Cars recently set an aim for using 25 % recycled plastics in every new car from 2025 (Volvo Cars, 2018) and is, together with several other companies, a contributing partner to the RISE-led research project called Sustainable Vehicle Interior Solutions (SVIS). The project receives financial support from the Strategic Vehicle Research and Innovation (FFI) program funded by Vinnova, Swedens' Innovation Agency (Sustainable Vehicle Interior Solutions, 2022).

Circular use of plastics is becoming more important as sustainability- and environmental related issues are receiving more focus. The focus is threefold, as it comes from consumers, legislative bodies such as the EU, and producers such as Volvo Cars alike. The benefits of circular use of plastics can be seen in the direct impact it has on lowering emissions from production. According to a report by the Association of Plastic Recyclers, recycled polypropylene lowers greenhouse emissions by 71 % (Franklin Associates, 2018). However, creating closed recycling loops is easier in some industries than in others. The packaging industry has the advantage of having collection systems in place and sorting units that are financed by the producers' responsibility fees. This makes the recycling process easier, as the different packaging materials are sorted into rather pure fractions that can be washed and mechanically recycled. For other industries, such as the automotive industry, the complexity of recycling plastic parts is high.

The plastics from vehicles are generally either mechanically recycled, chemically recycled or incinerated for energy recovery. While some of the components of a car are made from only one type of plastic, others are not. The material in these components thus must be separated before being recycled if the goal is to obtain a homogenous material. This can be a complex, time consuming and expensive operation. Reported attempts made by a dismantler to recycle the seat foam and other plastics from vehicles were deemed too difficult, too labor intensive and the obtained material amounts were deemed too small (B.J. Jody, 2010).

A way to further facilitate recycling of plastics in vehicles is to design for recycling. If components are designed in a way that makes them easier to disassemble and separate, the economic aspects of disassembling and separating plastic materials in the car would change. If for example an instrument panel could be effectively disassembled and separated in the future, up to 11 kg of plastics could be obtained for recycling. This could potentially be a source of high-quality plastics to use for recycling in new vehicles.

This degree project studies the effect of mechanical reprocessing on the properties of a polypropylene glass-fiber composite obtained from vehicle instrument panels, and how the potential negative effects of the reprocessing can be negated. To improve the properties of the reprocessed materials, two different types of impact modifiers, virgin polypropylene, maleic anhydride polypropylene (MAPP) and three different types of

glass fibers are added in various amounts. Other experiments are also evaluated, such as sieving and discarding small particles. The materials are then evaluated against each other and against real life automotive component material specifications, and their usefulness is explored.

The influence of the critical fiber length on the strength of the composite is evaluated using the Kelly-Tyson model. These values are, in turn, compared to strength values obtained using the Halpin-Tsai model. The strength values obtained through the Kelly-Tyson and the Halpin-Tsai models are then compared with the experimental values.

1.1 Aim

This degree project is a part of the SVIS project. The aim is to study the recyclability of glass fiber reinforced PP by characterization of the material and to match the recycled material to a specification of another automotive component. This is to be done through upgrading with additives or other methods. Included in this diploma work is also determining mechanical and physical properties of materials and material property development following processing.

1.2 Limitations

- The composite studied in this degree project is glass-fiber reinforced polypropylene (PPGF). Other materials included in the instrument panel such as acrylonitrile butadiene styrene (ABS) plastic are therefore removed before the material is studied.
- The amount of material is limited, constraining the amount of testing available.
- The work is conducted over 20 weeks and the complexity of the material characterisation and upgrading testing is planned with this considered.

2 Theory

When recycling polypropylene glass-fiber (PPGF) material, the biggest challenge is to ensure that the reprocessing has minimal effect on the composite properties as they can vary based on the aspect ratio of the fibers, the average fiber length and its distribution, and finally the interface between the polypropylene matrix and glass fibers (Kossentini Kallel, 2018) (Kang, 2021) (Evens, 2019) (Egbers, 2008) (Lekube, 2019). However, the expected loss in performance when recycling this material can be limited by the addition of additives such as stabilizers, antioxidants, compatibilizers, virgin or recycled fibers and impact modifiers (Mario Pietroluongo, 2020) (El Hajj, 2021) (Y.S. Thio, 2002) (M. Mihalic, 2019) (Rodríguez-Guadarrama, 2021). In this way, the materials' usefulness can be extended, as opposed to being incinerated.

Mechanical processing, including compounding and injection molding, reduce average fiber length which in turn lead to reduced material properties (Evens, 2019) (Egbers, 2008) (Lekube, 2019). The critical fiber length (L_c) plays an important role when it comes to strength in composite as it is the minimum length up to which a single fiber can sustain its maximum strength under load. The critical fiber length is given as:

$$L_c = \frac{\sigma_f D}{2\tau}$$

where D is the mean fiber diameter, σ_f is the tensile fiber strength and τ is the interfacial shear strength. The critical fiber length can be reduced if the interfacial shear strength is high. Usually, a fiber whose length is lower than that of the critical fiber length, $L < L_c$, would result in the fiber debonding and being pulled out of the matrix which means that the reinforcing effect is poor. It is therefore important to have fiber length equal to or greater than the critical fiber length to maintain effective stress transfer in the composite.

Processing and recycling PPGF leads to fiber breakage and thermal aging of the PP matrix. Usually in PPGF composites, the fiber length and matrix crystallinity influence the mechanical properties to a higher degree than degradation of the PP matrix, both of which might occur to varying degrees during recycling (Kossentini Kallel, 2018). Another factor that needs to be addressed is the importance of strong adhesion between fiber and matrix. Sizing compounds and compatibilizers have been commonly used to address this issue as they help improve adhesion, compatibility and reduce the melt viscosity and fiber attrition, thereby improving processability (Youngjae Yoo, 2011). In the case of reprocessing, using a straight screw configuration with no, or few, mixing elements is important as this helps preserve the fiber length to a higher degree as screws with mixing elements lead to more fiber breakage (Guan Gong, 2016). Furthermore, a relatively high temperature can be chosen to lower melt viscosity and help reduce fiber breakage in the polymer melt, due to shear forces (Kossentini Kallel, 2018).

In PP composites, several additives can be used to improve mechanical properties or maintain pre-existing properties. In terms of improving the impact strength in PP, additives such as elastomers and calcium carbonate, CaCO3, have been attempted with promising results (Y.S. Thio, 2002) (Rodríguez-Guadarrama, 2021). However, the studies found that there was always a trade-off between the stiffness and impact strength (Mihalic M, 2019). Another way to improve the mechanical properties of recycled PP composites is to add virgin material i.e., either virgin PP, virgin GF, or both. The fiber

length of added virgin fibers plays a role in the extent of improvements obtained (Kang, 2021). To facilitate better integration between the virgin fiber and the matrix, coupling agents such as MAPP can be added (Åkesson, 2013).

During recycling the initial product must be milled or crushed first to reduce it into granulates. The granulates have a large spread of particle sizes from the size of the mesh used during milling down to microscopic particles. A study investigated removing the smallest particles by sieving, around 7 wt%, from the milled granulate, reported an increase in strength and stiffness (Vojtech Senkerik, 2016).

3 Materials

This bullet point list describes all the different materials used in the project, giving their origin when known, their important properties and their recommended uses by their manufacturers when applicable.

- **Newly produced instrument panel (PPGF)**
  From a subcontractor to Volvo Cars, these new instrument panel from production are not coated with polyurethane foam or skin and comes free from ventilation shafts and consoles made from other materials. This is the main material studied in the project. It has a glass fiber content of 20 wt%.

- **End-of-life instrument panel (AzPPGF)**
  From a six-year-old vehicle, this end-of-life instrument panel is coated with polyurethane (PUT) foam and has ventilation shafts and consoles assembled to it. Its geometry is essentially the same as the newly produced instrument panel.

- **Virgin glass fiber (Virgin GF)**
  From a subcontractor to Volvo Cars, this 60 wt% glass fiber masterbatch is used to produce new instrument panels and are the fibers used to produce the tested instrument panels. It's further used here in the upgrading. The virgin glass fibers had a mean diameter of 20 μm and a length of 20 mm.

- **Post-industrial glass fiber (PIGF)**
  From SAERTEX, these post-industrial glass fibers intended for weaving had a mean diameter of 15 μm and a mean length of 15 cm.

- **Post-consumer glass fiber (PCGF)**
  Origin unknown, these post-consumer glass fibers come from boat hulls made from thermoset glass fiber composite. The fiber content in the composite was 32 wt% and the matrix was removed by incineration at 650 ℃ for four hours. These glass fibers had a mean diameter of 15 μm and varying lengths of <10 mm.

- **Virgin polypropylene (Subcontractor – Volvo Cars)**
  This virgin polypropylene comes from a subcontractor to Volvo Cars, and it is used to produce masterbatches of 60 wt% PIGF and 60 wt% PCGF.

- **Polyolefin elastomer (POE)**
  This impact modifier comes from The Dow Chemical Company, grade Engage 11547. It is a polyolefin elastomer with a melt flow rate of 5 g/10min. Its recommended use is in injection molded polyolefin compounds and the automotive industry in general.

- **Styrene-ethylene-butylene-styrene (SEBS)**
  This impact modifier comes from Dynasol Group, grade Calprene H6180X. It is an 85/15 ethylene-bytylene/styrene thermoplastic co-polymer, with a melt flow rate of 10 g/10min. Its recommended use is, among others, technical compounding.

- **Maleic anhydride-grafted polypropylene (MAPP)**
  Eastman G 3015, produced by Eastman Polymer, maleic anhydride grafted polypropylene (MAPP) is a compatibilizer which is used to facilitate good adhesion between the fibers and the matrix.

3.1 Materials preparation

The instrument panel, as it looks when disassembled, is seen in Figure 1. When handling the end-of-life panel, the different parts were separated to obtain the desired material, see part 2 in Figure 1. The other two parts, part 1 and part 3, are made from other materials and are thus discarded.

The 10 instrument panels used in the reprocessing and upgrading section were delivered as part 2 in Figure 1 without any polyurethane foam or skin. The instrument panels needed to be reduced in size for use in the compounder. A band saw was used to cut 10 instrument panels into bits approx. 10x10 cm in size. These pieces were run through a Rapid 150 series milling machine (Rapid Granulator) which reduced them into granulates roughly 5x5 mm in size.

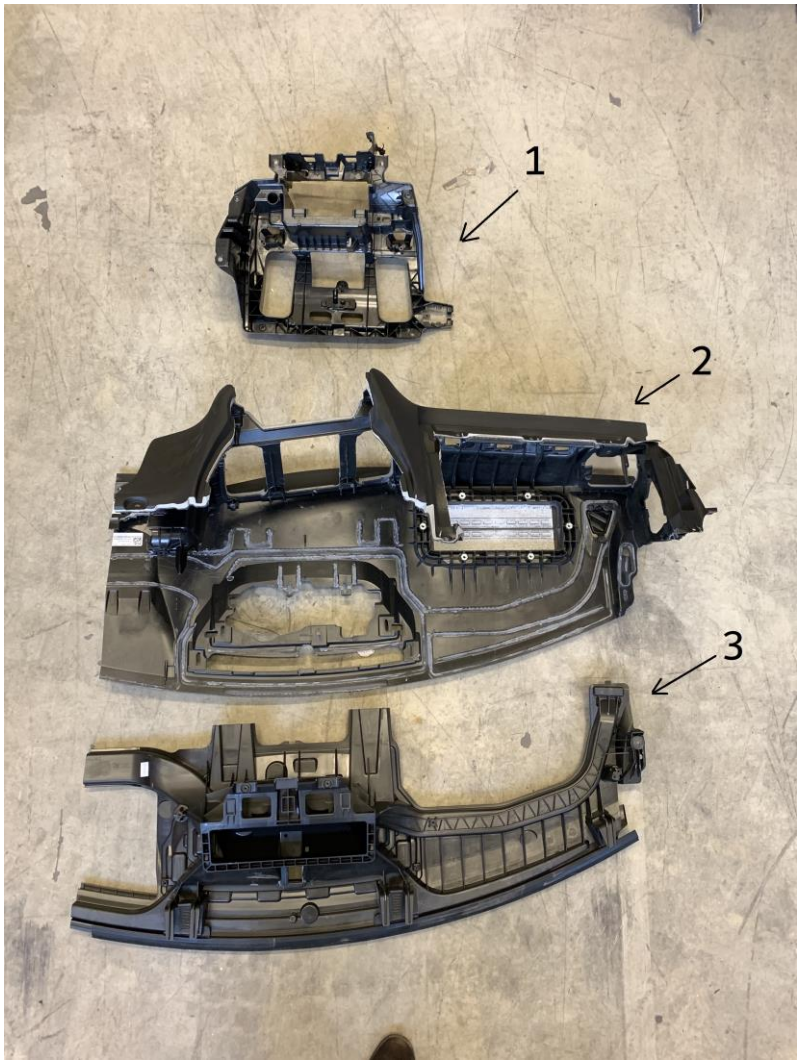


Figure 1 - Parts of the instrument panel. The middle part, 2, is the same IP part which is reprocessed from other IPs in the project

A complete end-of-life (ELV) instrument panel had been mounted in a vehicle in Arizona, United States of America, for six years before being dismounted. The instrument panel contained several components fastened to each other with glue and metal clips, such as a console and cooling ducts, see part 1 and part 3 in Figure 1 respectively. It also contained polyurethane (PUT) foam glued on top of the panel, visible in part 2 in Figure 1.

The feasibility to manually remove residual materials, such as the polyurethane (PUT) foam, to obtain a clean PPGF material from the end-of-life instrument panel was investigated. A proper separation of these materials would be necessary in the automotive industry, as different types of polymers and composites when recycled together, result in a poor recyclate (B.J. Jody, 2010).

In this case, mechanical separation, which is a common separation method, was used to obtain material from the end-of-life vehicle instrument panel, also referred to as AzPPGF. The plastic parts on the instrument panel consisting of acrylonitrile butadiene styrene (ABS) plastic and an unspecified PP-composite were dismantled manually, see part 1 and part 3 in Figure 1. After this, the polyurethane (PUT) foam was removed using chisels and hammers, but some foam remained on the panel. The panel was then sawed and milled into granulates before being injection molded. AzPPGF granulates were not compounded before the injection molding to preserve the mechanical properties of the material as much as possible. The end-of-life panel represents naturally aged polypropylene (PP) composite, in comparison to the PP-composite obtained from newly produced instrument panels.

4 Method

4.1 Compounding

The compounding was performed using a Coperion ZSK 26 K co-rotating twin-screw extruder having a screw diameter of 26 mm and a screw length of 1000 mm. Only conveying elements were present on the screws for this step. A mixing element was later added for the upgrading step. A throughput of 8 kg/hr was maintained using a screw speed of 200 rpm with a residence time of less than a minute. The milled PPGF granulate was added through a side-feeder and no material was added into the main feeder of the compounder. A circular die was used to produce strands which were air-cooled before being pelletized. The entire compounding process can be seen as a flowchart in Figure 2.

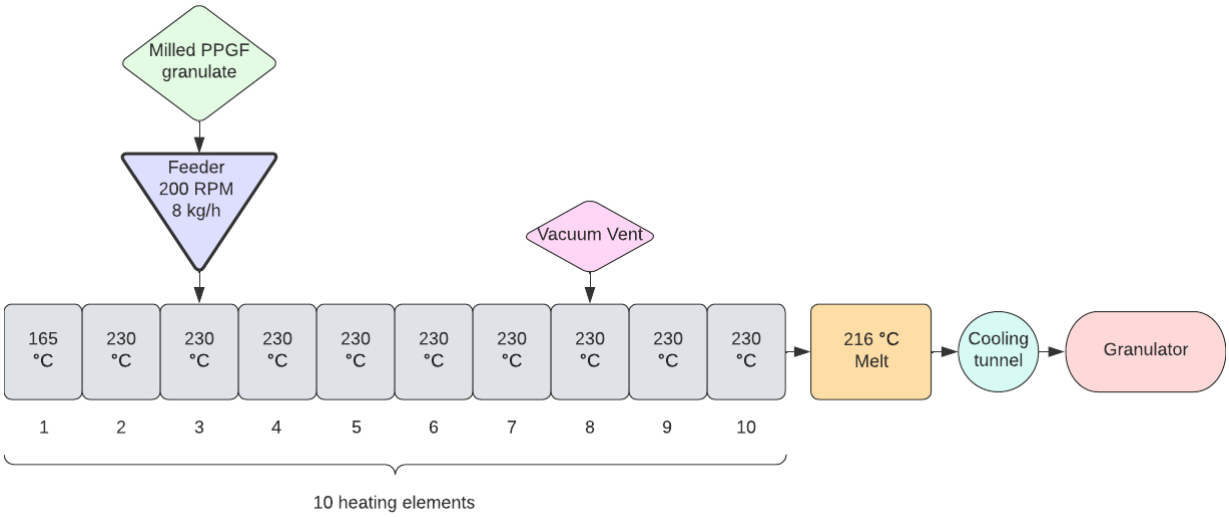


Figure 2 - Compounding process flowchart used during reprocessing.

For the upgrading, the compounder screw was changed to make sure that the milled granulate would mix properly with all the different additives. As such, a mixing element was added in the vicinity of the seventh and eight heating elements. All other parameters were unchanged, see Figure 3.

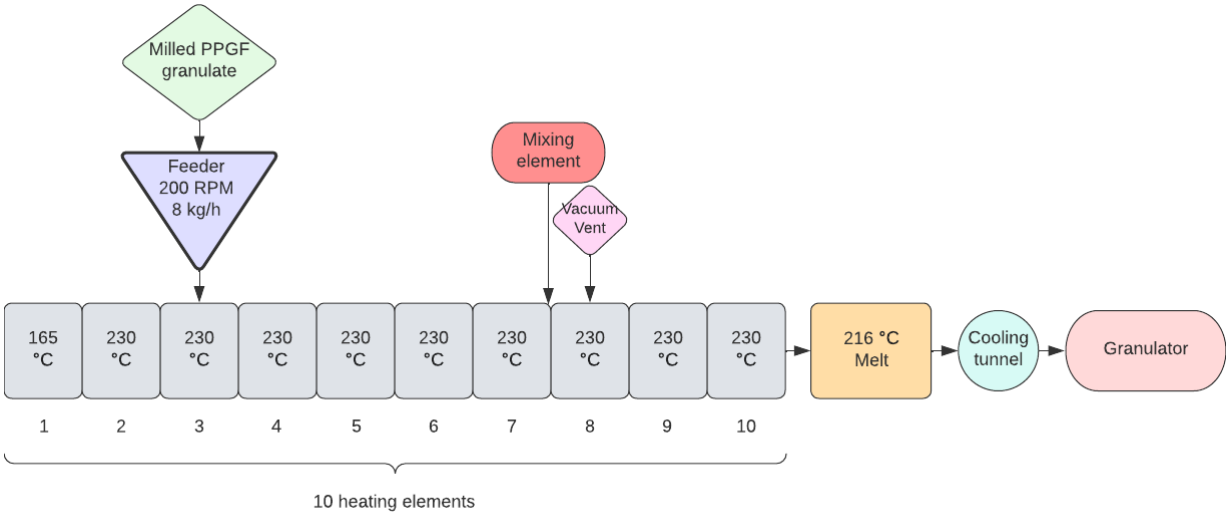


Figure 3 - Compounding process flowchart used during upgrading.

4.2 Injection molding

The compounded granulate was fed into an Engel ES 200/110 HL-V Injection molding-machine, and tests bars were molded according to ISO 294-1:2017. After each injection moulding step, most of the test bars were saved to be reprocessed (re-milled, re-compounded and re-injection molded) while some were saved for characterization. The injection molding parameters used can be seen in Table 1.

Table 1 – Injection molding parameters.

Injection speed	35 mm/s
Injection pressure	305-340 bar
Holding pressure	305-520 bar
Holding time	25 seconds
Cooling time	10 seconds

4.3 Material reprocessing and upgrading

After each completed processing cycle (Milling-compounding-injection moulding is considered one cycle), tensile bars were saved for mechanical, thermal and fiber length characterization tests while the rest were re-milled, re-compounded and injection molded, as shown in Figure 4. Furthermore, samples were collected after each subsequent step in the cycle (ex: milling or compounding) to do fiber length- and thermal measurements. For the complete thermal and processing history of these materials, see Appendix 1.

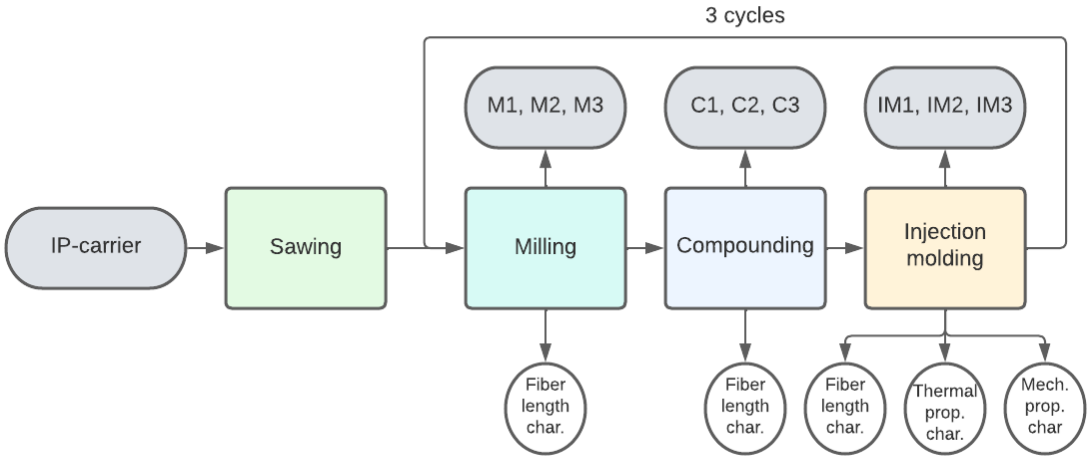


Figure 4 – The complete reprocessing process flow.

The upgrading section of the thesis work focused on improving material properties of the recycled PP composite from the first milling step. Material from the first processing cycle, M1, is used for all upgrading recipes. That is, samples made from material with one cycle of milling only, with no compounding or injection moulding done to it. Impact modifiers, MAPP, and glass fiber from industrial production residue (PIGF), post-consumer residue (PCGF) as well as virgin glass fibers were added in different amounts to M1. The compounding and injection molding procedure, as seen in the above steps, was also used for producing test bars in this part of the work.

The upgrading was done in three batches, looking at the three different glass fiber types, one in each batch. Also investigated were combinations of glass fibers with impact modifiers, as well as single additions of impact modifiers and just the virgin GF. All the recipes used in the upgrading batches can be seen in Table 2.

The PIGF was compounded into a masterbatch containing 60 wt% GF, 3 wt% MAPP and 37 wt% virgin PP, by manually feeding the PIGF in the side feeder at a rate of 25 g/min with the virgin PP and MAPP being fed in the main feeder at the back of the screw at a rate of 1 kg/h. The PCGF was compounded in to a masterbatch the same way as the PIGF. The virgin GF (which was a masterbatch containing 60 wt% GF) was mixed with milled granulate from the instrument panels, called M1, and directly fed in the side feeder. The different glass fibers can be seen in Figure 5.

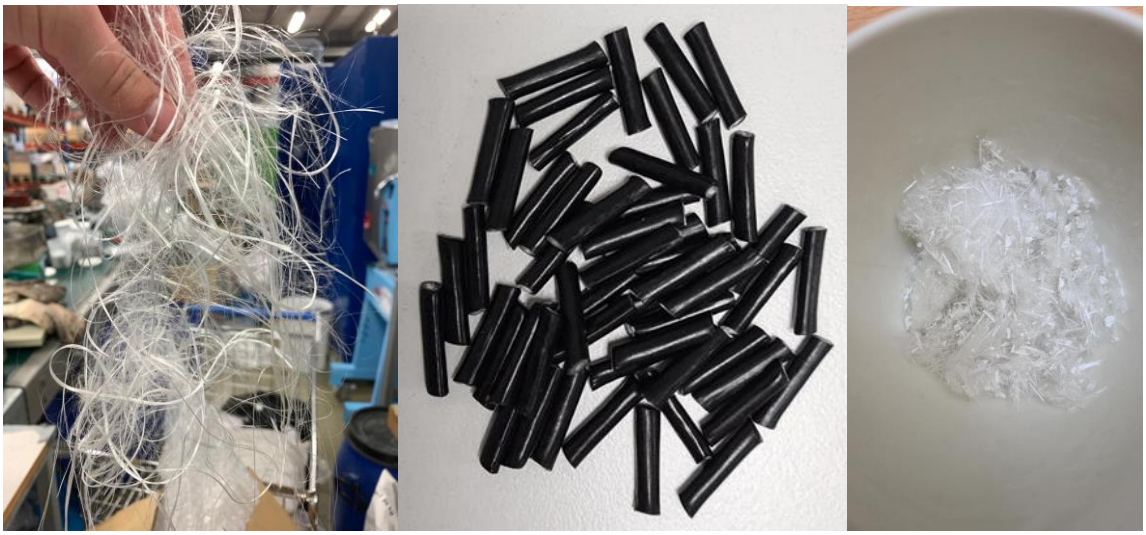


Figure 5 – Post-industrial glass fibers (L), virgin glass fibers (M), post-consumer glass fibers (R) as they looked when they were fed into the compounder.

Table 2 – Upgrading recipes: sample names and additions.

Sample name	**Additions**
POE 1 %	1 wt% polyolefin elastomer (POE)
POE 3 %	3 wt% POE
SEBS 1 %	1 wt% Styrene-ethylene-butylene-styrene (SEBS)
SEBS 3 %	3 wt% SEBS
Virgin GF 25	5 wt% virgin glass fibers, 4.6 wt% virgin PP
PIGF 25	5 wt% post-industrial glass fibers (PIGF), 3 wt% MAPP, 4.6 wt % virgin PP
PIGF 25 SEBS 1 %	5 wt% PIGF, 1 wt% SEBS, 3 wt% MAPP, 4.6 wt % virgin PP
PIGF 25 SEBS 3 %	5 wt% PIGF, 3 wt% SEBS, 3 wt% MAPP, 4.6 wt % virgin PP
PIGF 30	10 wt% PIGF, 3 wt% MAPP, 4.6 wt % virgin PP
PIGF 30 SEBS 1 %	10 wt% PIGF, 1 wt% SEBS, 3 wt% MAPP, 4.6 wt % virgin PP
PIGF 30 SEBS 1 % IM2 (reprocessed)	10 wt% PIGF, 1 wt% SEBS, 3 wt% MAPP, 4.6 wt % virgin PP
PCGF 25	5 wt% post-consumer glass fibers (PCGF), 3 wt% MAPP, 4.6 wt % virgin PP

4.4 Sieving

To investigate the impact of removing the shortest fibers from the milled material, manual sieving was performed on the milled IP-carrier material, also known as M1. Two batches, one with a 1 mm sieve mesh and other with a 2 mm sieve mesh, were made. 100 g of material was manually sieved at a time to allow the sieves to work properly. The 1 mm batch mesh was shaken for 1 minute for each load and the 2 mm batch mesh was shaken for 20 seconds for each load. A total of about 2.4 kg of material was sieved for each batch. After using the 1 mm sieve, about 1,3 % of the total material was discarded. After using the 2 mm sieve, about 17,6 % of the material was discarded. The batches were then injection molded. Fiber length characterization and mechanical tests were performed on the sieved batches to observe changes in mean fiber length and performance.

4.5 Material characterization

4.5.1 Fiber length measurements

Samples were prepared in a heated press with each sample consisting of 0.3 g of material pressed into a thin film at 200 °C with a pressure of 3 tons. Films were prepared after each processing step, within each cycle, to give insight into how processing steps were affecting the fibers.

A small section was cut and put into a Nikon Eclipse Ci-POL optical microscope. Any fiber fragments smaller than 30 µm are seen as filler material and are not counted. The fibers were measured using the 'NIS-Elements basic research' software, as shown in Figure 6.

To reduce bias when counting the fibers, a circle was drawn in the middle of the frame and only fibers within the circle were counted. 200 fibers were counted per sample.

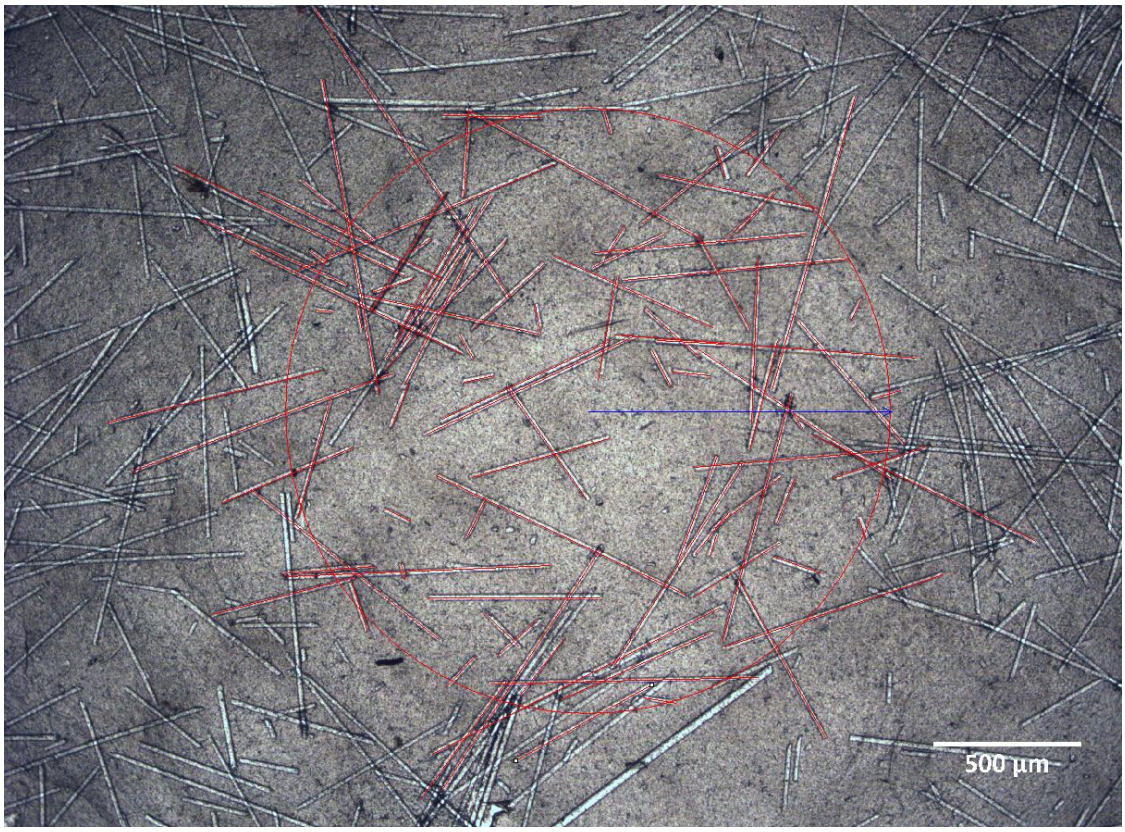


Figure 6 - Fiber length measurements done on a sample from AzPPGF using the NIS-Elements Basic Research software. Red lines were manually drawn on the fibers, which were then automatically measured by the software.

4.5.2 Mechanical testing

The mechanical testing was focused on two areas: Charpy Impact Tests and Tensile tests. Both tests were done according to ISO 179-2 and ISO 527-4 respectively, on injection molded test bars. After fracture, some test bars from both impact- and tensile testing were carefully removed to preserve the fracture surface for further study in SEM.

4.5.2.1 Impact test

Impact testing was done in a CEAST 9050 machine according to ISO 179-2. A 1 Joule pendulum was used, and 10 test bars per sample were tested at 23 °C. Some selected upgrading blends and a reference were also tested at a temperature of -30 °C.

4.5.2.2 Tensile test

Tensile testing was done in an MTS 20-M machine according to ISO 527-4. Five samples were tested per recycling cycle at a temperature of 23 °C.

4.5.2.3 Halpin-Tsai model

One way to theoretically calculate how the fiber length and fiber packaging affects the stiffness and strength of the composite, is to use the semi-empirical equations called the Halpin-Tsai model with the Nielsen correction (M.G. Aruan Efendy, 2019). For stiffness and strength, respectively, it states that:

$$E = \frac{E_m(1 + \xi\eta f)}{1 - \eta\psi f} \quad (1)$$

$$\sigma = \frac{\sigma_m(1 + \xi\eta^* f)}{1 - \eta^*\psi f} \quad (2)$$

in which

$$\eta = \frac{\frac{E_f}{E_m} - 1}{\frac{E_f}{E_m} + \xi} \quad (3)$$

$$\eta^* = \frac{\frac{\sigma_f}{\sigma_m} - 1}{\frac{\sigma_f}{\sigma_m} + \xi} \quad (4)$$

and

$$\psi = 1 + \frac{1 - \phi_{max}}{\phi_{max}^2} f \quad (5)$$

Where E_f and E_m denote the elastic modulus of the glass fibers and the matrix, respectively. Likewise, σ_f and σ_m denote the strength of the glass fibers and the matrix, respectively. ϕ_{max} is the maximum packing fraction for the fibers in their current arrangement and has a value of 0.82 for random packing of fibers. f denotes the fiber packing fraction and ξ can be estimated using the *Hewitt de Malherbe* correction for the longitudinal, transverse and shear loads:

$$\xi_{11} = \left(\frac{2l}{d}\right) + 40\, f^{10} \qquad (for\ E_{11}) \quad (6)$$

$$\xi_{22} = \left(\frac{2w}{d}\right) + 40\, f^{10} \qquad (for\ E_{22}) \quad (7)$$

$$\xi_{12} = \left(\frac{w}{t}\right)^{1.73} + 40\, f^{10} \qquad (for\ G_{12}) \quad (8)$$

With l, d, w, and t denoting the average fiber length, fiber diameter, sample width, and sample thickness of the test bars, respectively.

The density of PP and GF are set to $\rho_m = 0{,}9$, $\rho_f = 2{,}5$, respectively. This gives a GF volume fraction of $f = 8{,}26\%$ at 20 wt% in a PP matrix. From equation 5, the correction factor ψ is calculated to 1.027 at 20 wt%, 1.029 at 25 wt% and 1.036 at 30 wt% GF. The tensile strength of the matrix is set to σ_m = 31.6 MPa and the tensile strength of the GF is

set to σ_f = 1956 MPa (Fu, 2000). The stiffness of the matrix is set to E_m = 1.23 GPa and the stiffness of the GF is set to E_f = 72 GPa.

4.5.2.4 Kelly-Tyson model

To get an idea of the influence of the critical fiber length on the tensile strength of the composites, the Kelly - Tyson model was used. The critical fiber length is first determined by doing experiments, such as the "pull-out test", or approximated. A few assumptions must be made:

1. All the fibers are assumed to be aligned in the load direction.
2. The load is assumed to be applied on the fibers by shear forces at the interface of the fiber and matrix.
3. The global and the local stresses are similar (M.G. Aruan Efendy, 2019).

The critical fiber length, L_C, is then compared to the mean fiber length, L, of a specific material. The average fiber diameter is denoted as D, the fiber tensile strength as σ_f, and the interfacial shear strength as τ.

$$L_C = \left(\frac{\sigma_f D}{2\tau}\right) \quad 9$$

Depending on if the mean fiber length of the material is higher or lower than the critical fiber length, one of two different equations are used and a value K_{st} is obtained, which is a value of the efficiency of the stress moving from the matrix to the fibers.

If L < L_C

$$K_{st} = \left(\frac{L}{2L_C}\right) \quad 10$$

If L > L_C

$$K_{st} = 1 - \left(\frac{L}{2L_C}\right) \quad 11$$

The value of K_{st} is then used with the rule of mixtures to determine the Young's modulus of the composite, E_c, and the tensile strength of the composite, σ_c.

$$\sigma_c = \sigma_f V_f K_{st} + \sigma_m V_m \quad 12$$

$$E_c = E_f V_f K_{st} + E_m V_m \quad 13$$

Where V_f and V_m denote the fiber and matrix volume fractions, respectively. σ_f, σ_m, E_f and E_m denote the fiber and matrix strength and stiffness, the same as for equations 1 through 4.

4.5.3 Differential scanning calorimetry and thermal gravimetric analysis

A DSC analysis consisting of OIT-measurements (Oxidation Induction Time/Temperature) were conducted on different samples according to ISO-standard 11357:6. The time-based tests were done at a temperature of 230 °C in oxygen. OIT-measurements based on temperature or rather oxidation onset temperature was done with a temperature ramp-up in air on a TGA-instrument (Thermal Gravimetric Analysis) to observe at which temperatures the polymer matrix degrades. The latter measurement did not follow the mentioned standard since it was performed on a TGA instrument, following the registered heat flow during temperature increase of the sample. Both analyses were conducted to determine the effect on the PP matrix after repeated recycling steps and after natural aging in the case of the AzPPGF sample. Two measurements on each sample were conducted, and the mean value was presented.

4.5.4 Scanning electron microscopy

A JSM-6610LV scanning electron microscope was used to perform SEM-analysis on the fracture surfaces from samples collected after tensile testing. These were observed under low vacuum at between 80 to 90 Pa at a voltage of 15 kV and magnifications between 10x to 1000x.

5 Results & Discussion

The results are grouped into four sections, presented here following the different areas investigated in this thesis. They are, in order:

- Material reprocessing.
- Adding more glass fiber of different origins to blends.
- Adding impact modifiers to blends.
- Adding impact modifiers and glass fiber to a blend, and the result of reprocessing on this blend.

5.1 Material Reprocessing

5.1.1 Fiber length measurements

The fiber length of the samples decreased after each processing step. Figure 7 shows a reduction in the mean fiber length and a reduction in the standard deviation which could suggest the fiber length distribution becomes narrower with further processing. The largest drop in fiber length was observed for the C1 sample, from 712 µm to 434 µm, after the first compounding step.

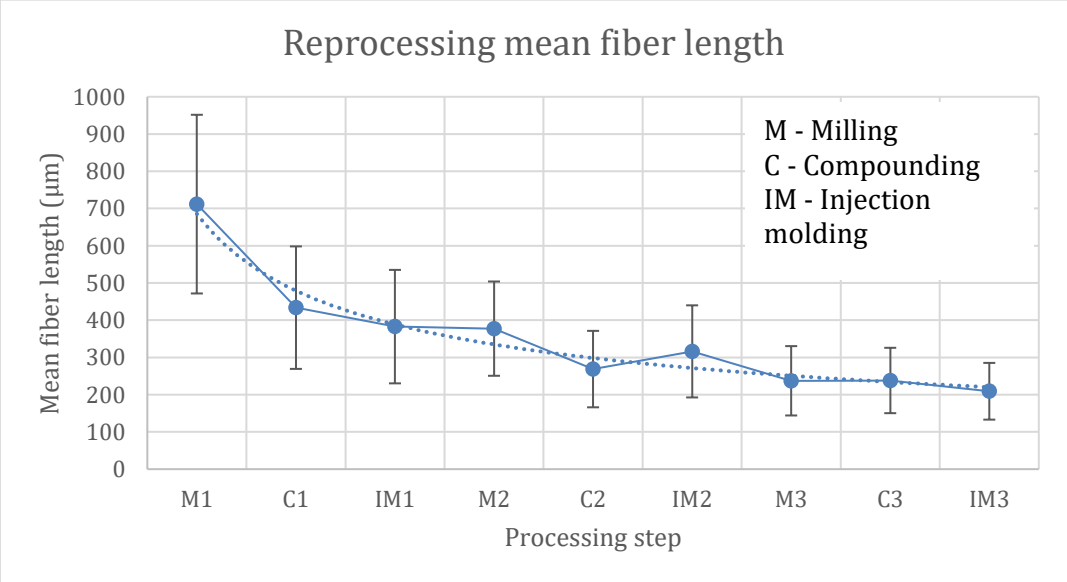


Figure 7 - Mean fiber length measurements for each processing step.

As seen in Figure 8, the fiber length distribution was measured for each processing step with the distributions after each of the three cycles' milling steps (M1, M2 and M3). Here it is shown how the material initially has a wide fiber length distribution that becomes narrower with further processing, with shorter fibers overall. Data of minimum fiber length, maximum fiber length, mean fiber length with standard deviation for the other processing steps, after each compounding and injection molding cycle, are found in Appendix 2.

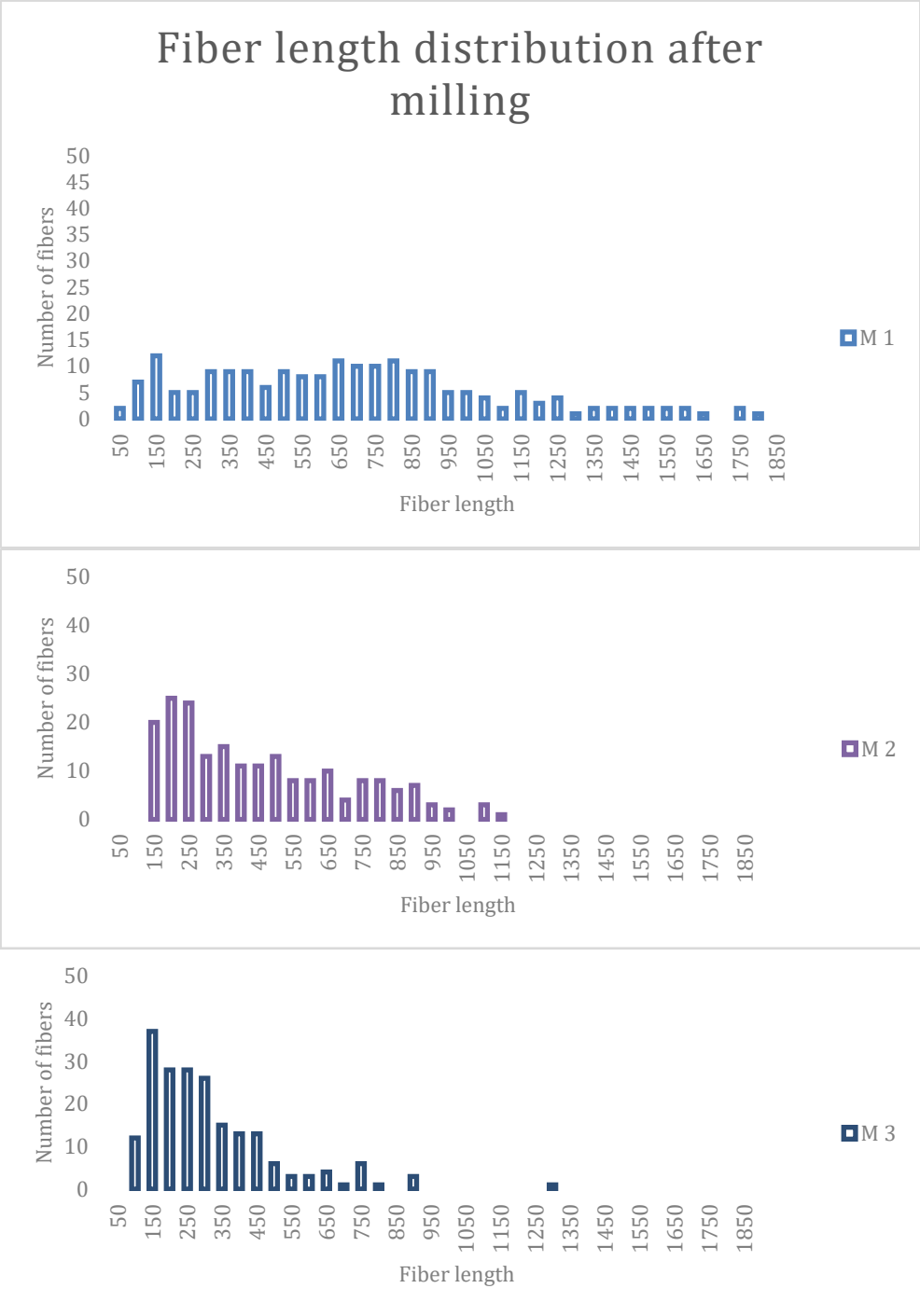


Figure 8 - Histograms showing fiber length distribution after each milling step, bin size 50 µm.

5.1.2 Mechanical testing

The tensile data plots are presented for the reprocessed samples after each cycle together with the end-of-life panel (AzPPGF), shown in Figure 9. It can be observed that the mechanical properties reduce with reprocessing with the third cycle showing the lowest values. The strength of AzPPGF is higher than for IM 1 but the low strain indicates possible degradation of the matrix. The complete data can be found in Appendix 3.

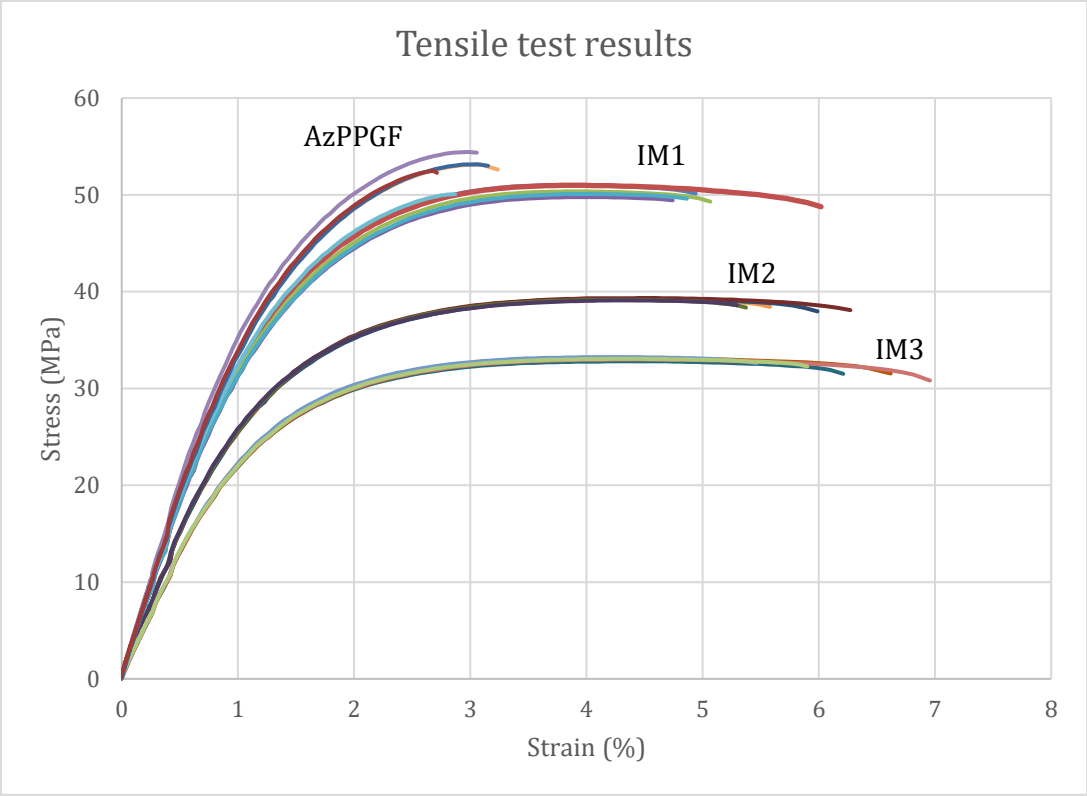


Figure 9 – Tensile Graph for reprocessing injection molding cycles 1 through 3 and AzPPGF.

Figure 10 shows the impact strength-behaviour of the milled instrument panel (M1), the reprocessing cycles (IM1, IM2 and IM3) and the end-of-life panel (AzPPGF), together with the fiber length for each of the samples. The figure indicates that reprocessing reduces the impact strength of the composite due to the breaking of fibers in each processing step.

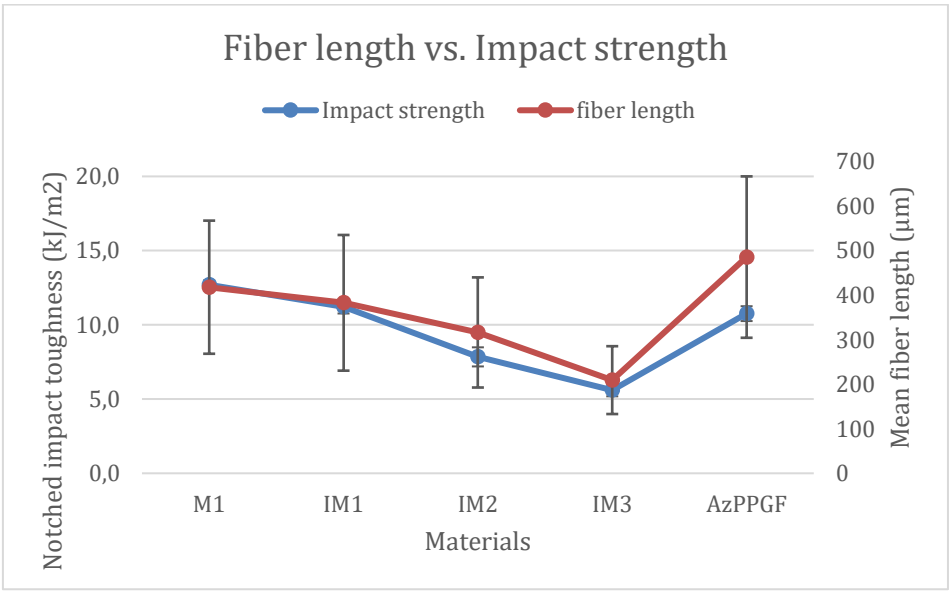


Figure 10 - Fiber length and impact strength for M1, IM1, IM2, IM3 and the end-of-life panel, respectively.

When comparing the measured mean fiber length for the materials to the tensile strength there is a clear correlation where a decrease in fiber length leads to a decrease in tensile strength, see Figure 11.

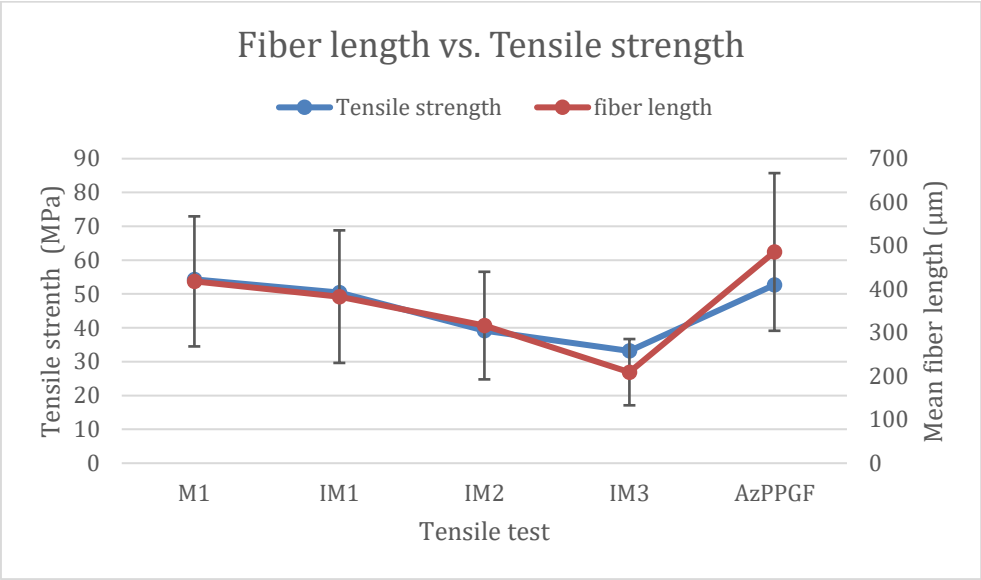


Figure 11 - Fiber length and tensile strength for M1, IM1, IM2, IM3 and the end-of-life panel, respectively.

5.1.3 Thermal analysis

Thermal analysis was performed on the reprocessed samples from the new instrument panel and the end-of-life cycle instrument panel, AzPPGF. Figure 12 shows the results of oxidation induction time measured at 230 °C i.e., the temperature used for compounding. The samples from the first milling cycle decomposed after roughly 5 minutes (5.2 minutes) while the samples from IM1, IM2 and IM3 decomposed after 3.3, 3.1 and 1.7 minutes, respectively. The AzPPGF sample decomposed after 1.7 minutes, indicating that the state of the matrices of the AzPPGF samples and the IM3 sample are similar in this regard. An OIT value of less than 2 minutes is regarded as a limit where the antioxidant has been depleted which means that the matrix is prone to polymer degradation.

Similar results were obtained from oxidative induction temperatures measurements, as seen in Figure 13, where M1 decomposed at 265 °C, IM1 and IM2 at 262 °C, while IM3 and the AzPPGF sample decomposed at 255 °C and 256 °C, respectively.

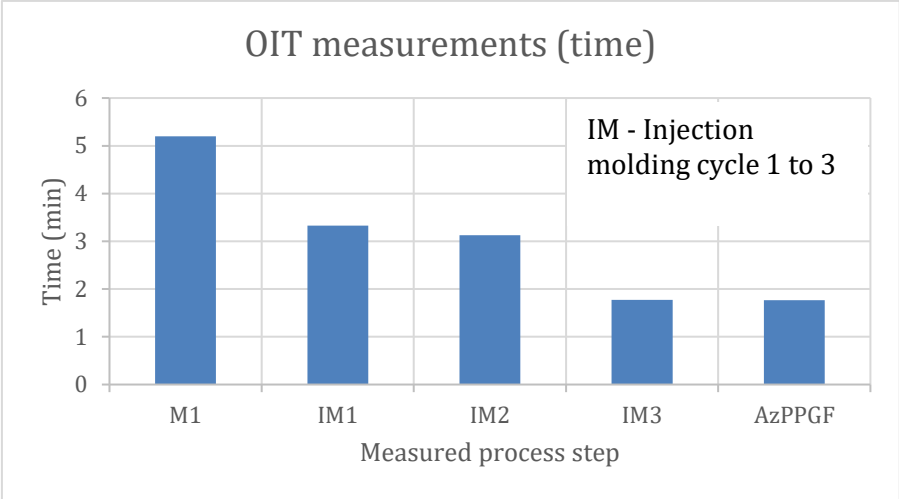


Figure 12 - Results from OIT measurements on selected samples from the reprocessing and the end-of-life panel (AzPPGF), measured at 230 °C.

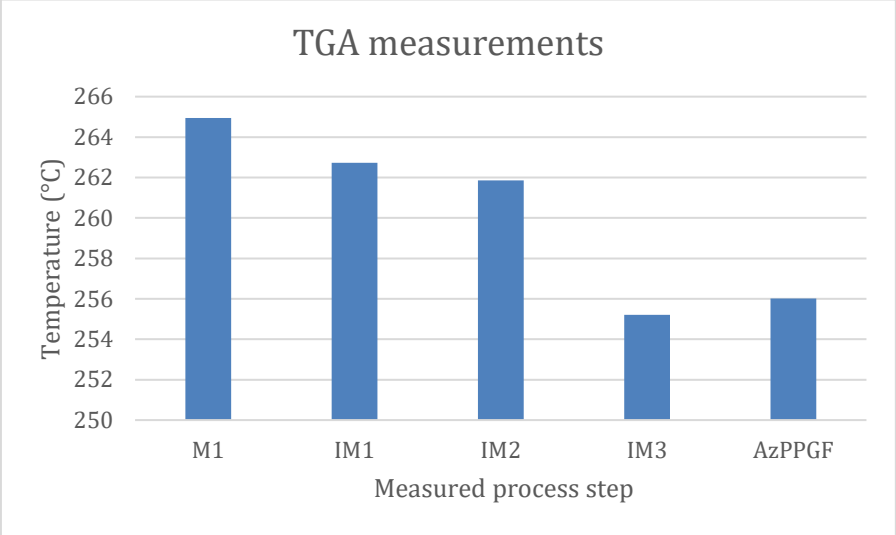


Figure 13 – Results from TGA measurements to determine the oxidation induction temperature for selected samples from the reprocessing and the end-of-life panel (AzPPGF).

The AzPPGF and IM3 samples show similar degradation times. This could indicate that the antioxidants in both materials have been depleted. The TGA analysis indicates that IM3 and AzPPGF degrade at approximately the same temperature. This indicates that the thermal history of three recycling cycles as in the case of IM3, or the thermal exposure of six years of natural aging as in the case of AzPPGF, possibly results in matrix degradation caused by depletion of antioxidants in both materials.

It is likely that the degraded polymer matrix of the AzPPGF is the cause of some of the lost properties in this material, compared to M1 which is its closest reference in terms of reprocessing history.

5.1.4 Sieving

During the sieving, the amount removed in the 1 mm sieve mesh was 1,3 wt%, and in the 2 mm sieve mesh 17,5 wt% of material was removed. Despite the large difference in the amount of material removed, improvements in mechanical properties can be seen from both tests with only a small difference in the results between them. This means that most

of the material performance degradation comes from particles smaller than 1 mm in size, where the fibers are more likely to be below the critical fiber length and thus act as impurities. Sieving of small particles therefore appears to be a cheap and efficient way of improving the mechanical performance of a recycled thermoplastic composite material. For the results of the 1 mm sieve and the 2 mm sieve compared to the results of M1, see Figure 14. M1 in the figure corresponds to the originally milled material after injection molding without the compounding step.

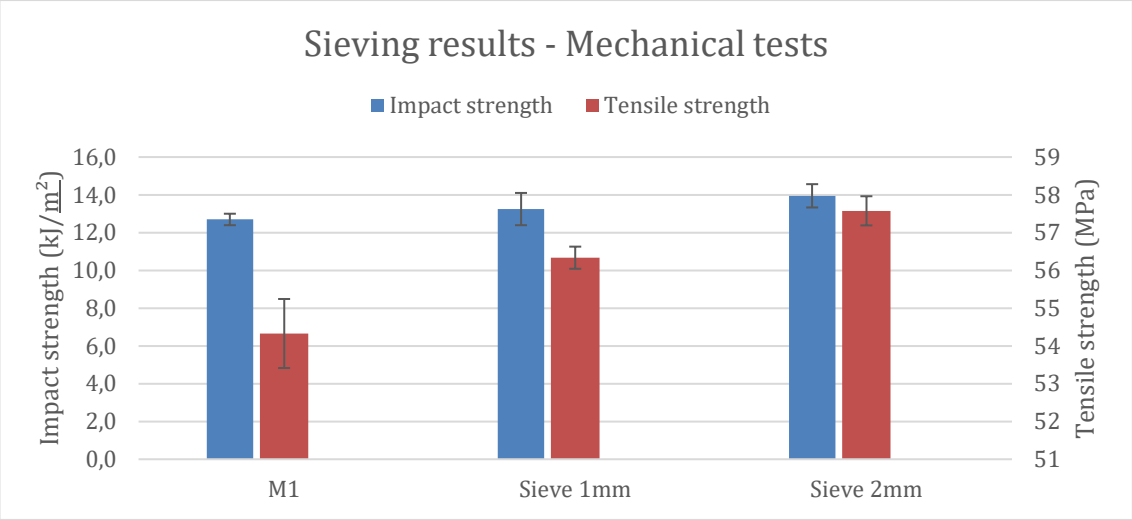


Figure 14 - Results from mechanical tests from sieving, compared to M1 as a reference

5.2 Upgrading

5.2.1 Glass fiber additions

Figures 15 and 16 show the effect of upgrading the M1 granulate with different types of glass fiber on the mechanical properties of the composites, and compare it to IM1.

As seen in Figure 15, the addition of 5 wt% virgin glass fibers (Virgin 25 GF), results in a significant increase of the stiffness and the tensile strength as compared to IM1.

The addition of 5 wt% post-consumer (PCGF 25) and post-industrial (PIGF 25) glass fibers does not seem to have any significant effect on the mechanical properties. In fact, the tensile strength for PCGF 25 is decreased compared to IM1 while the other properties are on par with IM1.

The addition of 10 wt% post-industrial glass fibers (PIGF 30) increases both tensile strength and stiffness.

As seen in Figure 16, the addition of 5 wt% virgin glass fibers (Virgin GF 25) results in a decrease of strain at break and an increase of the impact strength. The addition of 5 wt% post-industrial glass fibers (PIGF 25) has a small influence on the properties when compared to IM1, while the addition of 5 wt% post-consumer glass fibers (PCGF 25) reduce the value of both strain at break and impact strength compared to IM1.

The addition of 10 wt% post-industrial glass fibers (PIGF 30) seems to increase the impact strength and lower the strain at break compared to IM1.

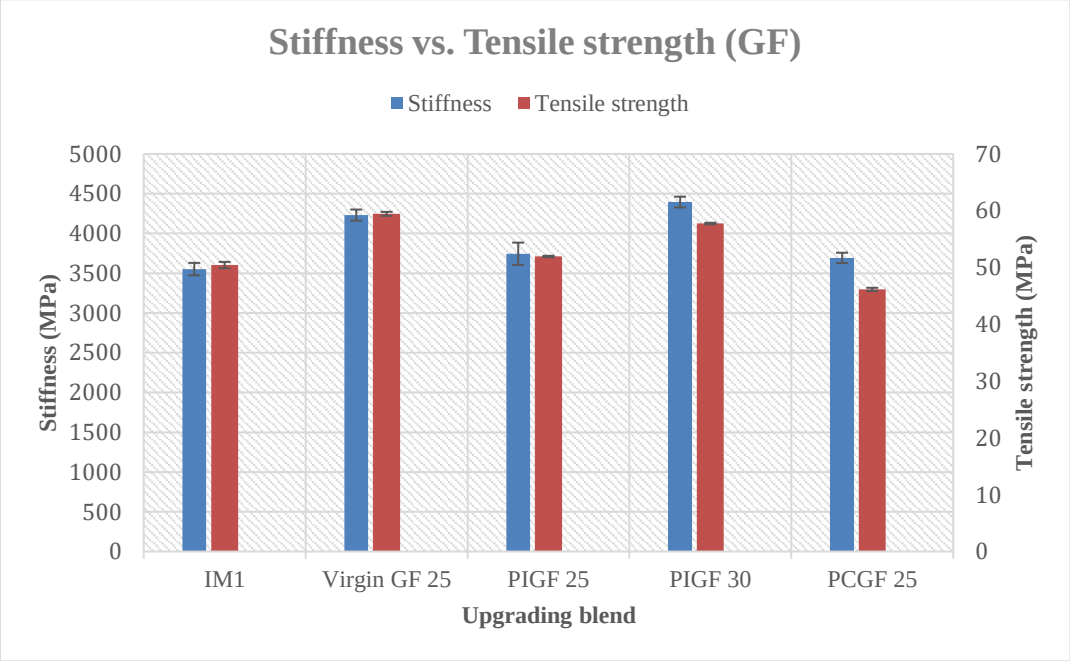


Figure 15 - Stiffness and tensile strength values for all the glass fiber samples with 5wt % added glass fibers. IM1 with a total of 20 wt% GF is included in the plot as a comparison.

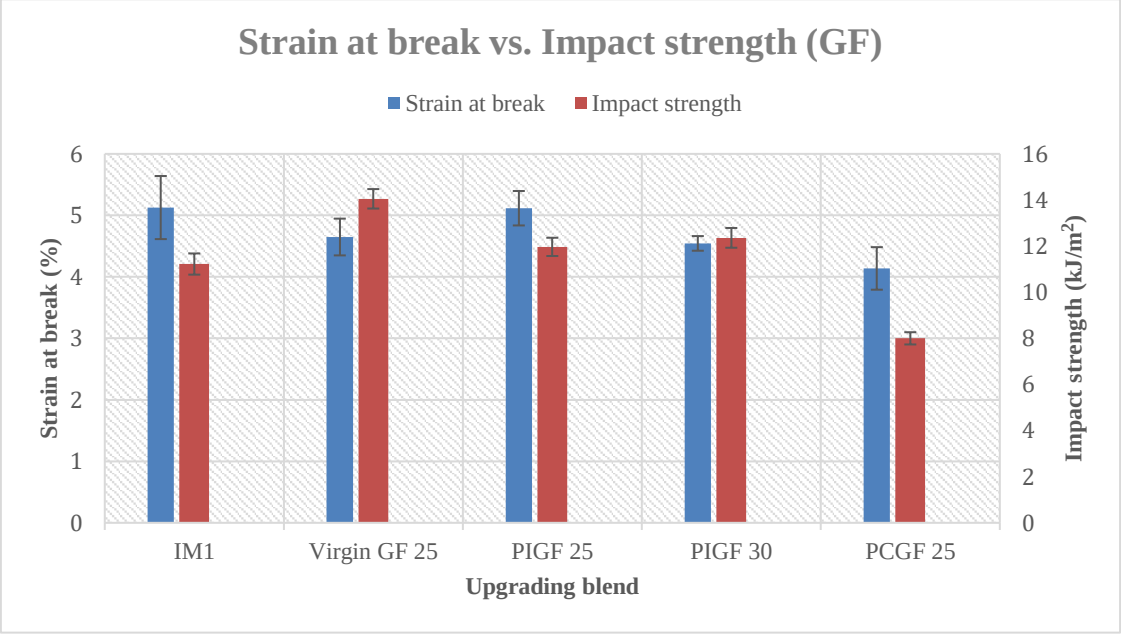


Figure 16 – Strain at break and impact strength values for all the glass fiber samples with 5wt % added glass fibers. IM1 with a total of 20 wt% GF is included in the plot as a comparison.

Figure 17 shows the results from Charpy impact tests that were performed at both 23 °C and at -30 °C, to study the effect of temperatures on the impact behaviour of the composites. An expected decline in impact performance was observed in all the tested samples at -30 °C.

The sample with 5 wt% added virgin glass fibers (Virgin GF 25) had a low temperature impact value close to that of the IM1 at room temperature, with 11,2 kJ/m^2 for IM1 at 23 °C and 10,6 kJ/m^2 for Virgin GF 25 at -30 °C.

The sample with 10 wt% added post-industrial glass fibers (PIGF 30) performed only slightly better than IM1 at both temperatures, while the sample with 5 wt% added post-consumer glass fibers (PCGF 25) performed significantly worse than all the other samples at both temperatures, with a value of 8 kJ/m^2 at 23 °C and a value of 5 kJ/m^2 at 23 °C.

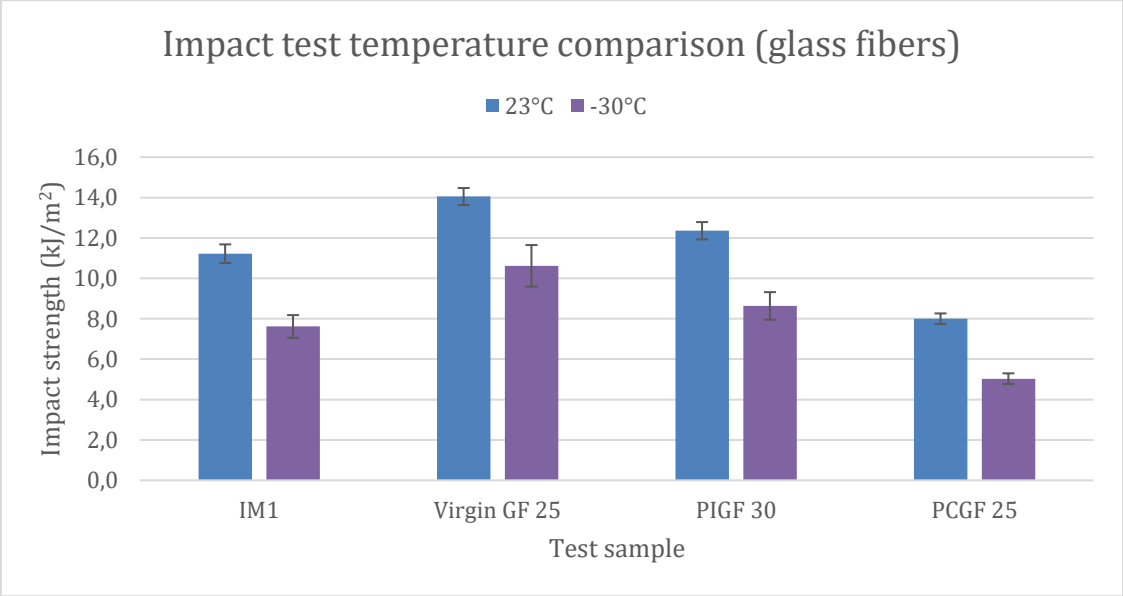


Figure 17 - Results from Charpy impact tests performed at 23°C and -30°C

The stiffness remained about the same when post-consumer glass-fibers (PCGF 25) was added for upgrading, which is expected since the stiffness is measured in the elastic region of the tensile test.

The impaired properties are measured in the plastic region of deformation and the results show that the fibers don't reinforce the matrix properly.

The impact strength is reduced to such a degree that the post-consumer glass fibers (PCGF 25) seem to act as impurities in this material. A possible explanation is the lack of adhesion between the fibers and the matrix. The original boat hull composite was incinerated to remove the thermoplastic matrix. As such, any sizing that it might have had would then also be removed.

The mean fiber length of IM1 is 383 microns, compared to 238 microns in PCGF 25. This difference likely plays a large part in the reduced mechanical properties of PCGF 25 compared to IM1. As a glass fiber addition of 5 wt% yielded this large reduction in mean fiber length in the material (38% lower) compared IM1, it means that extensive fiber breakage has occurred during processing.

As for the post-industrial glass fibers, specifically the PIGF 25 sample, it had a mean fiber length of 302 microns. This too is lower than the mean fiber length of IM1, also indicating fiber breakage in the case of PIGF 25. The virgin glass fiber sample, Virgin GF 25, has a mean fiber length of 487 microns. This is higher than all the other samples, and it is evident that the glass fibers of this sample have been better preserved during processing.

Out of all the tested fibers added to the original milled polypropylene glass-fiber granulates, the virgin GF performed the best. This is likely due to the fibers already being impregnated with a virgin PP in a commercially produced masterbatch. This is done by coating bundles of fibers with the polymer and then chopping long pellets to retain a fiber length of > 10 mm. The master batches for the PIGF and PCGF were prepared by compounding free fibers with virgin PP. The high load of fibers (60%) could mean that high viscosity and high shear forces resulted in master batches with short fibers.

5.2.2 Impact modifier additions

Two impact modifiers were tested, SEBS (styrene-ethylene-butylene-styrene) and POE (polyolefin elastomer) both at 1 wt% and 3 wt%. Figure 18 shows that a reduction in stiffness and tensile strength was seen in all samples compared to the reference, IM1.

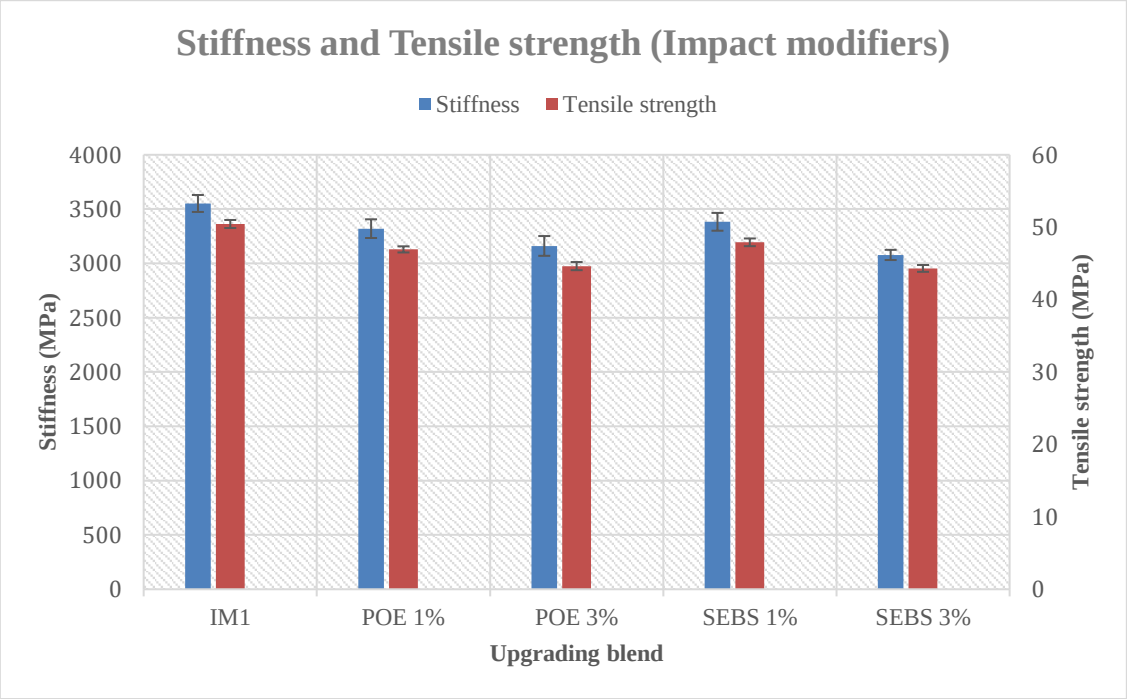


Figure 18 - Stiffness and tensile strength values for the impact modifier samples, no glass fibers added. IM1 with a total of 20 wt% glass fibers is included in the plot as a comparison.

The strain at break and impact strength shows improvements over the reference, IM1, for all samples except for POE 1 wt%, shown in Figure 19. The addition of 3 wt% SEBS shows the greatest improvements of these properties. Overall, the performance of the SEBS is slightly superior to the POE, with a similar loss of stiffness and tensile strength as the POE, while obtaining higher impact strength and strain at break.

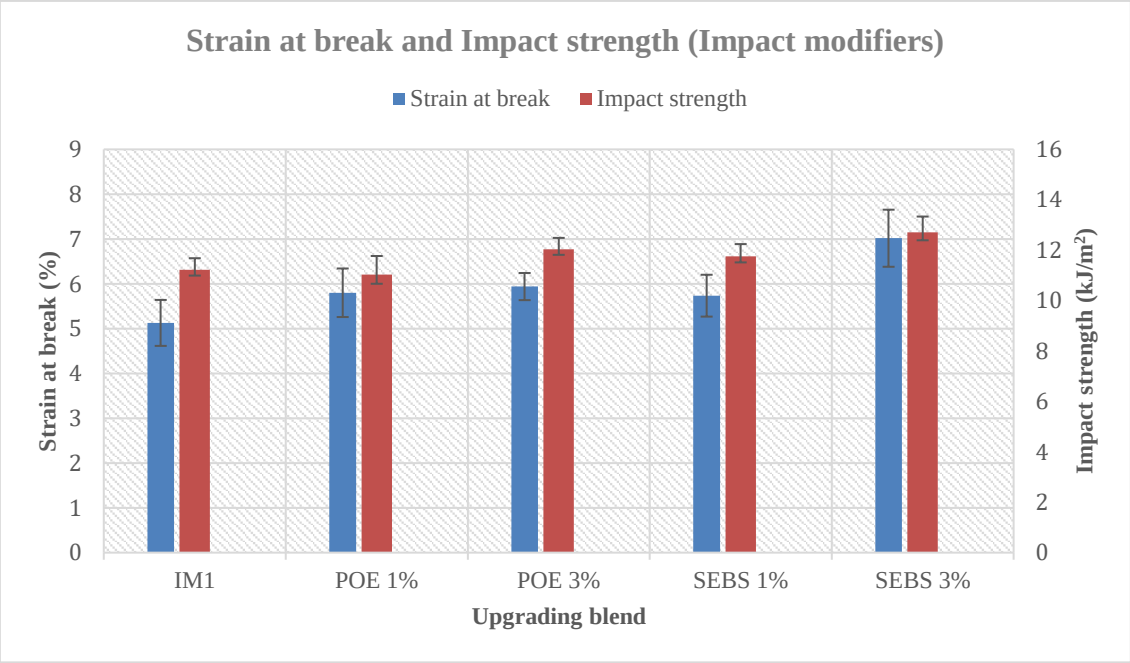


Figure 19 – Strain at break and strength values for the impact modifier samples, no glass fibers added. IM1 with a total of 20 wt% glass fibers is included in the plot as a comparison.

Figure 20 shows the results from Charpy impact tests that were performed at 23 °C and at -30 °C for the samples with 3 wt% SEBS and POE added, compared to the IM1. The results show that the addition of impact modifiers have almost no effect on the impact strength at low temperature.

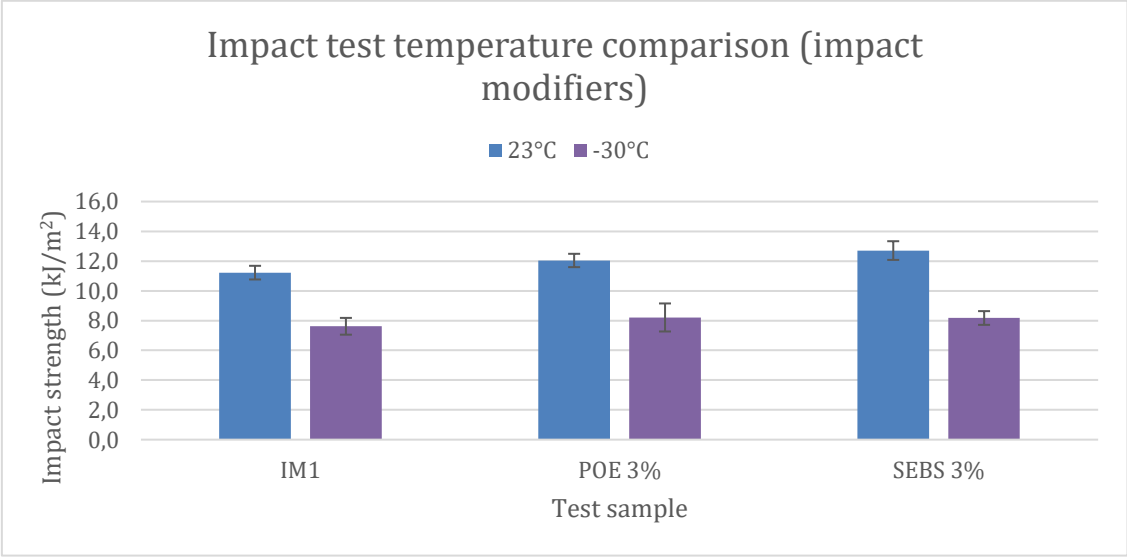


Figure 20 - Charpy impact tests performed at 23 °C and -30 °C on the different impact modifiers. Only POE and SEBS at a concentration of 3 wt% are included, with IM1 included in the plot as a comparison.

SEBS showed better overall properties at 3 wt% than POE at 3 wt%. At -30 °C, 3 wt% addition of both POE and SEBS produced a very small increase in impact strength, indicating that their strengthening capabilities are reduced at low temperatures.

The influence of adding impact modifiers to the original milled material, M1, in relation to the mean fiber lengths is shown in Figures 21 and 22. The fiber length and tensile strength remains close to that of the reference material IM1, which can be seen in Figure

21. Thus, the addition of impact modifier does not contribute to reduction of the fiber length.

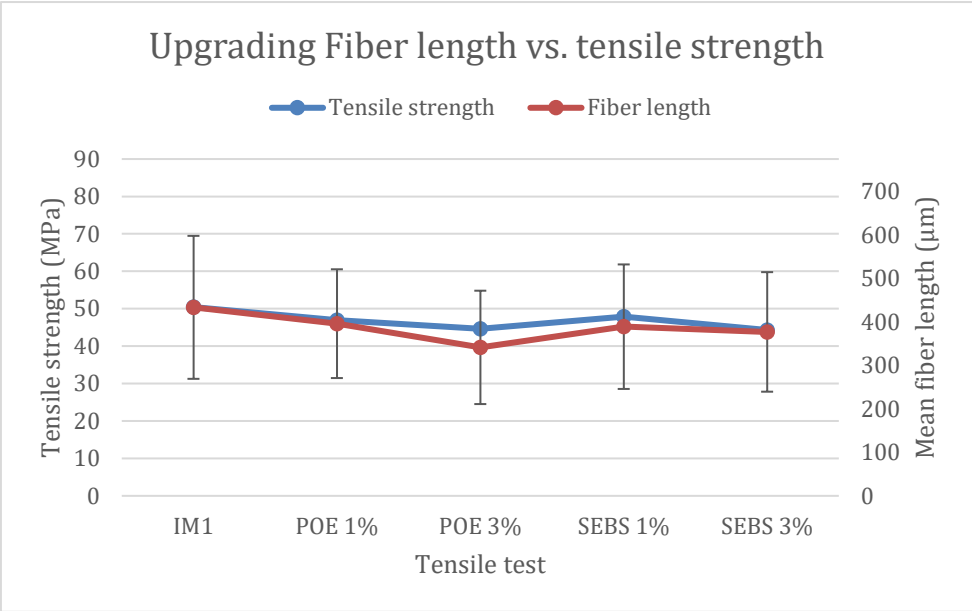


Figure 21- Fiber lengths and tensile strength for IM1, and with addition of impact modifiers POE 1 %, POE 3 %, SEBS 1 %, and SEBS 3 % respectively.

There is a clear increase of the impact strength with retained fiber lengths on all the materials studied except for POE 1 %, which is shown in Figure 22.

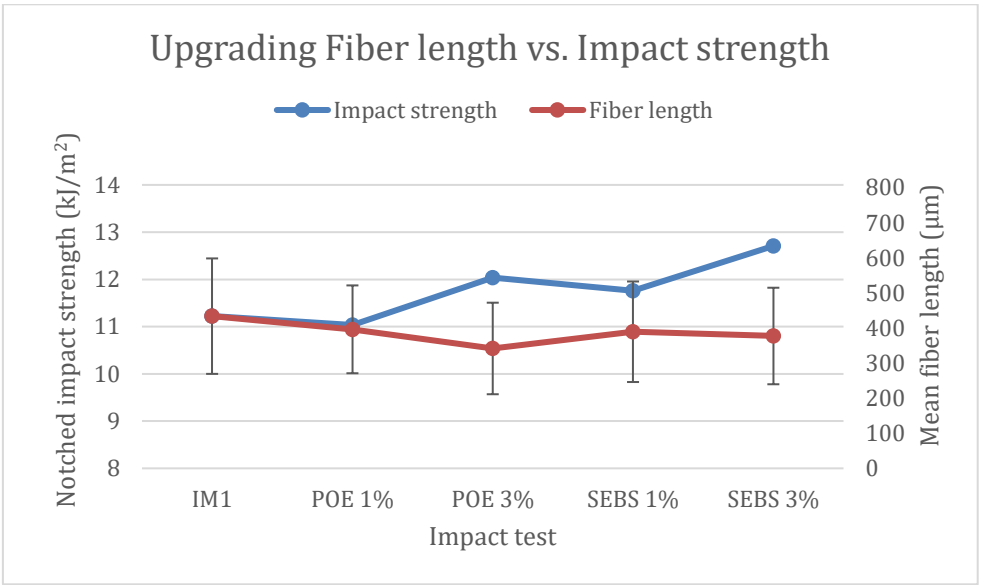


Figure 22 – Fiber lengths and tensile strength for IM1, and with addition of impact modifiers POE 1 %, POE 3 %, SEBS 1 %, and SEBS 3 % respectively.

5.2.3 Glass fiber and impact modifier addition

Experiments with a combined addition of impact modifier and glass fibers was performed by adding 1 wt% of SEBS to IM1, together with 10 wt% of post-industrial glass fiber (PIGF), resulting in a sample denoted PIGF 30 SEBS 1% IM1. A reprocessing experiment of this sample, i.e compounding and then injection molding test bars of PIGF 30 SEBS

1% IM1, resulted in the sample denoted PIGF 30 SEBS 1% IM2. These blends were compared to IM1, PIGF 30 and IM2.

Figures 23 and 24 show that the impact modifier had no positive contribution to the mechanical properties, possibly because of the quantities of 1 and 3 % impact modifiers were too low to have a significant effect on the impact strength. The results also show that 10 wt% addition of post-industrial glass fibers had no effect when the sample had been recycled twice in total, as compared to IM2 which has done the same.

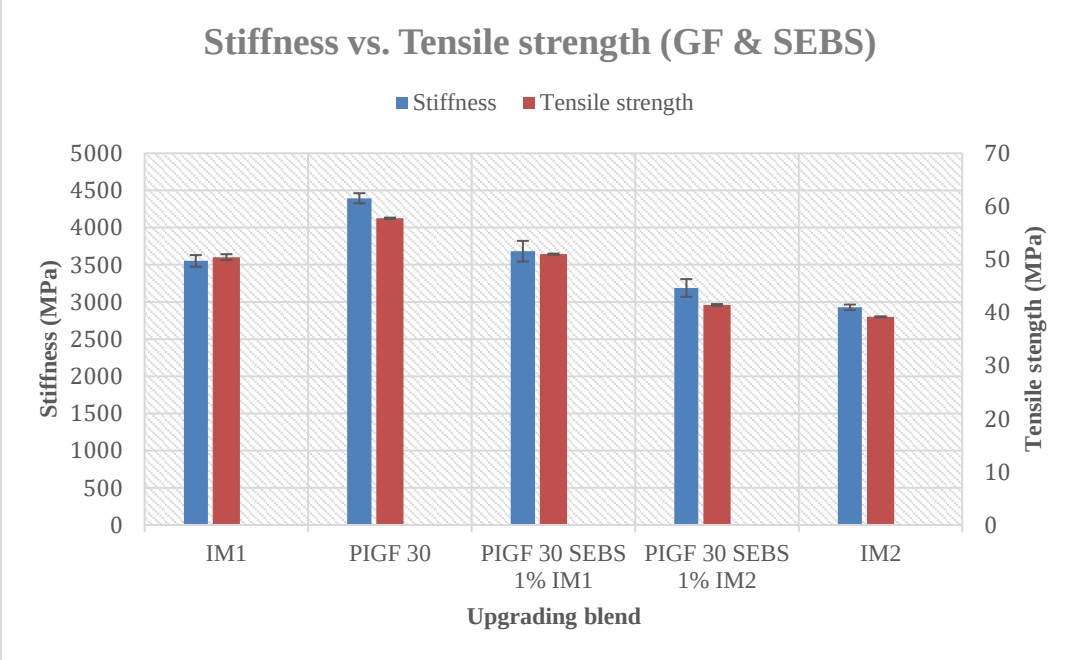


Figure 23 - Stiffness and tensile strength values for the sample with both impact modifier and 10 wt% post-industrial glass fibers added, called PIGF 30 SEBS 1% IM1 and PIGF 30 SEBS 1% IM2. IM1, PIGF 30 and IM2 are included in the plot as a comparison.

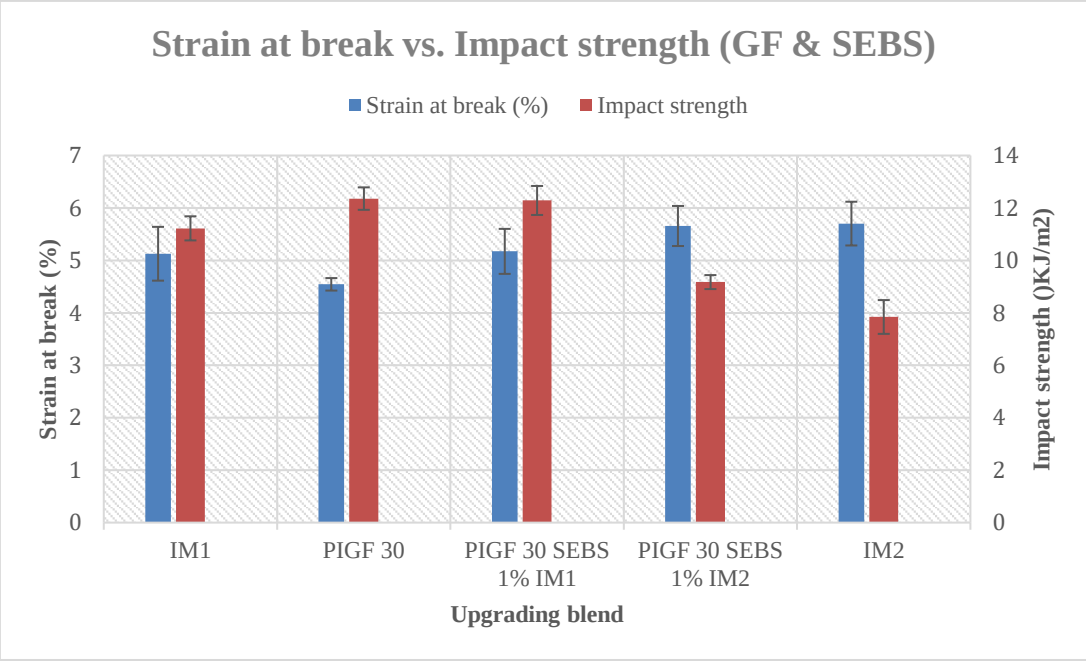


Figure 24- Strain at break and impact strength values for the sample with both impact modifier and 10 wt% post-industrial glass fibers added, called PIGF 30 SEBS 1% IM1 and PIGF 30 SEBS 1% IM2. PIGF 30 and IM2 are included in the plot as a comparison.

5.3 Theoretical analysis of composite properties

Halpin-Tsai and Kelly-Tyson models were used to help make a comparison of the experimental tensile modulus and strength. The Young's modulus data for both the models, as seen in Figure 25, showed a good agreement with the experimental data over a range of different aspect ratios and glass fiber concentrations. This could also be related to the fact that at this stage the factors determining the properties depend more on the volume fraction and aspect ratio of the fibers, as they are within the elastic region, rather than the interface properties.

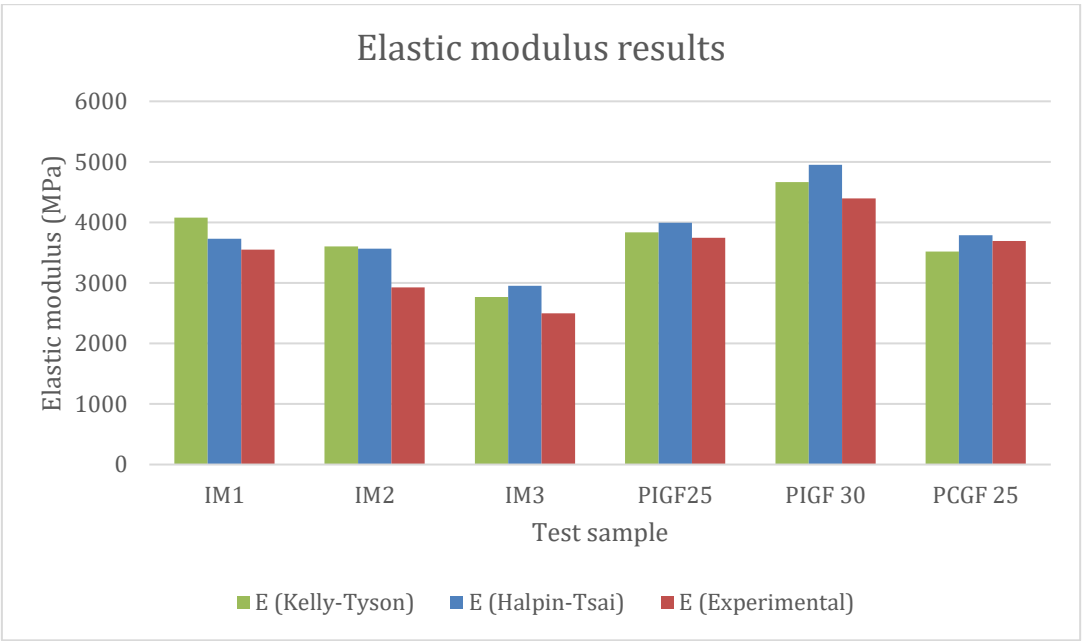


Figure 25 – Comparison of the theoretical and experimental Young's modulus data of the different PPGF composites.

The tensile strength data, as seen in Figure 26, showed large difference between the experimental and the theoretical values but despite the large difference between the theoretical and experimental tensile strength data, it was seen that the Halpin-Tsai model and Kelly-Tyson model were in close agreement with each other over the entire range of samples, see Table 3. This would suggest that the arrangement of the reinforcements in the composite and their aspect ratio were very close to the critical aspect ratios of the material.

Additionally, the large differences between the theoretical and experimental values could also be because the theoretical models assume the fibers to be well-dispersed within the matrix, aligned in the flow direction and have perfect fiber-matrix adhesion. Since fiber-matrix adhesion is one of the key-factors that decide the strength of the composite, these assumptions would have a significant over-estimation of the theoretical values.

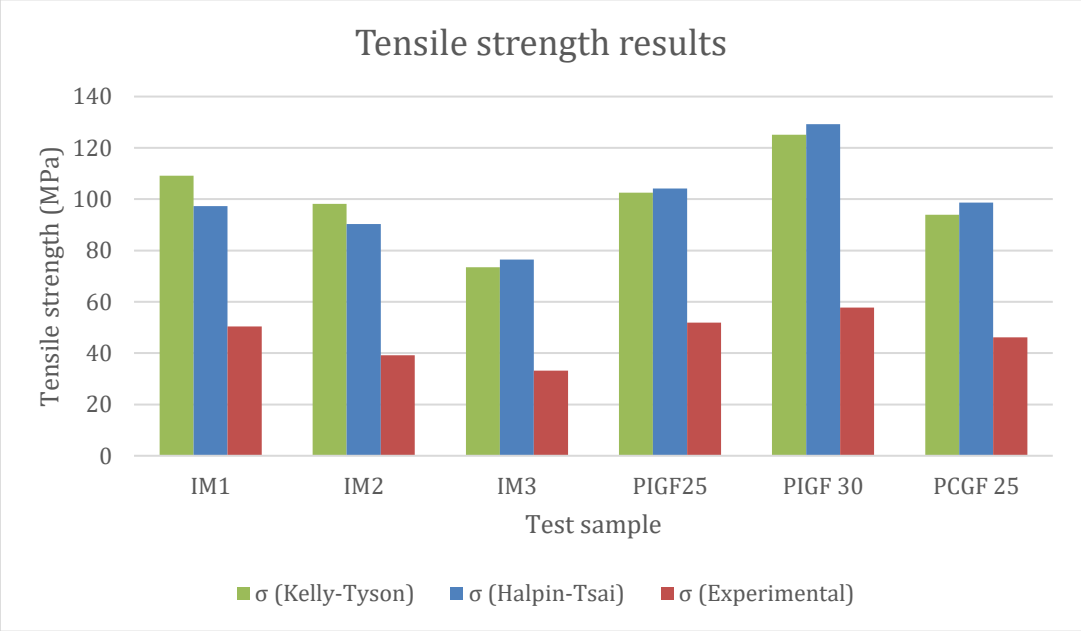
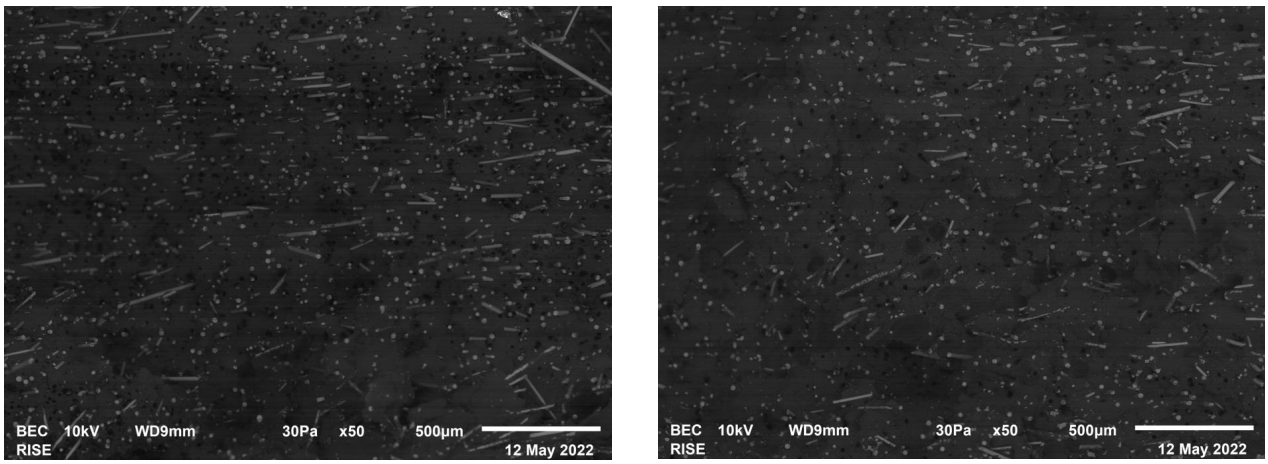


Figure 26 - Comparison of the theoretical and experimental tensile strength data of the different PPGF composites.

In Table 3, the interfacial shear strength of the composite, calculated from eq.9, was in the range of 47-51 MPa. Apart from IM2, IM3 and PCGF25, this value was lower than the experimental tensile strength suggesting that fiber pull-out due to the poor interface could be the dominant failure mechanism, see Figure 27 and Appendix 4. However, the theoretical interfacial shear strength value was higher than the experimental tensile strength for the IM2, IM3 and PCGF composites suggesting that the Kelly-Tyson model does not consider the changing aspect ratios (IM2, IM3) and the interface effects (PCGF). This was highlighted in the PCGF composites which showed high theoretical interfacial shear strength despite showing poor mechanical and impact properties, mainly due to unsized fibers acting like stress concentrators.

Table 3 - Elastic modulus and tensile strength experimental values of the Halpin-Tsai and Kelly-Tyson model

Test sample	IM1	IM2	IM3	PIGF 25	PIGF 30	PCGF 25
Mean fiber length l (μm)	382,78	316,27	209,19	269,94	283,49	238,59
Average fiber diameter d (μm)	20	20	20	19	18,33	19
Fiber volume fraction f (%)	8,26	8,26	8,26	10,7	13,4	10,7
Interfacial shear strength τ (MPa)	51,47	51,47	51,47	48,90	47,18	48,90
E Halpin-Tsai (MPa)	3729	3564	2950	3996	4951	3790
E Kelly-tyson (MPa)	4080	3603	2765	3835	4664	3517
E experimental (MPa)	3580	2603	2498	3745	4395	3693
σ Halpin-Tsai (MPa)	97,36	90,34	76,52	104,11	129,30	98,63
σ Kelly-tyson (MPa)	109,18	98,22	73,46	102,56	125,13	93,92
σ experimental (MPa)	50,44	39,2	33,17	51,95	57,75	46,16



(a) *(b)*

Figure 27 - SEM micrograph, 50x magnification, of fracture surface from (a) post-industrial and (b) post-consumer glass fiber composite.

5.4 Results compared to real-life automotive component requirements

At the start of the project, Volvo Cars provided material specifications on PPGF-materials that are currently, or in the future will be, used in their vehicles. The load floor support is an interior component assembled in the trunk, that was identified as a possible target for recycled and upgraded instrument panel. It is made from PPGF with 20 wt% glass fibers. Table 4 presents the material specification from Volvo, compared to some of the materials produced in this project.

Table 4 – Material comparisons

Properties	Volvo specification	IM1	SEBS 3 %	Virgin GF 25	PIGF 30
Glass fiber content [wt %]	20	20	20	25	30
Stiffness [MPa]	3700	3552	3078	4231	4395
Tensile strength [MPa]	46	50,4	44,3	59,5	57,8
Tensile elongation at break [%]	4,4	5,1	7,0	4,7	4,5
Charpy Impact Strength Notched 23 °C [kJ/m^2]	12	11,2	12,7	14,1	12,4
Charpy Impact Strength Notched -30 °C [kJ/m^2]	6	7,6	8,2	10,6	8,6

IM1 has properties that are very close to the material specification provided by Volvo Cars. The material providing the best results is Virgin GF 25, which has 5 wt % of added virgin glass fibers. However, it has a higher density and a higher cost compared to IM1. PIGF 30 has generally lower, or equal, properties as Virgin GF 25, but has an even higher density. SEBS 3 % provides an increase in impact strength and elongation at break compared to IM1, but a decrease in stiffness and tensile strength. It is, however, worth noting that IM1 was processed without any mixing elements.

5.4.1 Fiber content vs. density

Significant improvements in mechanical properties were obtained for the samples with 5 wt% added virgin glass fibers (Virgin GF 25), and 10 wt% post-industrial glass fibers (PIGF 30). These composites, however, have higher densities than the source 20% GF material, IM1. This fact questions the feasibility of using them in automotive components where part weight is of great importance. It can more easily be argued that addition of glass fibers can be beneficial if part weight is not an issue such as in a building material, for instance.

A calculation comparing 20, 25 and 30 wt% PPGF composite densities can be made using the rule of mixtures, where the density ρ is given by:

$$\rho = \frac{v_f \rho_f}{V} + \frac{v_m \rho_m}{V}$$

Where V is the total volume, v_f and v_m are the fiber and matrix volume fractions, respectively, and ρ_f and ρ_m are the fiber and matrix densities, respectively. Assuming a PP density of 946 kg/m^3, and glass fiber density of 2500 kg/m^3. Part weight will increase by up to 12,3% from an increase in glass fiber content from 20 to 30 wt%, see Table 5.

Table 5 - Fiber content versus density calculation results

	20% PPGF	25% PPGF	30% PPGF
Density (kg/m^3):	1257	1335	1412
Difference (%):	-	6,2	12,3

When it comes to fiber length, fibers that fall below the critical fiber length are still able to contribute somewhat to the material's mechanical properties. For this reason, the short fibers in the material are still of some use. This usefulness however comes at the cost of the fibers being less efficient, by weight, in strengthening the material. This leads, for the shortest fibers, to an increase in weight while the improvement in mechanical properties is small (T. Morii, 2009).

6 Conclusions

It was found that the fiber length reduces with processing, and it is important that this is taken into consideration when reprocessing materials, especially if this is done several times.

Sieving small particles increases the tensile strength. Short fibers, with lengths below the critical fiber length, do not provide the composite with strength and can instead act as impurities which lowers the strength of the composite.

Adding glass fibers can only be considered if a higher density is acceptable. Only glass fibers with proper sizing will contribute well to the improvement of properties.

The two impact modifiers added in this study at 1 wt% and 3 wt% only gave minor improvements to impact strength. If a large increase in impact strength is desired, more impact modifier should be added. The trade-off being that it will yield a softer material.

Both theoretical calculations and experimental results conclude that the material properties of a PPGF composite material stem from the fiber-matrix adhesion properties. Fibers with high aspect ratio are needed for better transfer of loads between the matrix and the fibers.

The theoretical calculations of the Young's modulus, both while using the Halpin-Tsai and the Kelly-Tyson models, match experimental values well. This is not the case when it comes to tensile strength as this depends on the interface to a large degree, which is not considered in the models. The experimental results for tensile strength being lower than the theoretical ones allow us to conclude that the interfacial strength of the measured composites is not ideal.

The instrument panel from an end-of-life vehicle has sufficient mechanical properties to be recycled but needs addition of antioxidants and stabilizers.

A recycling process with ELV instrument panels as raw material would include:

- Disassembly, specifically removing of polyurethane foam
- Milling
- Sieving, removing the smallest particles
- Compounding with addition of stabilizers
- Shaping

7 Further work

Recycling of ELV panels is suggested for further studies if suitable disassembling methods are provided. ELV panels as raw material for recyclate need addition of antioxidants and stabilizers and studies of the thermal properties are suggested.

Qualitative study of the interfaces between fibers and matrix is suggested. DMTA of thin injection molded samples would provide relevant data and give insights to the status of the adhesion. This will be important knowledge for any further upgrading with addition of PIGF or PCGF.

Upgrading of PPGF recyclate with recycled glassfiber from industrial waste should be studied by adding the long fibers to the recyclate during compounding without having prepared a master batch of fibers. This will likely contribute to a longer mean fiber length.

Post-consumer fibers that have been incinerated need a proper sizing before being used for upgrading. Sieving and thus removing the shortest fiber would also be relevant to obtain better results when upgrading.

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Appendix

Appendix 1 – Thermal process history

Material	Processing history	Thermal history
M1	Sawing, milling	None
M2	IM1 + milling	1 compounding, 1 Injection molding cycle
M3	IM2 + milling	2 compounding, 2 Injection molding cycles
C1	M1 + Compounding	1 compounding cycle
C2	M2 + Compounding	2 compounding, 1 Injection molding cycle
C3	M3 + Compounding	3 compounding, 2 Injection molding cycles
IM1	C1 + Injection molding	1 compounding, 1 Injection molding cycle
IM2	C2 + Injection molding	2 compounding, 2 Injection molding cycles
IM3	C3 + Injection molding	3 compounding, 3 Injection molding cycles

Appendix 2 – Mean fiber length results from the reprocessing

Feature	Mean	Std.Dev.	Minimum	Maximum	Process
Length	711,73	479,85	29,08	2813,58	M1
(µm)	433,72	328,98	39,89	1586,21	C1
	382,78	304,71	26,3	1425,06	IM1
	377,4	253,2	57,19	1094,31	M2
	268,76	205,28	25,48	1327,1	C2
	316,27	247,31	40,28	1572,99	IM2
	237,33	186,25	23,34	1213,19	M3
	238,13	175,59	22,58	916,74	C3
	209,19	152,32	38,09	991,96	IM3

Appendix 3 – Tensile and impact test data. Parenthesis values indicate standard deviation.

Sample	E-Modulus (Mpa)	Strain At yield (%)	Strain at yield (Mpa)	Strain At Break (%)	Charpy impact test (KJ/m²)
M1	3822 (92)	3,33 (0,08)	57,33 (0,27)	4,66 (0,45)	12,7 (0,3)
IM1	3552 (78)	3,93 (0,08)	50,44 (0,55)	5,13 (0,51)	11,2 (0,5)
IM2	2928 (37)	4,35 (0,13)	39,20 (0,09)	5,70 (0,42)	7,8 (0,6)
IM3	2497 (50)	4,35 (0,11)	33,04 (0,16)	6,23 (0,59)	5,6 (0,4)
AzPPGF	3713 (125)	2,99 (0,09)	52,70 (1,85)	3,01 (0,21)	10,8 (0,5)
Sieve 1mm	3749 (51)	3,49 (0,05)	56,34 (0,39)	4,59 (0,08)	13,2 (0,6)
Sieve 2mm	3841 (61)	3,42 (0,07)	57,58 (0,44)	4,44 (0,40)	13,9 (0,7)

Sample	E-Modulus (Mpa)	Strain At yield (%)	Strain at yield (Mpa)	Strain At Break (%)	Charpy impact test (KJ/m²)
POE 1%	3320 (86)	4,19 (0,12)	46,94 (0,42)	5,80 (0,54)	11,0 (0,7)
POE 3%	3161 (91)	4,39 (0,10)	44,63 (0,56)	5,94 (0,30)	12,0 (0,4)
SEBS 1%	3383 (82)	4,25 (0,07)	47,92 (0,53)	5,74 (0,47)	11,8 (0,5)
SEBS 3%	3078 (47)	4,83 (0,16)	44,31 (0,47)	7,02 (0,64)	12,7 (0,6)

Sample	E-Modulus (Mpa)	Strain At yield (%)	Strain at yield (Mpa)	Strain At Break (%)	Charpy impact test (KJ/m²)
Virgin GF 25	4231 (70)	3,56 (0,07)	59,45 (0,35)	4,65 (0,30)	14,1 (0,4)
PIGF 25	3745 (140)	3,87 (0,40)	51,95 (0,12)	5,12 (0,28)	12,0 (0,4)
PIGF 25 SEBS 1%	3681 (49)	4,08 (0,89)	50,56 (0,31)	5,35 (0,28)	12,5 (0,4)
PIGF 25 SEBS 3%	3577 (131)	4,41 (0,17)	48,23 (0,27)	5,92 (0,52)	13,8 (0,6)
PIGF 30	4195 (68)	3,62 (0,06)	57,75 (0,14)	4,54 (0,12)	12,4 (0,4)
PIGF 30 SEBS 1% IM1	3683 (139)	3,95 (0,10)	51,00 (0,11)	5,17 (0,43)	12,3 (0,6)
PIGF 30 SEBS 1% IM2	3188 (119)	4,27 (0,11)	41,44 (0,16)	5,66 (0,38)	9,2 (0,3)
PCGF 25	3693 (65)	2,84 (0,04)	45,16 (0,28)	4,14 (0,35)	7,8 (0,3)

Appendix 4 – SEM images from upgrading. Figure 28 shows the fracture surface of a sample with post-industrial glass fibers (PIGF). Figure 29 shows the fracture surface of a sample with post-consumer glass fibers (PCGF).

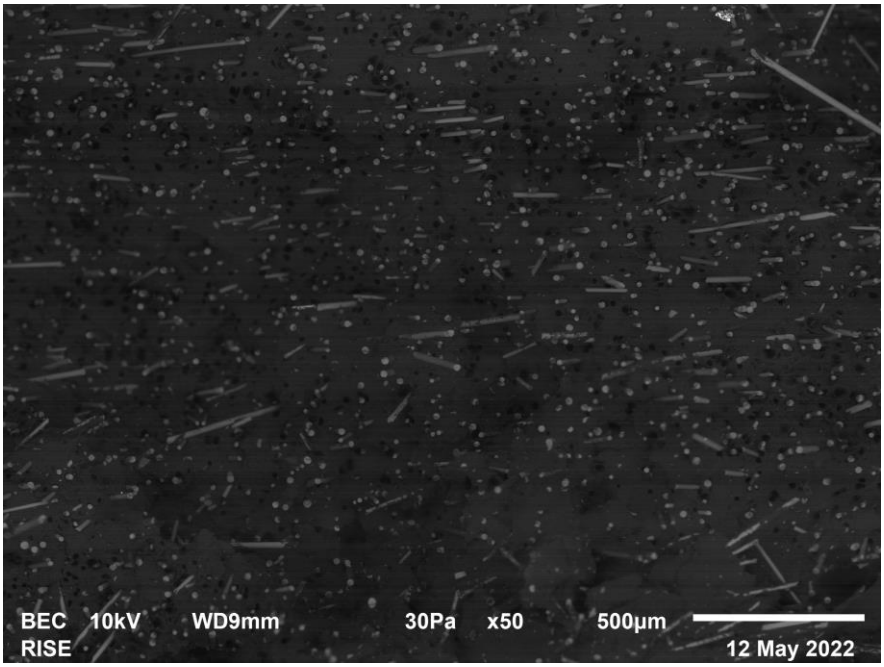

Figure 28 - SEM micrograph, 50x magnification, of fracture surface from a post-industrial glass fibers sample.

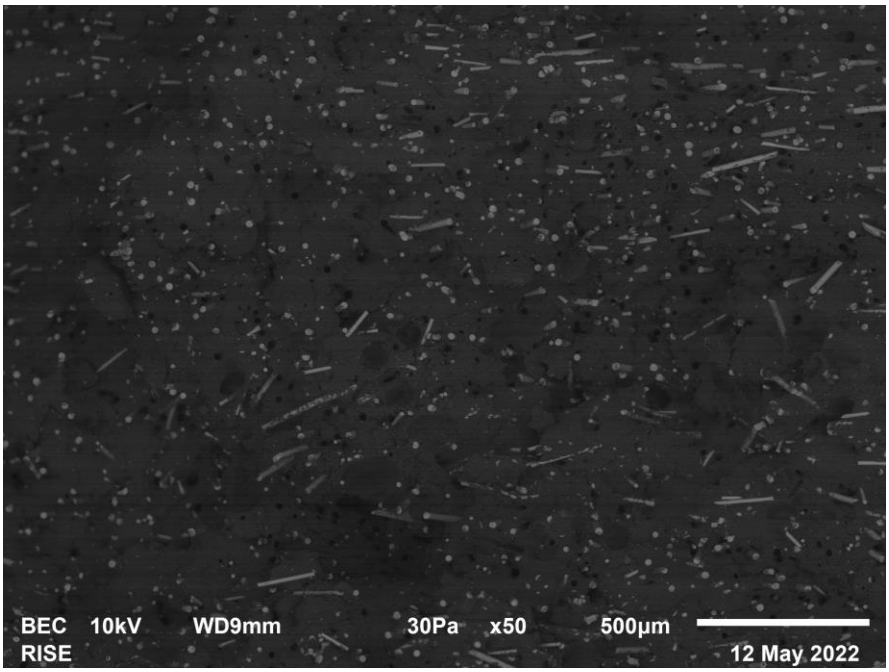

Figure 29- SEM micrograph, 50x magnification, of fracture surface from a post-consumer glass fibers sample.

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