PolyCE

Post-Consumer High-tech Recycled Polymers for a Circular Economy

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Summary

This document has the scope to serve as a practical guide to evaluate polymer feedstock materials, mainly post-consumer (PCR) and post-industrial (PIR) recycled plastics as candidates for additive manufacturing (3D printing) applications.

The document also investigates the most effective and efficient processing strategies and conditions for recycled polymers processing in 3D Printing (in both single and multi-material applications), and the most promising strategies to improve the strength and quality of 3D-printed parts.

The conditions examined in the present document will refer to fused filament fabrication (FFF), a 3D printing process that uses a continuous filament of thermoplastic material that is extruded through a heated nozzle for the production of the final part with a layer-by-layer approach. It is also shown results of 3D printed parts obtained by a new micro-extruder, pellet-based machine.

The content of the document is based on previous literature studies as well as experiments conducted by Ghent University.

The investigation identified the melt flow rate (MFR), the Young modulus, the material ductility, volume variation (shrinkage), and the material homogeneity as key parameters for a polymer feedstock material to be suitable for a successful FFF 3D printing process. In order to produce 3D printed parts with acceptable quality, it is recommended that the plastic filament presents a homogeneous composition with good dimensional stability, an MFR higher than 10 g/10 min, a moderate Young modulus (> 0.4 GPa), and certain ductility (the material cannot be very brittle). Furthermore, the smaller the shrinkage the better. The effect of the shrinkage of the polymer from the melt, which can cause warpage, can be reduced by using higher bed and chamber (envelope) temperatures. The micro-extruder 3D printer was able to produce final parts using a flexible, low-Young modulus material that was unable to be produced by the FFF method.

In Chapter 3, the key learnings from tasks 7.8 and 7.9 are listed, presenting the various challenges faced in single and multi-material printing of recycled polymers as well as the strategies used to overcome them.

Finally, as a compendium, the specific results of the single and multi-material 3D printing tests are presented in Appendix A.

Content

1 Introduction

Additive manufacturing (AM), also known as 3D printing or rapid manufacturing, has strongly developed over the last years [1]. Although AM was initially used mainly for rapid prototyping, its use in direct manufacturing of end-products is growing fast [2], [3]. Nowadays, with the commercialization of personal AM machines ('3D printers'), it is possible to manufacture finished parts at home [2].

The different sectors where the use of AM is currently bringing relevant innovations are the consumer/electronic products, medicine and medical engineering, architecture, and the automotive, aviation, construction, and food industries [4].

Among the several polymer-based AM technologies available, the extrusion-based additive manufacturing (EAM) methodology, also known as fused filament fabrication (FFF) or fused deposition modelling (FDM) is the most used. FFF consists of forcing a polymer filament through a heated nozzle promoting its melting, followed by the continuous deposition of the molten material as tracks in the horizontal plane and consecutively stacking of the tracks by vertical displacement, generating three-dimensional shapes [5].

The present document presents key parameters for a polymer feedstock material to be suitable for a successful 3D printing process by FFF.

The key learnings from the WP7 are also presented in Appendix A.

2 Materials and methods

The content of this document is based on previous literature studies as well as experiments conducted by Ghent University.

The main tests were done using two low-cost commercial printers: a Prusa i3 MK3S for the single material processes and a Prusa MK3S MMU2S for the multi-material processes.

Further tests were then conducted with a SpiderBot 4.0 HT by Qualup with the scope to overcome part of the limitations faced with the Prusa counterparts.

Finally, a commercial uPrint® from Stratasys was used to investigate the possibilities to use recycled ABS as for high-end FDM processing.

As only exception, the tests on thermoplastic polyurethane (TPU – IROPRINT 78 E 2705), a flexible, low Young modulus material in pellets-shape used a micro-extruder for pellet-based FDM designed and built at CPMT. The tests, in this case, were limited to a single layer print as the printing head is still under development and does not yet allow full parts manufacturing.

The other materials tested include:

- Post-Consumer PC/ABS blend
- Post-Industrial PC/ABS blend
- Post-Industrial ABS (by UGent)
- Post-Consumer ABS (by MGG)
- Post-Consumer ABS (by MGG, EvoSource 4136)
- Post-Consumer ABS (by MGG, EvoSource 4136 compounded at CPMT with 2 m.% polymer-based process improvement additive - PPI)

3 A guide to feedstock material selection

The first part of the investigation focuses on the key material properties that make a material printable through fused filament fabrication (FFF).

FFF requires the material in a filament form to be fed from a large spool through a moving, heated printer extruder head, and be deposited on the growing work.

It is worthwhile to mention that, one of the key learnings from task 7.8, that investigated the properties of ABS polymer through consecutive cycles of 3D printing and recycling, was that the material properties can decrease substantially during the filament processing and again in the AM process [5].

For this, and other reasons that are going to be presented in this chapter, it is crucial to identify recommended intervals for the different properties for a successful part manufacturing with the desired properties.

The intervals are, where available, synthetically reported in Table 1.

It is also important to remember that polymers can be hygroscopic, and this tendency to absorb humidity can directly affect the printing quality, reducing layers strength and cohesion. It is therefore suggested to dry the filaments before their use.

I. Melt Flow Rate (MFR)

The melt flow rate (MFR) is a measure of the flowability of the melt of a thermoplastic polymer.

MFR is defined as the mass or volume of polymer flowing in ten minutes through a capillary of a specific diameter and length by a pressure applied via prescribed alternative gravimetric weights for alternative prescribed temperatures.

In polymer processing the value of MFR is often correlated to the suitability of the polymer to a specific process. Different studies on the subject conducted at the CPMT [6] suggested that the MFR can be used as a predictor for a successful 3D printing process. The conclusion of the studies is that an improvement in the properties of the 3D printed part was observed for MFR values lower than 10 g/10min [7].

Previous studies at the CPMT also shown that the value of the MFR can increase when the material is processed, as its viscosity tends to decrease [5].

II. Young Modulus

The Young modulus is a mechanical property that measures the stiffness of a material. It is defined as the ratio of stress below the proportional limit to the corresponding strain.

The young modulus is an important parameter in 3D printing, as the mechanism commonly used in 3D printing to push the filament through the nozzle requires a certain rigidity to avoid buckling. Soft materials (e.g. TPU, SEBS) do not generally work on standard 3D printers.

A previous study observed that the buckling of the filament can be avoided if the ratio between the compression modulus of the filament and the melt viscosity is higher than the critical buckling stress [8]. In this sense, a higher compressibility modulus (which is normally proportional to the Young modulus), or a lower melt viscosity, reduce the possibility of buckling of the filament.

Based on an investigation on the material properties of the common filaments on the market, the filament with the lowest Young Modulus for application in the standard 3D printing gear system was identified at about 0.4 GPa [9-10].

III. Ductility

Brittle materials, when subjected to stress, break with little elastic deformation and without significant plastic deformation. An excessively brittle material can lead to failures in the process of feeding or interruptions in the continuity of the filament, leading to a failure of the 3D printing process.

The ductility of the materials is in general measured by the fracture strain of a representative volume element of material subjected to homogeneous loading conditions.[11].

The limit value of the fracture strain that allows to confidently use a 3D printing filament avoiding feeding issues is in general dependent on the material and conditions (both temperature and feeding rate can affect this value).

Based on an investigation on the material properties of the common filaments on the market, however, materials that exhibit a strain at break above 6% are generally considered to be ductile enough for a smooth feeding process [12,13].

Previous studies at the CPMT also shown that the material ductility tends to decrease after processing [5].

IV. Shrinkage/Warping

Shrinkage occurs due to variation in the specific volume of the material between the processing temperature and room temperature.

The shrinkage of the material and a non-uniform cooling can cause residual stresses leading the material to warp [14,15].

While the problems related to a high variation of the specific volume can be tackled also during the printing process (e.g. with the use of local heating, closed chambers, heated bed, glue, etc.) it can be a good idea, where possible, to select a material blend with a reduced variation in the specific volume of the material between the processing temperature and room temperature.

V. Impact strength

The impact strength of a material is defined as its capability to resist a sudden applied load or force. It is normally conveyed as the amount of mechanical energy absorbed in the process of deformation under the applied impact load.

The requirements in terms of impact strength are recommended to be higher than the final part requirements, as in previous studies at the CPMT decrements up to about 20% were observed after processing [5].

Table 1 - Recommended intervals for different properties relevant for the FFF process of plastics

Property	Intervals	Risks
Melt Flow Rate	> 10g/10min [6]	Decrement in properties were observed for higher values of MFR.
Young Modulus	> 400 MPa	Feeding mechanism is in general not reliable for very flexible materials.
Ductility	Strain at break > 6%	Brittleness is often cause of failures in the feeding mechanism.
Specific volume variation	As low as possible.	Can lead to warping and detachment of the part from the bed.
Impact strength	At least 20% higher than the final part requirement	Decrements normally occurs after compounding and filament production

4 Key Learnings from the demonstrator obtained in task 7.8 & 7.9.

The objectives of the Tasks 7.8 “3D printing technology optimized for PCR plastics from WEEE” and 7.9 “Validation of PCR plastics from non-WEEE streams in new EE applications” were aligned into the 3D printing of the top lid cover of a Philips Senseo® Original coffee brewing system.

In this second part of the investigation the main challenges faced in the task 7.8 & 7.9 are presented, together with and the strategies used to overcome them.

I. Smoother surface using a layer thickness gradient (LTG)

Due to the curvature of the demonstrator, it was usually hard to have a high resolution of the parts, avoiding the ‘steps effect’ as visible in Figure 1a.

One of the solutions would be to use a really thin layer, but this would increase the duration of the print by several times (up to 4 times the original time, depending on the settings), also increasing the susceptibility to failures. This effect was mitigated introducing a layer thickness gradient, as visible in Figure 1b.

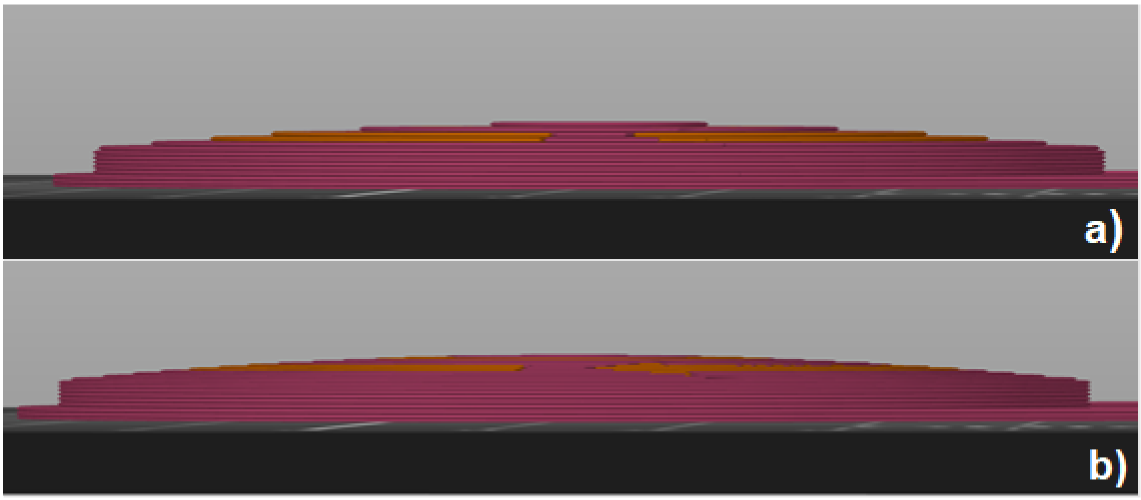

Figure 1 – Effect of layer thickness gradient (LTG) in the smoothness of the part surface. a) Thick layer; b) Thin layer.

In Figure 1b, the layers at the top are thinner, allowing a better resolution, while for the bottom part (Figure 1a), the thickness was kept constant at a higher value. The smoothness of the surface is comparable to what we would have using a constant thin layer, in up to 1/3 of the needed printing time and less susceptible to failures.

II. Melt Flow Rate MFR

For the different materials a specific range of temperature (nozzle temperature) and pressure (determined for the slicer used in these tests by the 'Extrusion multiplier') was identified.
In previous studies conducted at CPMT [6], it was concluded that the optimal processing temperature should give a MFR value higher than 10 g/10 min.

III. Warping

Warping is usually present when the specific volume of the material changes between the processing temperature and room temperature and the cooling is not uniform.
This is in part resolved by using a closed heated chamber and a heated printing bed.
The positioning of the demonstrator has a strong effect on the temperature gradients in the final part and appeared to also have a significant effect on the warping.
In particular, the warping appeared to be noticeably reduced when the convex surface faces the printing bed. In this condition however the presence of supports was required that, in the mentioned conditions of heated bed and chamber led to excessive cohesion between the part and its support, affecting the quality of the top surface.
Improvements were also observed in the adhesion of the material to the platform with the use of specific glues.

IV. Material selection (Multi-material)

a) It is crucial that the different materials selected for a multi-material printing have similar processing parameters (ideally the same). In the printing of PC/ABS + virgin ABS, the ABS was selected to have processing temperatures close to the PC/ABS to reduce the dead time between the layer and the points of failure for the printing.

b) The mechanism commonly used in 3D printing to push the filament through the nozzle requires a certain rigidity and does not allow the use of soft materials (e.g. TPU, SEBS). This was the case of the TPU tests. The use of the micro-extruder allowed to overcome this limitation, but the machine is still being optimized and at the current state is not able to print a full demonstrator.

c) The requirements in terms of impact strength are recommended to be higher than the final part requirements, as in previous studies at the CPMT decrements up to about 20% were observed after processing.

V. Adhesion/Cohesion

For some of the tested materials, it was observed an insufficient quality of the bond between successive layers. In the FDM™ process, the temperature history of the interfaces has been identified to be an important parameter in determining the bond quality between the layers and overall part strength. This is because the primary bonding mechanism between layers is thermal fusion and polymer interdiffusion, which depends on the thermal energy of the semi-molten polymer and the area of contact between the layers [16].
For this reason, the quality of the printing when using a heated chamber appeared to be noticeably better and less susceptible to failure, due the temperature of a generic layer n being higher at the moment of the n+1 layer deposition, as visible in Figure 2.

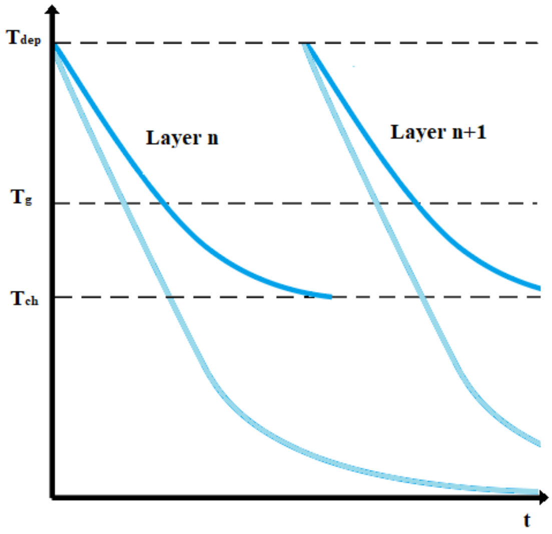

Figure 2 – In the case of heated chamber (dark blue) the temperature of the layer n is higher at the moment of the deposition of the layer n+1 compared to the reference case (light blue).

VI. Orientation

The orientation of the part is also one of the crucial aspects to consider in additive manufacturing, in both single and multi-material application.

In multi-material application the printing process has additional points of failure due the additional components present and, especially in single nozzle 3D printers, in the process of switching the filaments. When the different materials sections are localized in a limited number of layers, a good positioning of the part can make sure that the AM process begins with the manufacturing those layers. This could save a discrete amount of time, compared for example to the case in which the whole part is manufactured and the section with the higher chances of failures is printed for last.

In general, a good positioning of the part can also affect its adhesion on the printing bed and, as mentioned in point III has a strong effect on the temperature gradients in the part, enhancing or reducing the resulting warpage.

In case support materials are present, a good positioning should also ensure, when possible, that the external surfaces of the part are not in contact with the supports, as this can noticeably lower the surface quality.

5 Conclusions

In conclusion, it was possible to identify in the MFR, impact strength, ductility, Young modulus, and the specific volume variation from processing to room temperature the most important parameters to ensure that a material is 3D printable.

The warping due to the specific volume variation is the only parameter on which is possible to intervene, even if only to a limited extent, during the printing process, using a closed, heated chamber and bed, and material specific glues.

For the other parameters, the only option is to intervene during the compound phase, with the integration of additives or by a blend with a suitable material to obtain a blend more suitable to 3D printing applications.

It is therefore crucial to characterize the candidate materials before the compounding and filament production.

6 Notes and References

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Appendix A – Tasks 7.8 & 7.9 Demonstrator

In this section the results of the multi-material 3D printing for the Tasks 7.8 & 7.9 Demonstrator will be presented for each of the tested materials.
The equipment used for the tests initially consisted of two Prusa MK3s 3D printers, one of which was equipped with a MMU2S multi-material unit. Later on, to overcome some of the printers' limitations a SpiderBot 4.0 HT by Qualup was also used. The main specification of the two printers is presented in Table A1.

Table A1 – Main characteristics of the machines used.

	Prusa MK3S	SpiderBot 4.0 HT	Units
Printing Bed Shape	Rectangular	Circular	
Build volume (X×Y×Z) / (π×r^2×Z)	25 x 21 x 21 cm	π x 11^2 x 18 cm	cm^3
Filament	1,75 mm	1,75 mm	mm
Nozzle	0,4 mm	0,4 mm	mm
X/Y resolution	0,01 mm (adv)	>0,01 mm (adv)	mm
Min, layer thickness	0,01 mm (adv)	>0,01 mm (adv)	mm
Max Temperature	300 (adv)	470 (adv)	°C
Heated Bed	YES	YES	
Heated Bed Max Temperature	100	150	°C
Closed Chamber	NO	YES	
Heated Chamber	NO	YES	
Heated Chamber Max Temperature	N/A	90	°C
Liquid cooling	NO	YES	
Multi-Material support	YES, with MMU2S	OPTIONAL (not present)	
Built-in LTG	YES	NO	

The materials tested, as mentioned in Chapter 2 are:

- Post-Consumer PMMA blended with virgin ABS (by Sitraplas)
- TPU IROPRINT 78 E 2705 (pellets) & TPU IROPRINT F 80112 (filament)
- Post-Consumer PC/ABS blend
- Post-Industrial PC/ABS blend
- Post-Industrial ABS (by UGent)
- Post-Consumer ABS (by MGG)
- Post-Consumer ABS (by MGG, EvoSource 4136)
- Post-Consumer ABS (by MGG, EvoSource 4136 reprocessed at CPMT with m.% polymer-based process improvement additive)

I. Post-Consumer PMMA blended with virgin ABS (Sitraplas)

The material is a post-consumer Polymethyl methacrylate (PMMA) blended with virgin Acrylonitrile Butadiene Styrene (ABS) to improve its ductility.
The material presented a good flowability at a nozzle temperature of 240-250 °C.
The material presented a high tendency to warp during the cooling process and a bad adhesion to the printing and bad cohesion between the layers.
To reduce the warping and improve adhesion and cohesion, the part was printed in a closed heated chamber and bed, with material specific glues to improve the adhesion to the printing bed. Even in these conditions the part still exhibited a high degree of warping, as visible in Figure 1A.

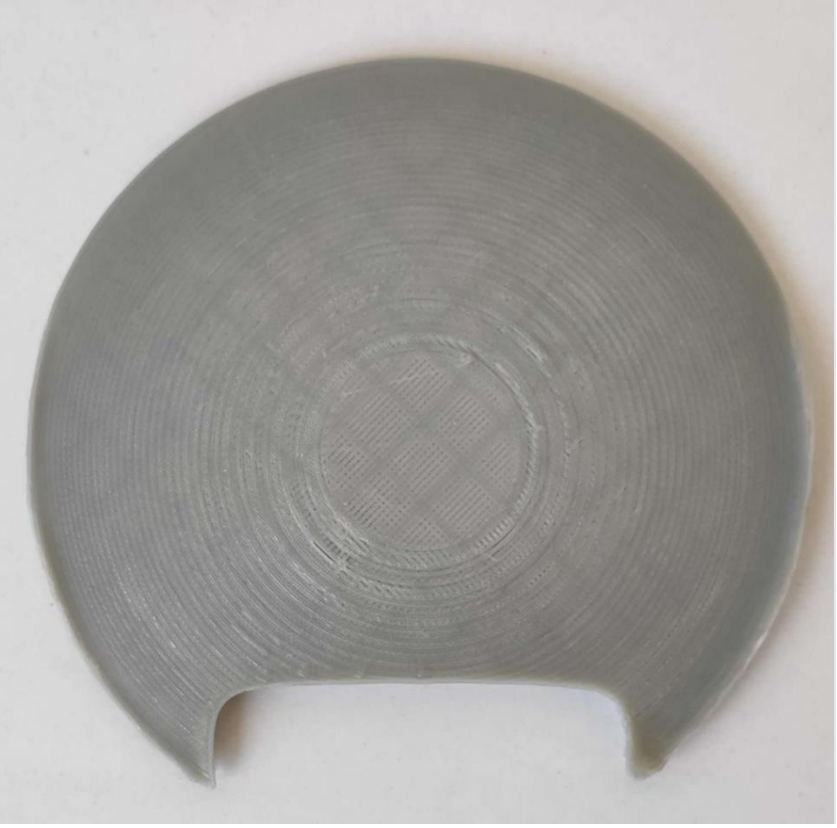

Figure 1A – Demonstrator realized in Post-Consumer PMMA/ABS blend using a SpiderBot 4.0 HT printer. The effects of warping are visible towards the edges.

The warping behavior noticeably improves when the part is printed with the convex surface facing the printing bed, with a heated chamber and bed. In these conditions, however, the cohesion between the supports and the part's surface led to a bad surface finishing.
The material appears not to be suitable for the printing of large parts, with low thickness.
A heated chamber and bed are strongly advised. The conditions used for the 3D printing process, as well as the main results, are shown in Table A2.

Table A2 - Conditions used for the 3D printing process and main results.

Color	Opaque	
Material	PMMA/ABS blend	
Source (PC/PI)	PC	
Processing temperature	240-250	°C
Printing bed temperature	100	°C
Closed chamber	YES	
Closed chamber temperature	100-120	°C
Min. layer thickness (in tests)	0.1	mm
Filament homogeneity	Good	
Flowability	Good	
Variation in diameter along the length	Low	
Adhesion	Mediocre in heated closed chamber	
Cohesion	Good in heated closed chamber	
Warping	Very high in heated closed chamber	
Finite part dimensional accuracy	Low	
Finite part surface quality	Low	

II. TPU IROPRINT 78 E 2705 (pellets) & TPU IROPRINT F 80112 (filament)

The material is a polyester-based thermoplastic polyurethane (TPU) filament (IROPRINT F 80112), was too flexible for application in the standard 3D printers.

The TPU in pellets-shape (IROPRINT 78 E 2705) was tested in a micro-extruder additive manufacturing 3D printer, presenting good flowability at 2 RPM and at a barrel temperature of 210°C.

The material was used for the production of ISO 527 Type 1A tensile bars. The results are presented in Figure 2A.

The material appears to be a good candidate for 3D printing, but the low rigidity of the filament does not allow its application in 3D printers that use the uses a traditional pushing gears mechanism. The conditions used for the 3D printing process, as well as the main results, are shown in Table A3.

Figure 2A – Tensile bars ISO 527 Type 1A made in TPU using the micro-extruder additive manufacturing 3D printer developed at CPMT.

Table A3 - Conditions used for the 3D printing process and main results.

Color	Opaque	
Material	TPU	
Source (PC/PI)	Virgin	
Processing temperature	210 [micro-extruder barrel temperature]	°C
Printing bed temperature	n/a	°C
Closed chamber	NO	
Closed chamber temperature		°C
Min. layer thickness (in tests)	0.3	mm
Filament homogeneity	Good	
Flowability	Good	
Variation in diameter along the length	Low	
Adhesion	Good	
Cohesion	Good	
Warping	Low	
Finite part dimensional accuracy	n/a	
Finite part surface quality	n/a	

III. Post-Consumer PC/ABS blend

The material is a blend of post-consumer Polycarbonate and Acrylonitrile Butadiene Styrene ABS plastic which combines the strength and heat resistance of PC with the flexibility of ABS.
The material was tested and present a good flowability for 3D printing at a nozzle temperature of 260-280°C.
The material has a tendency to warp while cooling; the effect was mitigated with a heated chamber and bed, and material specific glues.
A final part was completed in single material with relatively high step size. The part, as visible in Figure 3A presents a bad surface quality.

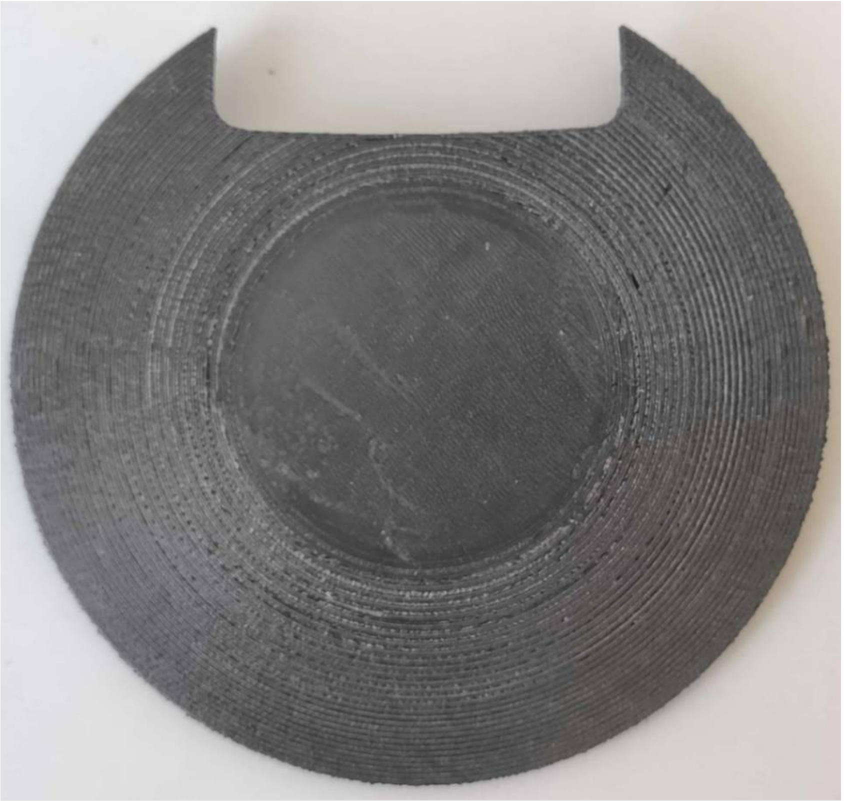

Figure 3A – Demonstrator realized in Post-Consumer PC/ABS blend using a Prusa MK3s printer.

The printing problems are attributed to the combination of the high processing temperature and long printing times due to the big dimensions of the part often resulting in thermal runaway errors.
The failures in the multi-material prints are attributed to the MMU2S unit that appears not to be reliable for large parts.
The low homogeneity didn't allow the material application in the SpiderBot 4.0 HT 3D printer, due to the longer distance between the pushing gears and the printing unit, connected through a long slim tube (Bowden system).
The bad dimensional stability, low ductility, and low homogeneity of the filament make the material not adequate for the additive manufacturing of parts, especially the ones requiring long printing

times. The conditions used for the 3D printing process, as well as the main results, are shown in Table A4.

Table A4 - Conditions used for the 3D printing process and main results.

Color	Black	
Material	PC/ABS blend	
Source (PC/PI)	PC	
Processing temperature	260-280	°C
Printing bed temperature	100	°C
Closed chamber	YES	
Closed chamber temperature	80-100	°C
Min. layer thickness (in tests)	0.2	mm
Filament homogeneity	Very low	
Flowability	Good	
Variation in diameter along the filament	High	
Adhesion	Good in heated closed chamber	
Cohesion	Good in heated closed chamber	
Warping	Mediocre in heated closed chamber	
Finite part dimensional accuracy	Good	
Finite part surface quality	Low	

IV. Post-Industrial PC/ABS blend

The material is a blend of post-industrial polycarbonate PC and Acrylonitrile Butadiene Styrene (ABS) plastic which combines the strength and heat resistance of PC with the flexibility of ABS.
The dimensional stability and visual homogeneity of the material are good.
The material was tested, presenting a good flowability for 3DP at a nozzle temperature of 270-280°C.
The material has a tendency to warp while cooling, the effect was mitigated with a heated chamber and bed, and material specific glues.
Most of the printing attempts used the SpiderBot 4.0 HT 3D printer, due to the combination of the high processing temperature and long printing times often resulting in thermal runaway errors in the Prusa MK3S.
It was possible to print a part at a relatively small step size, increasing noticeably the surface quality of the finite part.
The material appears to be a good candidate for 3D printing; however, due to the high processing temperatures, it is not recommended for 3D printing of large parts in lower-end 3D printers. The conditions used for the 3D printing process, as well as the main results, are shown in Table A5.

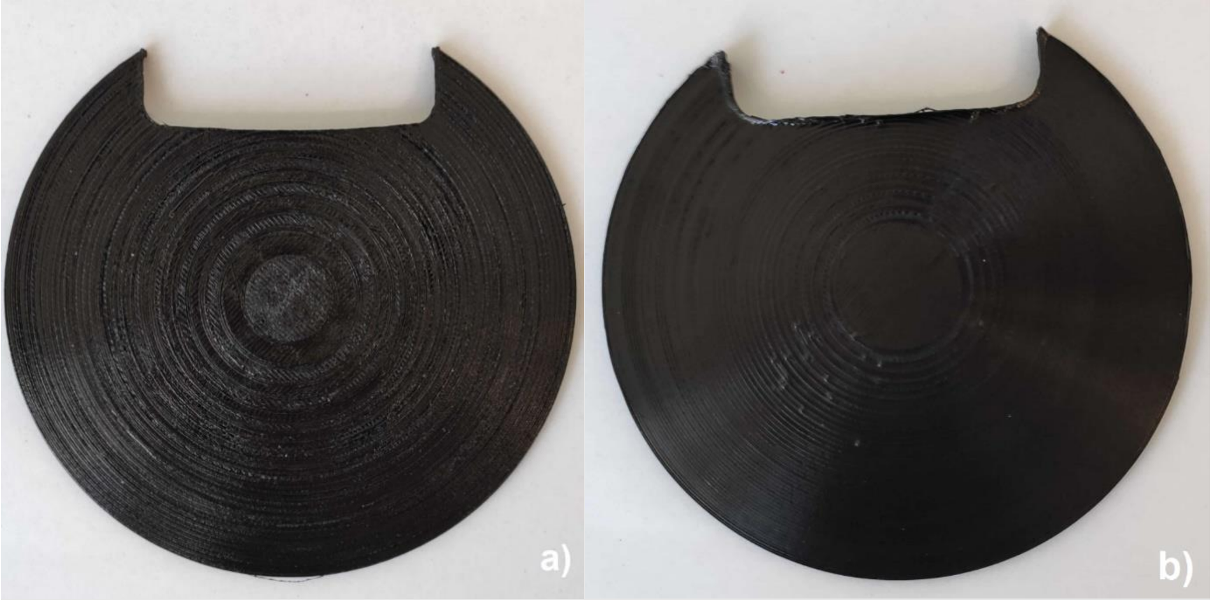

Figure 4A - Demonstrator realized in Post-Consumer PC/ABS blend using a SpiderBot 4.0 HT with a layer thickness of 0.3mm (a) and 0.15mm (b).

Table A5 - Conditions used for the 3D printing process and main results.

Color	Black	
Material	PC/ABS blend	
Source (PC/PI)	PI	
Processing temperature	260-280	°C
Printing bed temperature	100	°C
Closed chamber	YES	
Closed chamber temperature	80-100	°C
Min. layer thickness (in tests)	0.1	mm
Filament homogeneity	Good	
Flowability	Good	
Variation in diameter along the filament	Low	
Adhesion	Good in heated closed chamber	
Cohesion	Good in heated closed chamber	
Warping	Mediocre in heated closed chamber	
Finite part dimensional accuracy	Good	
Finite part surface quality	Good	

V. Post-Industrial ABS (UGent)

The material is a post-industrial Acrylonitrile Butadiene Styrene (ABS) plastic.
The filament presents a good diameter uniformity and ductility. It was tested at various temperatures and present a good flowability for 3DP at a nozzle temperature of 240-260°C.
The material also has a tendency to warp while cooling; the effect was mitigated with heated chamber and bed.
A multi-material demonstrator was printed with virgin ABS. Different failures were also registered for this case and are mostly attributed to failures in the multi-material unit that appears not to be reliable for large parts.

A complete part was printed with a relatively small step size, using the SpiderBot 4.0 HT 3D printer, increasing noticeably the surface quality of the finite part. The conditions used for the 3D printing process, as well as the main results, are shown in Table A6.

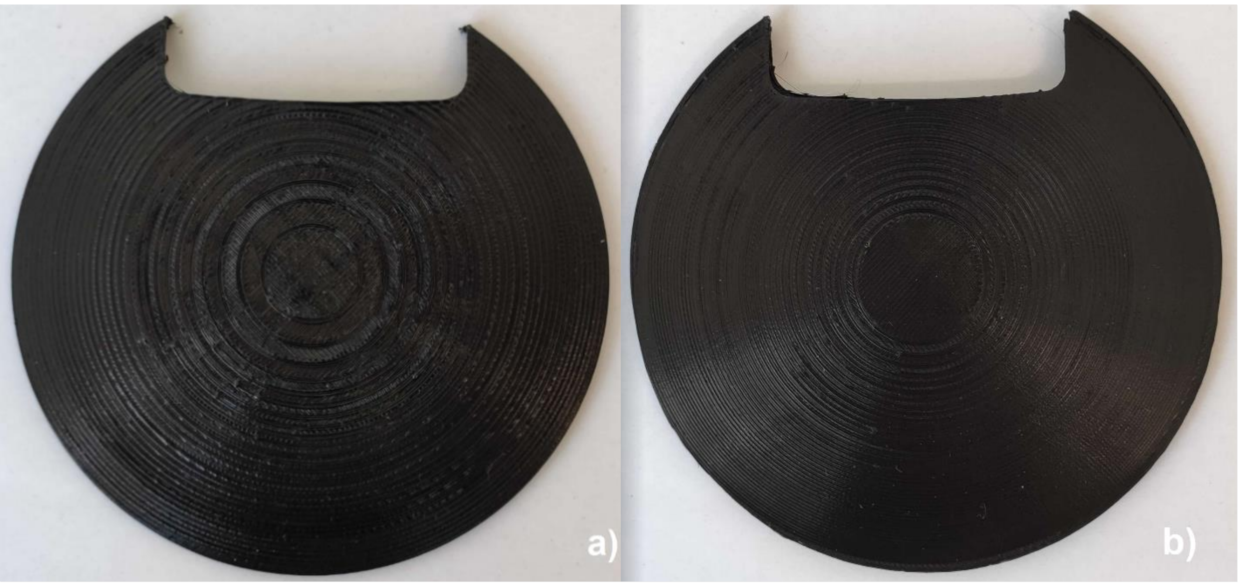

Figure 5A - Demonstrator realized in Post-Industrial ABS using a SpiderBot 4.0 HT with a layer thickness of 0.3mm (a) and 0.15mm (b).

Table A6 - Conditions used for the 3D printing process and main results.

Color	Black	
Material	ABS	
Source (PC/PI)	PI	
Processing temperature	240-260	°C
Printing bed temperature	80-90	°C
Closed chamber	YES	
Closed chamber temperature	60	°C
Min. layer thickness (in tests)	0.1	mm
Filament homogeneity	Good	
Flowability	Good	
Variation in diameter along the filament	Low	
Adhesion	Good in heated closed chamber	
Cohesion	Good in heated closed chamber	
Warping	Low in heated closed chamber	
Finite part dimensional accuracy	Good	
Finite part surface quality	Good	

Figure 6A - Demonstrator realized in Post-Consumer PC/ABS (black) and virgin ABS (white) using a Prusa MK3s with MMU2S multi-material unit with a layer thickness of 0.3mm.

VI. Post-Consumer ABS (MGG)

The material is a post-consumer Acrylonitrile Butadiene Styrene (ABS) plastic from MGG. The filament presents a good diameter uniformity and ductility.
The filament production at Sitraplas was unsuccessful and only a limited amount of material was available for testing (not enough material for a full part).
The material was extruded at 255°C.
The filament visually presented a non-homogeneous flow during the extrusion.
The same imperfections were observed during the 3D printing process and resulted in a high surface roughness compared to the other types of ABS tested. The conditions used for the 3D printing process, as well as the main results, are shown in Table A7.

Table A7 - Conditions used for the 3D printing process and main results.

Color	Black	
Material	ABS	
Source (PC/PI)	PC	
Processing temperature	255	°C
Printing bed temperature	80-90	°C
Closed chamber	YES	
Closed chamber temperature	OFF	°C
Min. layer thickness (in tests)	0.1	mm
Filament homogeneity	Good	
Flowability	Good	
Variation in diameter along the filament	Low	
Adhesion	Good in closed chamber	
Cohesion	Good in closed chamber	
Warping	Low	
Finite part dimensional accuracy	Good [brick]	
Finite part surface quality	Good [brick]	

VII. ABS EvoSource 4136 (MGG) + effect of 2 m.% polymer-based process improvement additive – PPI Plastic Science by Design

The material is a post-consumer Acrylonitrile Butadiene Styrene (ABS) plastic from MGG. The filament presents a good diameter uniformity and ductility.
The filament presents diameter variation that do not allow for the 3D printing of large parts as they lead to the pushing mechanism failure.
The material was successfully used for a brick printing test that presents good dimensional accuracy and a slightly high surface roughness.
The addition of a process improvement additive (PPI) increased noticeably the flowability, reducing the processing temperature. The top surface finishing of the final part appeared to be smoother compared to the case without additive. The conditions used for the 3D printing process, as well as the main results, are shown in Table A8.

Table A8 - Conditions used for the 3D printing process and main results.

Color	Grey	Grey	
Material	ABS	ABS + process improvement additive (PPI)	
Source (PC/PI)	PC	PC	
Processing temperature	240-260	220-240	°C
Printing bed temperature	80-90	70-80	°C
Closed chamber	NO	NO	
Closed chamber temperature	OFF	OFF	°C
Min. layer thickness (in tests)	0.1	0.1	mm
Filament homogeneity	Good	Good	
Flowability	Good	Good	
Variation in diameter along the length	High	High	
Adhesion	Good	Good	
Cohesion	Good	Good	
Warping	Mediocre in closed chamber	Low in closed chamber	
Finite part dimensional accuracy	Good [brick]	Good [brick]	
Finite part surface quality	Good [brick]	Good [brick]	
Notes		Better top-surface finishing	