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# Mechanical properties comparison between new and recycled polyethylene terephthalate glycol obtained from fused deposition modelling waste

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**Abstract**

The recycling of materials and the efficient use of resources are nowadays fundamental in a circular economy perspective. This concept also applies to additive manufacturing (AM) where waste can be reused to produce new material. Using mostly thermoplastic polymers, fused deposition modeling (FDM) is an AM technique that allows to melt waste materials and, successively, using a suitable extruder, obtain new filament. In the process, polymers are subject to multiple re-melting and polymer orientations by extrusion operations. The aim of this work is to evaluate the influence of the recycling process over polyethylene terephthalate glycol-modified (PETG) mechanical properties by tensile testing of samples produced using pure and recycled material. Furthermore, filament itself has been tested to evaluate recycle process influence before FDM printing.

**KEYWORDS**

additive manufacturing, circular economy, FDM, material testing, mechanical characterization, polymers recycling, recycling, tensile testing

## 1 | INTRODUCTION

In an additive process, waste is really reduced to a minimum, and the quantity of raw material contained in the finished product, in addition to being practically equal to that necessary to produce it, can also be suitably calculated in relation to the function of the component, its structural requirements, and its aesthetic appearance. Among the AM technologies for plastics, fused deposition modeling (FDM) is a widespread "material extrusion" technique (according to ISO/ASTM 52900: 2015[1]), which uses a thermoplastic filament to build parts layer after layer. Producing new filament starting from generic waste material is a good example of primary recycling (reuse of processing waste), but doing it using a similar type of material, coming from FDM waste, print supports or end-of-life parts, is certainly an added value in terms of the quality of the recycled polymer. In order to understand mechanical properties variation through recycle process, two hardware product start-ups—Felfil srl (Turin, Italy) and MaCh3D srl (Parma, Italy)—conducted an experimental study on polyethylene terephthalate (PETG) co-polyester filament in its first two life cycles, measuring the mechanical properties of both the pure filament as well as the material transformed through FDM technology.

## 2 | FILAMENT PRODUCTION

The PETG filament was produced from commercial virgin pellets (PETG Selenis Genius 80 M), dried at 60°C for 7 h and then extruded with the addition of 2% black universal masterbatch. The extrusion process was carried out using the

  

Felfil Evo system (Figure 1), at 215°C and with a screw speed of 9 rpm and 1.25 m/min, obtaining a filament with a diameter of 1.75 mm ± 0.07 mm, which was then wound through the Spooler.

The experimental campaign was divided into two phases. The first—which coincides with the first cycle of life of the material—included the production of the filament from virgin pellets and specimens with two different 3D printing systems, a Prusa MK3 and a BQ Witbox 1. The second phase—which coincides with the second cycle of life of the material—exclusively concerns recycled polymer obtained 100% from end-of-life PETG—such as the specimens made in the first phase of the testing and the processing waste generated. The scraps were shredded through the Felfil Shredder system (Figure 1) to obtain a plastic material granulate with a maximum granule size equal to 8.0 mm; for filament extrusion, the grains followed the same conditioning and process as the virgin pellet.

## 3 | SPECIMENS PRODUCTION

The obtained filament spools were used to print the specimens in two different orientations in space: the first involved printing the specimens in the XY plane in the Y direction while the second consisted in printing the specimens vertically, along the Z direction, as depicted in Figure 2. Printing parameters are reported in Table 1 and remain constant on the two printers.

The replication of the same campaign using different machines (and users) made it possible to evaluate the influence of the machine itself on the mechanical properties of the material produced. The printing files were generated with the Ultimaker Cura v4.6.1 slicer software[2] and shared for production on the two different printers. The 0° infill orientation for the specimens printed horizontally and 90° for those printed vertically, with respect to the axis of the specimen, aims to investigate two extreme situations: in fact, the first represents the condition in which best results in terms of mechanical properties are generally obtained,[3–6] while the latter gives the worst values. It should be added that in

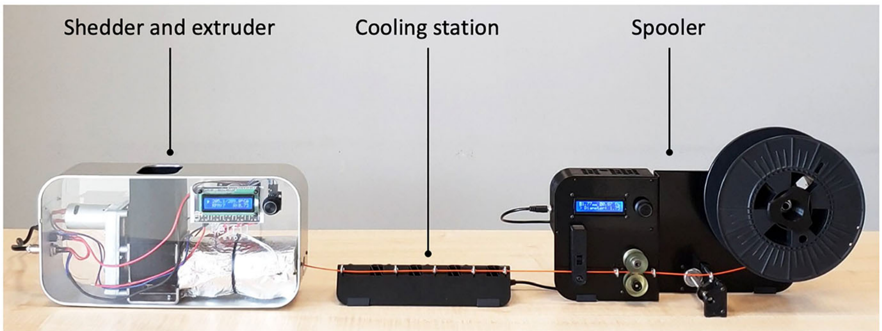


FIGURE 1 Felfil EVO and spooler desktop extrusion system

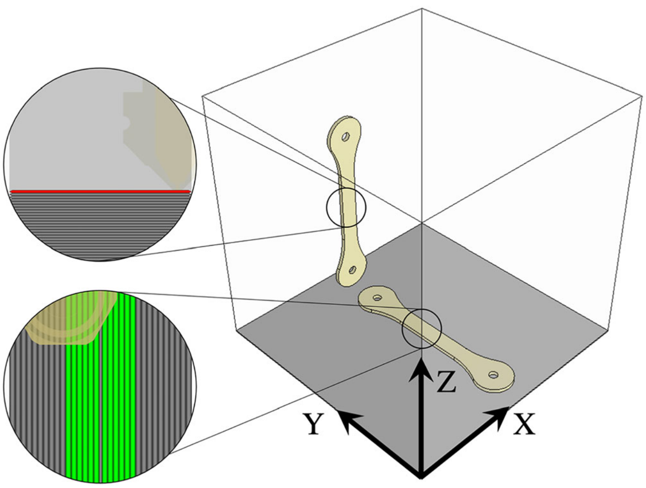


FIGURE 2 Specimen position on the build plate

the first case, the material is stressed along the deposition direction, while in the second case, it is the bond existing between the superimposed layers to be loaded.

## 4 | EXPERIMENTAL SETUP

The mechanical properties, both for specimens and filament, were measured through tensile test, according to the ASTM D638 standard.[7] The tests were carried out on a desktop format MaCh5 universal testing machine, depicted in Figure 3A,B, produced by MaCh3D, capable of a maximum load of 5 kN and a total stroke of 110 mm.

The machine technology is based on a proprietary shape of the grips that is counter shaped to the head of the specimens, with the advantage of reducing the test execution times, eliminating the degrading effects of traditional grips on

**TABLE 1** Printing parameters used for specimens production

| Parameter | Value |
|---|---|
| Material | PETG |
| Layer height | 0.2 mm |
| Infill % | 100% |
| Specimens/job | 5 |
| Infill orientation | 0° - Horizontal |
| | 90° - Vertical |
| Printing speed | 40 mm/s |
| Temperature | 240°C |
| Build plate adhesion type | Brim |

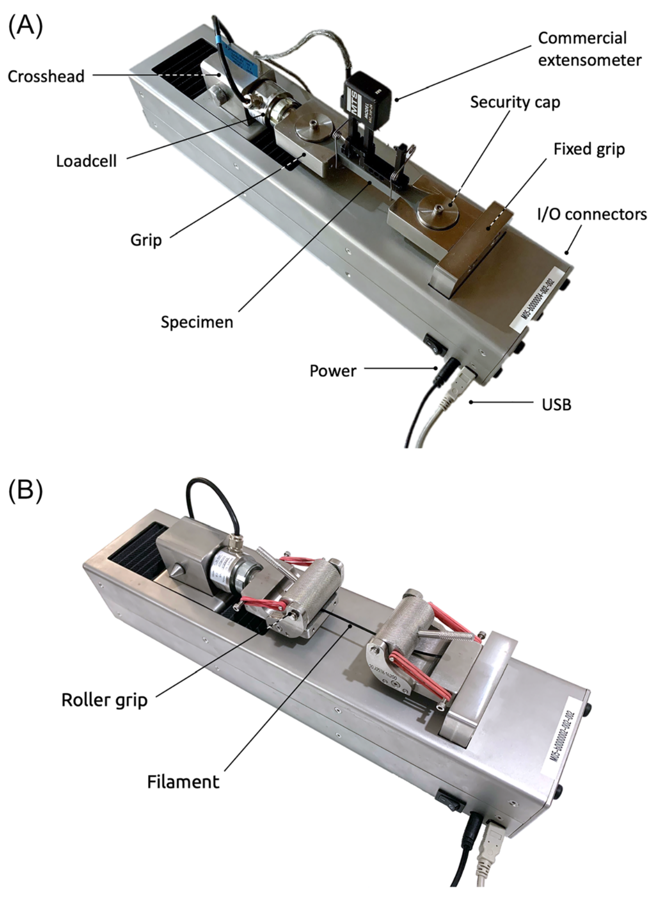


**FIGURE 3** MaCh5 universal testing machine in tensile testing configuration (A) and with roller grips used to characterize PETG filament (B)

the specimen and minimizing operator error by excluding the influence of subjective factors during the test setup.[8] The loads are recorded with a 5-kN load cell, while the deformation of the specimen is measured with a commercial extensometer, with a measuring base of 50 mm, directly acquired by the MaCh3D system. Even though the equivalence between ASTM and MaCh3D specimen has already been assessed,[8] further cross-validation has been carried out for the material used. Five specimens have been produced starting from pure material according to parameters in Table 1, in the horizontal orientation, (Table 1) using 0° and 45° infill, both for MaCh3D and ASTM geometries, for a total of 20 specimens. ASTM specimens have been tested on an MTS servo-hydraulic machine, with 250-kN load capacity, using a loadcell of 20 kN. Testing parameters are the same used on MaCh5 and detailed below. Results comparison, in terms of elastic modulus and ultimate stress, are reported in Figure 4: although slight differences, the average values are comprised in the dispersion band of the two sets of data.

The tests on the filaments were carried out again using MaCh5, adopting special grips equipped with eccentric rollers which allow to block the filament during the test, as indicated in Figure 3B. In this case, it was not possible to use the extensometer (due to the difficulty of fixing it to the filament); therefore, the distance between the contact points of the eccentrics, of about 57.6 mm, was considered as a basis for strain measurement. Tensile tests are performed in displacement control, with a test speed of 5 mm/min and a sampling rate of 5 Hz.

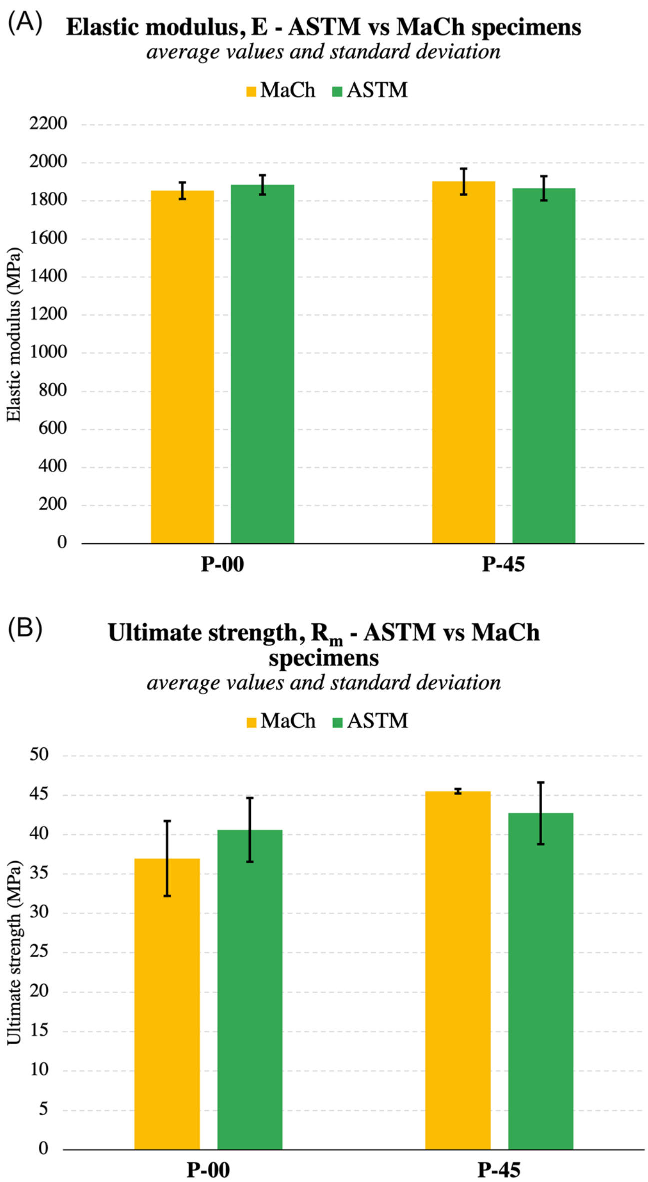


**FIGURE 4** Comparison between ultimate strengths (A) and elastic modulus (B) of MaCh3D and ASTM specimens geometries

## 5 | RESULTS

The mechanical properties of the virgin and recycled materials were analyzed on specimens produced in horizontal and vertical orientation using the Prusa MK3 printer.

Figure 5 shows the master stress–strain curves, obtained averaging values from five repeated tests, and the relative dispersion bands. It emerges that the characteristics of the recycled material are lower, in terms of elastic modulus (E), ultimate stress ($R_m$), and elongation at break ($A_t$) compared with those of virgin material. The experimental results also show that the mechanical properties of the vertically printed specimens have lower values than the horizontal configuration, confirming the literature data. The comparison between the results obtained with the recycled and virgin material for specimens made with both printing orientations (horizontal and vertical) highlights the lower mechanical performance and toughness of the recycled one. Table 2 shows the mechanical properties of virgin and recycled material.

A further comparison has been made between the two printers: in this case, it was carried out only with virgin material. In Figure 6, the mechanical properties of the material obtained through Witbox I and Prusa MK3 are compared: it can be deduced that the latter determines slightly better average mechanical properties, except in the case of the elastic modulus of the horizontal specimens which is marginally better in the case of Witbox I. It must be noted, however, that average values are comprised in the standard deviation of the two data sets.

Regarding filament testing, in Table 3 are reported the mechanical properties of the virgin and recycled filament. As previously described the elastic modulus was calculated using the displacement between the grips.

Also in this case, the recycled material has slightly lower mechanical properties than the virgin one. During the tests, however, in no case, the filament reached the rupture of the specimen, showing a marked visco-plastic behavior after reaching the maximum tension, with an elongation greater than 85%. This viscous behavior was not found in the case of specimens, suggesting that the printing process introduces an embrittlement of the material with respect to the filament state.[9] It is not possible to make a direct comparison between the mechanical properties of the filament and the printed material, due to the different test procedures. Figure 7 shows a qualitative comparison between specimens and filament. The parameter that is less influenced by different test methodologies is the ultimate stress, which would seem higher in the printed material than in the filament, in the case of both virgin and recycled polymer. This behavior could be justified by the particular internal architecture of the specimen, where the single rasters of extruded

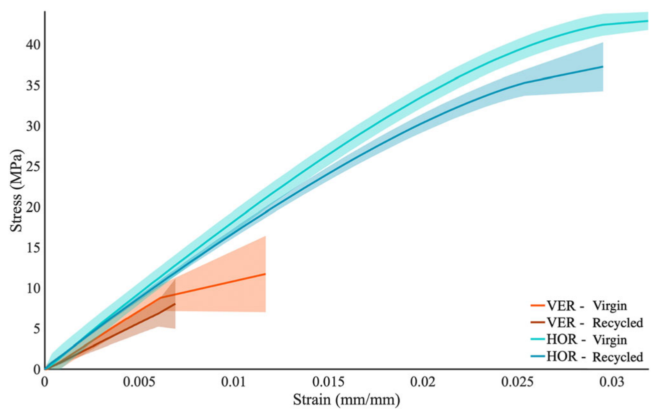


**FIGURE 5** Stress–strain master curves for Prusa MK3 printed specimens, both recycled and virgin, in the two different spatial configurations

**TABLE 2** Average mechanical properties of specimens printed using Prusa MK3

| Orientation | Material | E (MPa) | $R_m$ (MPa) | $A_t$ (%) |
|---|---|---|---|---|
| Horizontal | Virgin | 1818 ± 51.3 | 43.0 ± 1.1 | 3.2 ± 0.23 |
| | Recycled | 1730 ± 71.8 | 37.3 ± 3.0 | 2.9 ± 0.33 |
| Vertical | Virgin | 1488 ± 191.1 | 11.7 ± 4.7 | 1.2 ± 0.92 |
| | Recycled | 1164 ± 270.0 | 8.1 ± 3.1 | 0.6 ± 0.16 |

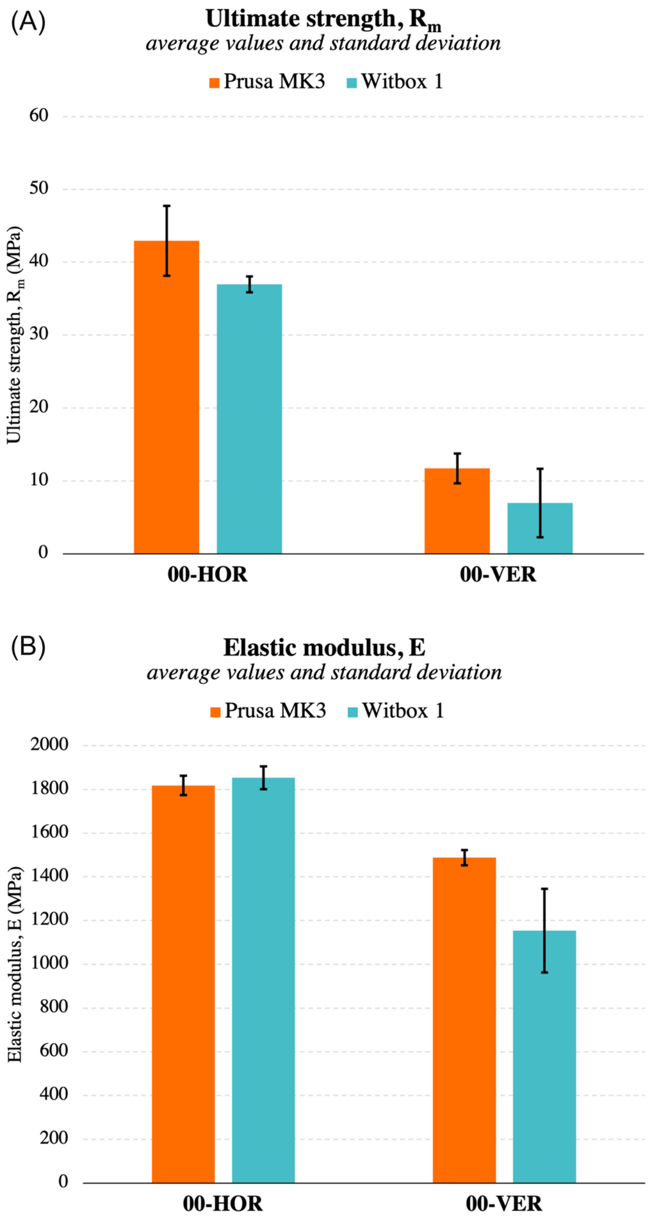


FIGURE 6 Comparison between ultimate strengths (A) and elastic modulus (B) of specimens obtained the two different printers

TABLE 3 Filament mechanical properties

| Mech. Prop. | Virgin | Recycled |
|---|---|---|
| $E_{app}$ (MPa) | 568 ± 66.4 | 488 ± 19.9 |
| $R_m$ (MPa) | 36 ± 2.3 | 31.5 ± 1.3 |
| $A_t$ (%) | 86.3 ± 0.38 | 85.9 ± 0.92 |

material contribute to a better resistance of the material thanks to an enhanced orientation of the polymer chains in the direction of the load as well as the contribute resulting from side-by-side rasters.

On the contrary, filament ultimate stress could be negatively influenced (therefore underestimated) due to the deformation occurring underneath grip rollers. This second hypothesis is confirmed by the fact that in some tests, the filament necking takes place just below the gripping rollers. Moreover, test speed could have an important influence on the viscous behavior of the filament. The value of 5 mm/min, suitable for the printed specimens, might be too low for the filament due to its visco-elastic nature, a hypothesis that is also confirmed from literature.[9]

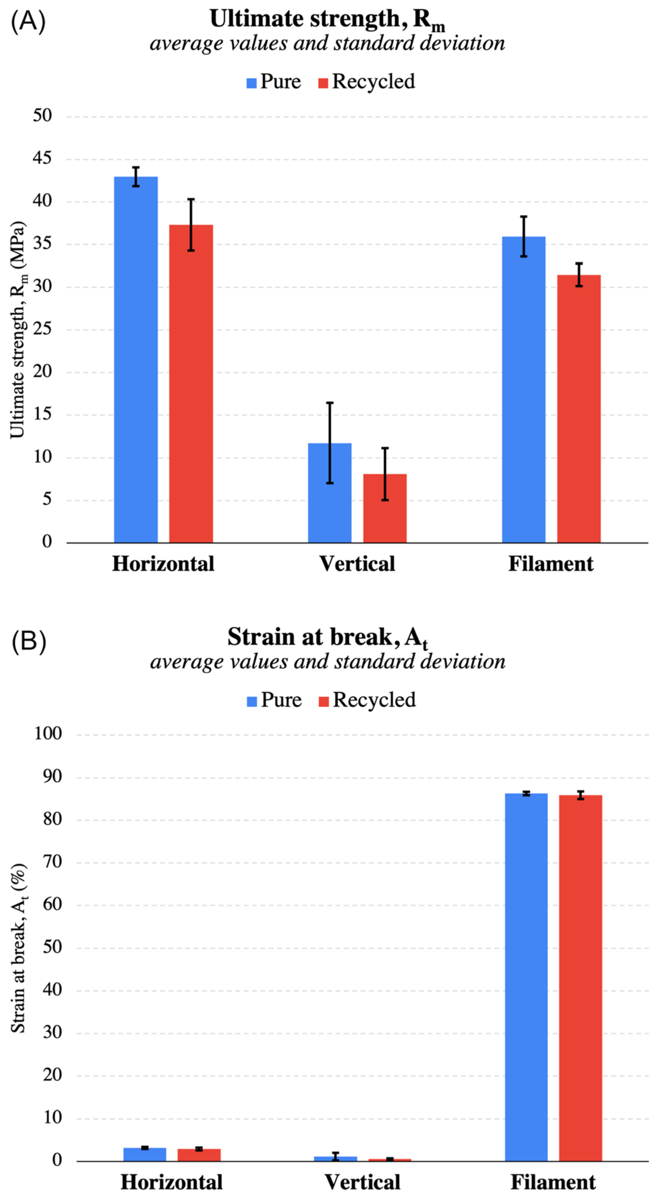


**FIGURE 7** Comparison between ultimate strengths (A) and elongation at break (B) of specimens and filament

## 6 | CONCLUSIONS

Recycling and efficiency are fundamental to enable circular economy policies in as many manufacturing fields as possible. From this point of view, additive manufacturing is much ahead of other technologies, given the possibility of producing complex geometries without impacting production costs[10] and therefore the use of optimized shapes, which consume the least possible quantity of material. Additionally, for manufacturing techniques based on the use of thermoplastic polymers, such as FDM, non-compliant parts and/or print supports can be efficiently recycled. The recycled material, however, has slightly lower mechanical properties than the virgin one. A careful characterization of the filament obtained is therefore necessary before using it to obtain functional parts. Moreover, the degradation of mechanical properties increases with the number of recycling cycles, as shown in the work of Cruz et al.[11]

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### DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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