Research Article

Influence of plastic recycling—a feasibility study for additive manufacturing using glycol modified polyethylene terephthalate (PETG)

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Abstract

This paper presents a feasibility study for the production of recycled glycol modified polyethylene terephthalate (PETG) material for additive manufacturing. Past studies showed a variety of results for the recycling of 3D-printing material, therefore the precise effect on the material properties is not completely clear. For this work, PETG waste of the same grade was recycled once and further processed into 3D printing filament. The study compares three blend ratios between purchased plastic pellets and recycled pellets to determine the degradation effect of one recycling cycle and possible blend ratios to counter these effects. Furthermore, the results include a commercially available filament. The comparison uses the filament diameter, the dimensional accuracy of the printed test specimen and mechanical properties as quality criteria. The study shows that the recycled material has a minor decrease concerning the tensile strength and Young's modulus.

Keywords Additive manufacturing · Plastics recycling · PETG · 3D printing · Mechanical testing

1 Introduction

In recent years, the production technology of additive manufacturing has developed rapidly both economically and technically. The most common technology in this context is the so-called "fused filament fabrication" (FFF) or fused layer process. FFF printers can use numerous plastics such as acrylonitrile–butadiene–styrene (ABS), polyamide (PA), polylactide (PLA) and glycol modified polyethylene terephthalate (PETG) in the form of a plastic wire, the so-called filament. Since additive manufacturing is a steadily growing market, its use in industrial companies and thus the quantities of plastic produced will increase. According to the Plastics Atlas [1], in 2017 various industry branches around the globe needed a quantity of around 407 million tons of plastic. In Germany, the production volume of the plastics processing industry in 2017 was over 14 million tons [1]. The recycling codes in Germany divide plastics into seven categories. Figure 1 shows the percentage distribution of the produced plastic from Germany in 2017.

Of the plastics produced, the majority are thermoplastics that can potentially be processed for additive manufacturing, as shown in the works of Exconde et al. [2] for PET and Chong et al. [3] for HDPE. The work of Song and Telenko [4] indicated that 34.6% of the used material in a maker space, which uses FFF-printers, ends up as waste. This shows that additive manufacturing with FFF printers is in need for recycling concepts. Furthermore, it was shown in the results of Zhao et al. [5] that closed-loop recycling for printing wastes is the most sustainable alternative. A

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material recycling approach in the field of additive manufacturing for pure PLA plastic was done in the works of Zhao et al. [5], Anderson [6], Sanchez et al. [7, 8].

Zhao et al. [5] carried out several recycling cycles on PLA. After only two cycles, an immense decline in the viscosity of the material was detected, so that processing was no longer possible. To counteract this deterioration, the recycled material was subsequently mixed with fresh granules and successfully processed again. The work of Anderson [6] compares virgin and recycled PLA specimen in different mechanical properties, one of which is the mechanical tension. Andersons results show a difference of approx. 4 MPa between the virgin and recycled specimen, which went through one recycling cycle. Sanchez et al. did two studies on the recycling of PLA [7, 8], in which they did five recycling cycles each. In their first work from 2015 Sanchez et al. [7] did not determine a significant decrease in the tensile strength of printed specimen. However, the elongation at the breaking point decreased by 10% after five recycling cycles. Their work from 2017 [8] is a continuative work based on the previous results 2015 [7]. Different life cycle assessment approaches are compared, one of which is the recycling approach used in 2015 [7]. The results of Sanchez et al. in 2017 [8] differ significantly from the previous results. In [8], the mechanical properties of the additively manufactured tensile specimens decrease by 35%. This shows that the results within the literature for the material PLA are not homogeneous, and thus no clear statement can be made.

This work presents a feasibility study for a material recycling approach of the plastic PETG for additive manufacturing. PETG is a PET-based plastic that is modified with glycol to obtain better properties for 3D printing. In this first step, the study will examine the recyclability for PETG in additive manufacturing. If the results are satisfactory, future work will investigate the recycling potential of PET. The study uses 3D-printing waste like misprints or support structures to create 3D-printing filament on a laboratory scale. In course of the study, three blends between recycled and virgin granulate are investigated with respect to the feasibility of filament production. The quality of the recycled filament is checked by the filament diameter, the dimensional accuracy of the printed test specimens, as well as their mechanical properties. Previous works in this area [5–8] showed widely varying results in some cases. However, the emerging problems, if any, started only after increased recycling cycles. For this reason the PETG plastic will be reused only once during this work. It is expected that a single source material reuse cycle will have minimal impact on material properties. However, no information on this can be found in the literature for the specific application related to PETG in additive manufacturing. The

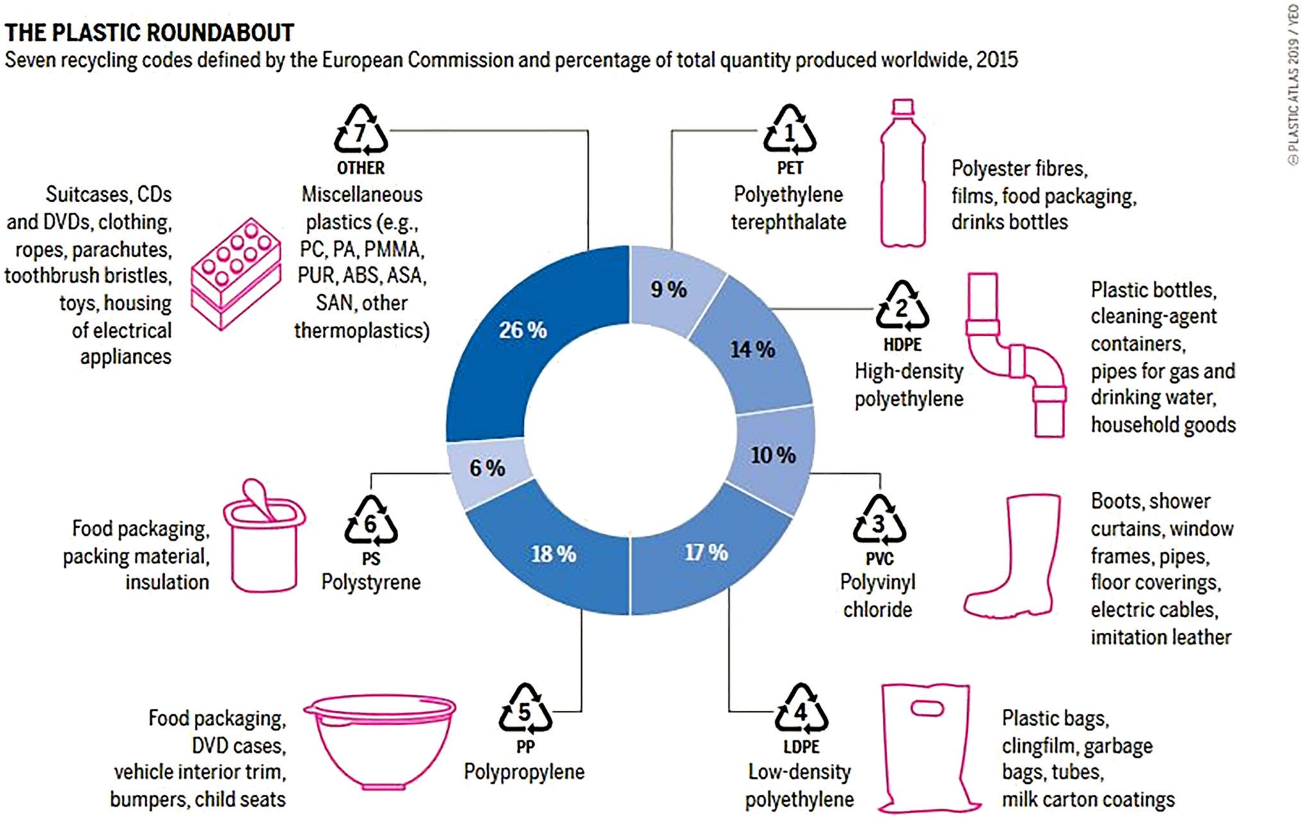

Fig. 1 Plastic Roundabout in Germany 2017 [1]

work of Ksawery et al. from 2017 [9] tested the mechanical properties of commercially available PETG material, without the recycling aspect. Therefore, to have a comparison with a material available on the market, the results include a PETG filament from the company Verbatim [10].

2 Theory and basics

The additive manufacturing technology Fused Filament Fabrication (short FFF) or Fused Deposition Modeling (short FDM) is the most common technology for 3D-printers. In this process, a moving print head heats the plastic and extrudes it in a liquid state through a nozzle onto the building platform. The printer manufactures the model layer by layer, like in any additive manufacturing process. A so-called slicing software generates the corresponding machine code according to the user requirements. The FFF 3D-printer uses plastic in the form of filament with a constant diameter of 1.75 ± 0.05 mm or 2.75 ± 0.05 mm [10]. The printer used for this work requires a 1.75 mm diameter filament [11].

In additive manufacturing, factors such as print direction, layer thickness and component orientation on the building platform exert an influence on the mechanical properties of the object. This was demonstrated in multiple works, like the work of Yu et al. from 2019 [12] or from 2002 in the results of Ahn et al. [13]. To showcase the sole influence of the recycled material without interactions, no further printing parameters changed during the work for this paper.

The PETG material used in this work is a glycol-modified PET material. Due to the modification, PETG has a lower viscosity and melting temperature than PET [14]. PETG has good mechanical properties, has a higher softening temperature than PLA at 80 °C [14], and is comparably difficult to print as PLA.

The material was reprocessed using a material recycling approach. In general, the similar grades of waste were separated, cleaned and shredded accordingly. In this case, PETG printing waste of a maker space at the university site. Inside the waste was only PETG material but from different filament manufactures, like Formfutura or Verbatim. Subsequently, the plastic parts are melted at high temperature and reprocessed. According to Hunold [15] only thermoplastics are suitable for this method. On the report of the German Federal Environment Agency [16] a high degree of purity of the input material is an important aspect of material recycling, especially in the field of 3D printing. During the recycling process, the plastic is subjected to high thermal stress due to heating. On the other hand, it is subjected to high mechanical stress through extrusion by means of an extruder screw. As a result, the plastic suffers thermal–mechanical degradation during the processing from granules to filament as stated in Rudolph's work from 2020 [17].In addition, the input material must be dried before the extrusion process to prevent bubble forming during subsequent filament production or excessive degradation of the polymer due to hydrolysis.

The tensile tests were performed according to the following DIN EN standards: DIN EN ISO 527-1:2019-12 [18], DIN EN ISO 527-2:2012-06 [19], DIN EN ISO 10350-1:2018-03 [20], DIN EN ISO 20753:2019-02 [21] and DIN EN ISO 20028-2:2017-07 [22].

According to [18], the stress–strain diagrams of plastics fall into one of four categories. Figure 2 shows the typical generalized curve for PETG.

The tensile strength shown in the later diagrams thus corresponds to the tensile strength or yield stress according to DIN EN standard DIN EN ISO 527-1:2019-12 [18]. The Young´s Modulus is determined via the gradient of a regression line for the stress/strain values in the strain range of $0.0005 \leq \varepsilon \leq 0.0025$. In this case, the strain values are used without dimensions [18].

3 Methods and materials

This feasibility study represents an initial investigation of the recycling of PETG waste into filament for additive manufacturing. Therefore, during this study only three different blends between recycled and purchased granulate were investigated. Table 1 shows the mixing ratios.

The study will show the difference between pure virgin material (sample 1) and clean recycled material (samples 3 and 4). Sample 5 is missing in this table, because it is the purchased Verbatim material. For sample 4, which is the same blend as sample 3 the recycled material was additionally cut to a uniform size by a pelletizing machine. Sample 2 represents a balanced mixture of virgin and

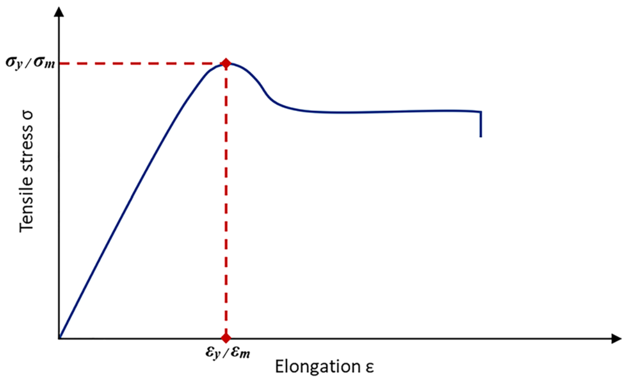

Fig. 2 Generalized curve of the stress–strain diagram for the material PETG. Based on DIN EN ISO 527-1:2019-12 [18]

Table 1 Mixing ratios of the samples tested

Sample	Proportion of purchased material in %	Percentage of recycled material in %
Sample 1	100	0
Sample 2	50	50
Sample 3	0	100
Sample 4	0	100

Table 2 Material characteristics of the granulate Mimesis DP 300 [23]

Parameters	Unit	Value
Intrinsic viscosity	dl/g	0.8 ± 0.02
Glass transition temperature	°C	80
Specific density	g/cm^3	1.29
Pellet shape		Cylindrical
Particle size	mg/20 chips	320 ± 50
Process temperature	°C	180 – 250

recycled material and should indicate, whether the effect of the recycled material can be diminished or completely eliminated by using a blend with virgin material Each sample weighed 200 g in total. For each blend one filament was made.

The purchased material was the PETG granulate Mimesis DP 300 from the company Selenis. The most important key data of the material are listed in Table 2. [23]

The following steps were carried out for all samples: PETG waste and misprints of similar grades were coarsely shredded by hand and then finally shredded to the required sizes with an electrically operated shredder. In order to allow for optimal extrusion, the granule size was set to a maximum of 3.18 mm during recycling in accordance with the Filabot manufacturer [24]. For this purpose, the shredded flakes were regularly screened in order to achieve the uniform granule size of the material. Subsequently, the four different material samples were weighed and mixed with the different blends. To exclude excess moisture in the material, the samples were stored in a drying cabinet for 5 h at 70 °C. After drying, the flakes were processed into filaments using an extruder (Filabot EX 2, see Fig. 3). Each sample represented a stand-alone filament.

Table 3 Parameters used for filament production from PETG

Parameters	Value
Extrusion temperature in °C	235
Speed of the extruder screw in revolutions per minute	20
Speed of the take-off roller in revolutions per minute	22

The Filabot EX2 extruder setup consists of an extruder, a cooling station (Airpath) and a winding station (Spooler). The extruder melts plastic flakes into a homogeneous mass and extrudes the plastic mass through a nozzle. The screw speed and the temperature can be specifically adjusted. When the continuous plastic strand leaves the nozzle the still hot filament is cooled down to room temperature by the adjustable airpath. Afterwards the filament is wound up with the spooler on commercial filament rolls.

When winding up the filament, the factors extrusion temperature, extrusion speed and winding speed must be adjusted to obtain a filament with a uniform diameter. Table 3 lists the filament extrusion parameters for all four samples. The cooling was running continuously at maximum level. These parameters resulted from previous experiments and showed promising outcomes for the filament diameter.

For sample 4, the material was mechanically cut to a uniform size with the aid of a pelletizer and then processed to filament like the other samples. Figure 4 shows the difference in shape between the starting materials. At the end of this step four different filament samples were produced.

To check the influence of the recycling process on the quality of the filament the following parameters are controlled:

- Diameter of the extruded filament
- Dimensional accuracy of the printed tensile specimens
- Mechanical parameters of the tensile tests.

The dimensional accuracy of the tensile test specimens and the measurement of the filament diameter will serve as a confirmation test that the degradation of the PETG plastic after one-time recycling causes only minimal

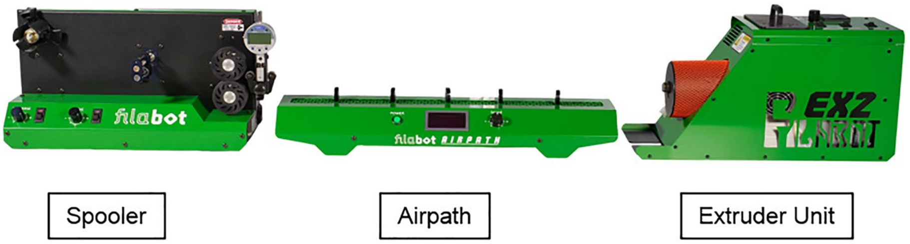

Fig. 3 EX 2 extruder from Filabot. A note on Extruder EX 2: the control of the speeds in the entire system is done by rotary potentiometers, which makes it impossible to give exact values. All values in Table 3 are experimentally determined values

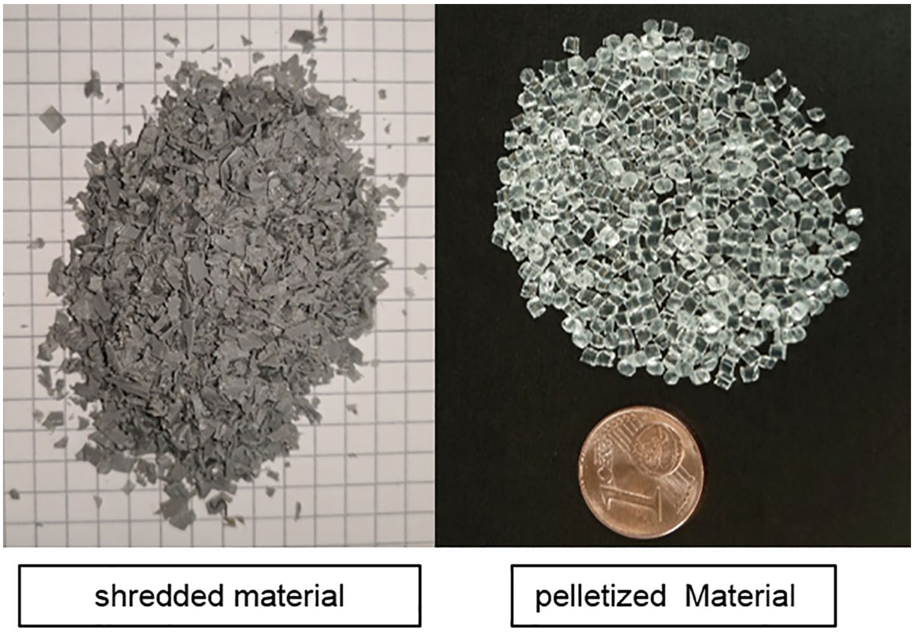

Fig. 4 Difference between shredded (left) and pelletized material (right). The materials had different starting colors

effects and thus minimal changes in the thermal and rheological properties.

The diameter of all four filament samples as well as the Verbatim Filament PETG 5002 [10] was measured with a vernier caliper. The diameter was measured at 20 measuring points, each point was 30 cm apart from the previous one. At each point two measurements were taken, the first one was done in a horizontal direction and the other one was offset by 90 degrees. With this procedure a possible ovality of the filament would be detected. Based on these 40 measurements per sample, an average value and the standard deviation was calculated.

The tensile specimens were tested for their strength properties in the subsequent tensile tests in accordance to DIN EN standards [18–22]. For the evaluations type 1B tensile specimens were produced in an additive manner. The form and relevant dimensions for the test specimen are visible in Fig. 5.

After quality control of the filament diameter, each material sample was printed on a Prusa i3 MK3S with a sufficient number of samples type 1B according to the above mentioned DIN standard. This means for each blend at least five specimen were printed. After the printing process was completed, all tensile samples were measured using a vernier caliper to ensure that all relevant dimensions were within tolerance. The target values and their tolerance ranges for the dimensions shown in Fig. 4 are listed in Table 4. The numerical values shown are taken from DIN EN ISO 527-2:2012-06 [19].

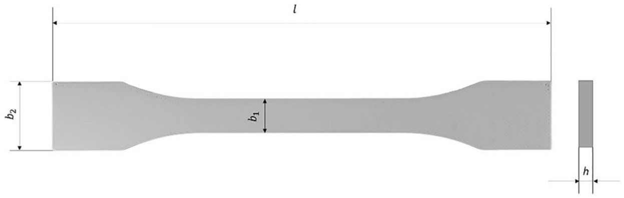

Fig. 5 Tensile test specimen 1B with the relevant dimensions for the later quality control in accordance with Refs. [18–22]

Table 4 Target values in accordance to DIN EN ISO 527–2:2012–06 [19] for the listed dimensions from tensile specimen 1B

Dimensions	Target value (mm)	Tolerance (mm)
Total length *l*	≥ 150	/
breadth b_2	20.0	± 0.2
breadth b_1	10.0	± 0.2
height *h*	4.0	± 0.2

In order to ensure that the climatic and printing conditions were as similar as possible, all samples were produced on the same 3D printer with the same settings. The program "PrusaSlicer" was used as slicing software. Table 5 describes the used parameters. These parameters were acquired through previous tests and yielded the best print quality. In order to counteract over- and under extrusion of the material, the previously determined average filament diameter was used in the program for each filament sample. Thus, the program automatically adjusts the feed rate of the material into the print head. Figure 6 shows the print orientation, which is the *x*–*y* orientation, and placement of a test specimen on the print bed for the Prusa i3 MK3S. In the course of these tests, a complete stiffness matrix in

Table 5 Used print parameters for all printed tensile specimens

Print parameters	Value
Print temperature in °C	250
Printing bed temperature in °C	95
Layer height in mm	0.2
Contours	3
Solid layers bottom	5
Solid layers top	4
Seam position	Random
Infill in %	100
Print speed in mm/s	60

all three spatial directions should not be determined. The aim of the tests was to elaborate the effect of the recycled material, therefore all specimens were manufactured only one printing direction, which is the x–y orientation visible in Fig. 6.

For the tensile tests an MTS 20/M two-column machine with spindle drive was used, which can apply a test force of up to 100 kN. The tensile test was performed according to DIN EN ISO 527 with a test speed of 1 mm/min. The change in length of the specimen was determined with the help of an extensometer, whereby a preload force of 50 N was applied to the tensile specimen. This procedure was used for all five filament samples. Figure 7 shows the test setup for the performed tensile tests.

The Young's modulus was calculated in Microsoft Excel using the "Trend Line" function. For this purpose, the stress values for $0.0005 < \varepsilon < 0.0025$ were plotted in a line diagram. This can be seen as an example in Fig. 8. It is important that the elongation is not used in percentage.

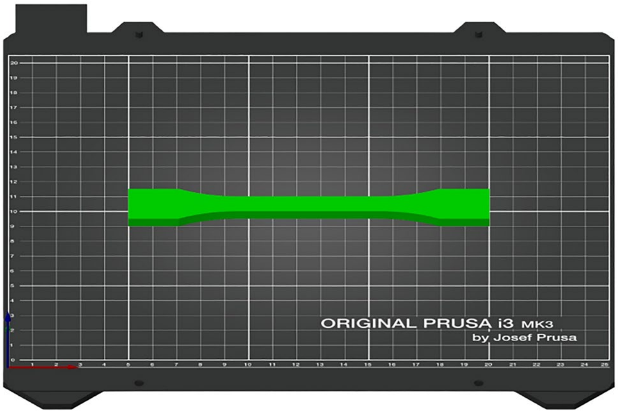

Fig. 6 Print orientation for the tensile test specimen

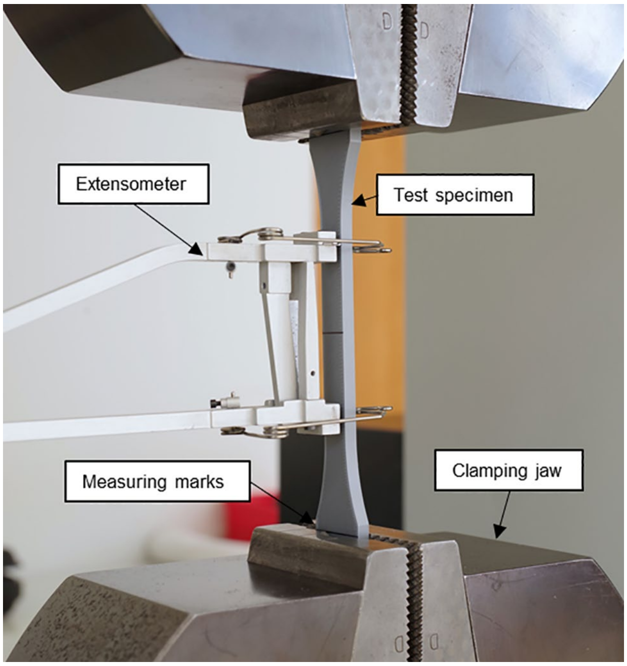

Fig. 7 Test setup for the tensile strength tests

4 Results and discussion

Table 6 shows the evaluation of the measured filament diameters. Sample 5 is the Verbatim Filament.

The results show a successful feasibility study for recycled PETG filament on a laboratory scale from similar grade 3D printing waste. Table 6 shows that the average diameter of all samples is within the tolerance range of 1.75 ± 0.05 mm. When the standard deviation is considered, sample 1 and sample 3 fall outside the tolerance range. Whereby sample 1 (100% virgin material) is outside the tolerance only at the upper limit. Sample 3 (100% recycled material, not pelletized) displays the largest deviation from the nominal diameter of 1.75 ± 0.05 mm. In comparison, sample 4 (100% recycled material additionally pelletized) demonstrates a better result. The pelletized starting material provides the improvement of the measured diameter. This shows that for the filament diameter with 100% recycled material a homogeneous pellet size and shape of the granulate is extremely important. The measured diameter of sample 2 (50% purchased material, 50% recycled material) supports this result, since 50% of the blend stems from the virgin granulate, which has a uniform shape and size.

After the successful fabrication of the four filament samples, the printed tensile specimens were checked for dimensional accuracy. The results of this evaluation can be seen in Table 7. In addition to the measured dimensions, Table 7 also lists the number of printed tensile specimens per filament sample. "Failed Prints" stands for tensile specimens that were not within tolerance and were not used for the subsequent tensile tests. The mean values and standard deviations shown in Table 7 were calculated on the basis of the five specimens used for the following tensile tests.

Table 7 shows that all filament samples were successfully processed and the subsequently tested specimens were all within the specified tolerance from Table 4. The successful printing of the tensile specimens demonstrates that a deviating filament diameter can be compensated by clever use of the slicing software. Table 7 demonstrates that all filament samples were suitable for further processing in a 3D printer. If the rejects of specimens that were not within the tolerance specifications are considered, it is noticeable that specimen 3 (100% recycled material) performs very well. No explanation can be found for the high reject rate of five tensile specimens for filament sample 2 (50/50 virgin and recycled material). The filament diameter of sample 2 with 1.75 ± 0.05 mm is excluded as a possible reason, because sample 3 (100% recycled material) has a much more inhomogeneous diameter of 1.71 ± 0.07 mm, but shows less reject samples. The low reject numbers of the recycled filament samples illustrate that for the user of an FFF printer, rheological as well as thermally no major changes in the filament result from the one-time recycling process.

An exemplary representation of the stress–strain diagrams for the test specimens of Filament Sample 1 can be seen in Fig. 9. The legend shows specimen 1.1 to 1.5. The first number represents the sample, in this case sample 1. The second number represents the specimen itself. The other stress strain diagrams are shown in the Appendix of this work.

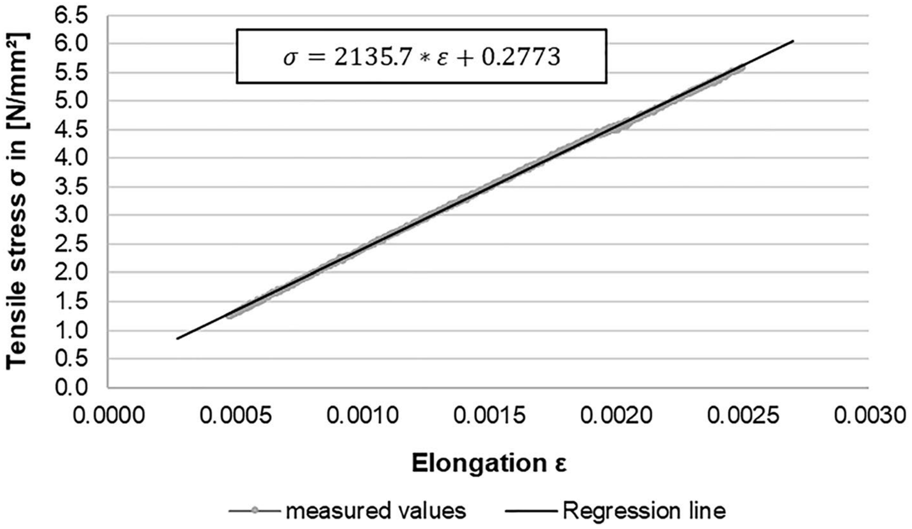

Fig. 8 Example calculation of the Young's modulus based on a data set of filament sample 1

Table 6 Evaluation of filament diameter

	Samples				
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Mean value	1.77	1.75	1.71	1.77	1.74
Standard deviation	± 0.05	± 0.05	± 0.07	± 0.02	± 0.01

Table 7 Calculated average for the measured values of all printed test specimen

Dimensions	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Total length *l*	150.27 ± 0.05	150.39 ± 0.06	150.45 ± 0.06	150.43 ± 0.06	150.35 ± 0.07
Breadth b_2	19.85 ± 0.03	20.06 ± 0.05	20.11 ± 0.04	20.01 ± 0.07	20.02 ± 0.09
Breadth b_1	9.88 ± 0.02	10.08 ± 0.06	10.15 ± 0.02	10.03 ± 0.05	10.03 ± 0.06
Height *h*	4.04 ± 0.02	4.09 ± 0.05	4.05 ± 0.03	4.06 ± 0.04	4.01 ± 0.02
Total amount printed	8	10	6	8	5
Failed prints	3 (37.5%)	5 (50%)	1 (16.6%)	3 (37.5%)	0 (0%)

All values in mm

Figure 9 shows that the stress–strain diagram for PETG corresponds generalized curve from Fig. 2, since after the maximum tensile strength (indicated by triangles in the diagram) the stress does not increase further, but decreases continuously. The results from Fig. 9 show that the tested samples have a small scatter in the maximum tensile strength. In terms of elongation at break and stress at break, the five specimens demonstrate very different behavior.

Based on the tensile test data, the following parameters were developed for all filament specimens: Young's modulus, tensile strength or yield stress, stress at break, the strain at maximum tensile strength and the elongation at break. The following diagrams always show the calculated mean values of the respective specimens, as well as their standard deviation. For easier understanding of the diagrams, the filament samples have been given abbreviations. "V" stands for virgin granulate, "R" for recycled granulate and "P" for pelletized. The overview of the tensile strength and yield stress of the respective filament samples can be seen in Fig. 10.

Figure 10 demonstrates that the range between the tensile strength for the filament samples is about 15 MPa. A comparison of results from sample 5 (Verbatim Material) and sample 1 (100% fresh granulate) displays that the tensile strength of sample 1 is 10% (5.2 MPa) higher. The difference in the tensile strength is attributed to the granulate from the company Selenis [23]. The tensile strength of sample 3 (100% recycled material) is 13 MPa lower on average then the tensile strength of sample 5 (Verbatim Material). This represents a decrease of 28.2% for the tensile strength through one recycling cycle. In relation the works of Anderson [6] and Sanchez et al. [7] had smaller decreases after one and five recycling cycles respectively. The reason for the large decrease could be that the recycling material, which is only of similar grades

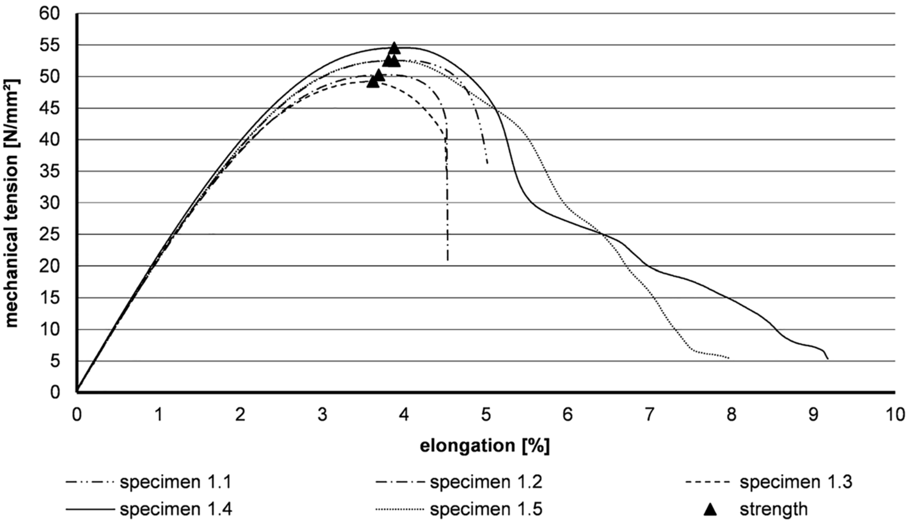

Fig. 9 Stress–strain diagram sample 1 (100% virgin material)

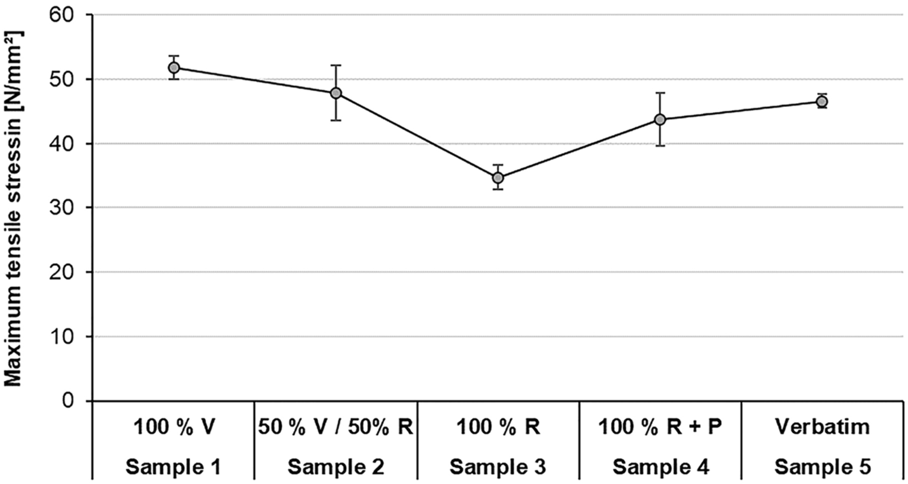

Fig. 10 Overview of maximum tensile strength for the different filament samples

and not based one purely one PETG material. The shape of the recycled material could be another cause for this.

The comparison between sample 3 and sample 4 shows that the maximum tensile strength of sample 4 is 20.5% (9 MPa) higher than sample 3. The only meaningful distinction between these two samples is the form of the raw material. The more uniform size and shape of the pellets leads to a more homogenous heating distribution during the extrusion of the filament. For more concrete evidence a size and particle distribution will be done in future experiments. The tensile strength of the pelletized sample has a decrease of 6.4% on average in comparison to sample 5 (Verbatim material), which is smaller compared to the decrease of 12.5% shown in the results of Anderson [6]. The comparison between sample 1 (100% fresh granulate), sample 2 (50/50 blend fresh and recycled granulate) and sample 4 (100% recycled pelletized granulate) displays that a mixture of 50% new granulate and 50% recycled granulate achieves almost the same results as 100% new granulate. These are positive results with regard to the recyclability of plastics and thus a more sustainable use of resources. The results of sample 2 could be improved by pelletizing the recycled plastic flakes. The high standard deviation of sample 2 can be attributed to the inhomogeneous pellet shape and size of the recycled portion of the blend. Figure 11 shows an overview of the Young's modulus for the different test samples.

Figure 11 illustrates that sample 1 (100% virgin material) has the highest young's modulus and sample 3 (100% recycled material) the lowest, with a difference of 35% (750 MPa). The standard deviations within the respective test series are highest for sample 4.

The results of the tensile strength (see Fig. 10) and E-Modulus from Fig. 11 for sample 5 (Verbatim material) with 46.6 MPa and 1800 MPa are below the manufacturer's specifications of 50 MPa and 2020 MPa [10]. This difference may be due to divergent parameters during the 3D printing process. The presented results from this work deviate a lot from the presented results from Ksawery et al. [9], who also examine filament that is available on the market. Their results are between 458 and 1436 MPa [9] for different PETG materials and varying specimens. The huge difference in the results for the tensile modulus can stem from the tested materials aswell as different printing parameters. A meaningfull comparison to the results of this work is not possible.

Figure 11 shows an overview of the Young's modulus for the different filament samples. The test results demonstrate that the Young's modulus varies between 1400 and 2150 MPa. The two lowest values are achieved by sample 3 (100% recycled material) and sample 4 (100% recycled pelletized material). The significantly higher Young's modulus of sample 4 is attributed to the more homogeneous initial material. In this regard, the Young's modulus of sample 4 is on average 90 MPa smaller compared to sample 5. This is a relative loss of 5%. In the previous works of Zhao et al., Anderson and Sanchez et al. [5–8], only a minimal decrease over several cycles was detected. The data of Sanchez in 2015 [7] showed an increase for the tensile modulus. The presented 5% loss slightly contradict the results from preceding results. For a more accurate statement in this respect, more extensive tests will have to be carried out in the future. One reason for the decrease in tensile modulus could be the blending of different PETG grades. The results of sample 2 (50% new material, 50% recycled material) demonstrate a Young's modulus that is 8% (138 MPa) greater than the tensile modulus of sample 5, indicating that the degradation of the recycled material can be counteracted well with fresh virgin material. It should be noted that a potential proportion of recycled material can also be incorporated into the Verbatim material. Nevertheless, these are extremely positive results for

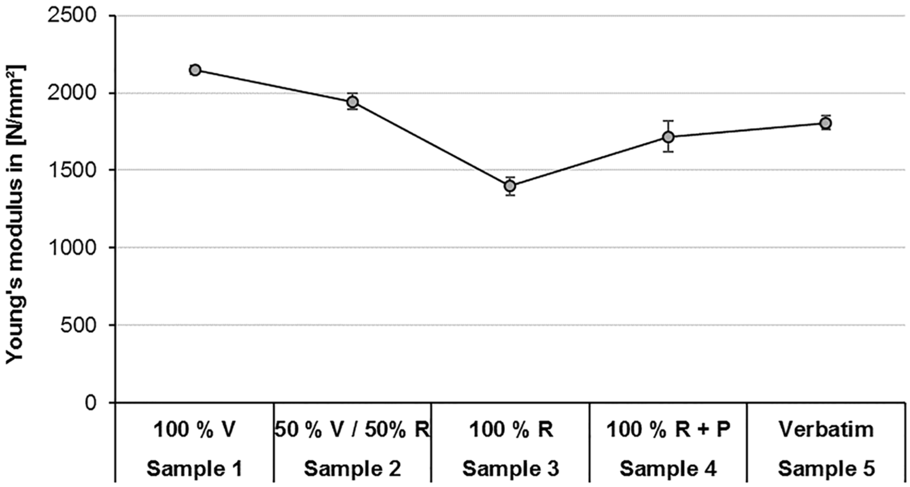

Fig. 11 Overview of the Young's modulus for the different filament samples

a possible circular economy for additive manufacturing. Figure 12 shows an overview of the elongation at the maximum tensile strength.

Figure 12 indicates that the elongation at maximum tensile strength is minimally different across all filament specimens. Samples 2 and 4 show an increased standard deviation. The observed results for elongation at maximum tensile strength from Fig. 12 show a homogeneous result across all filament samples. The variation of the elongation values is 0.5%, which means that no direct statement can be made about the effect of the recycled material. The high standard deviation for sample 2 and sample 4 can't be explained with the accumulated data in this study. Figure 13 illustrates the comparison of the breaking stresses for all filament samples.

The measurement points presented in Fig. 13 for the respective filament samples all show an enormously high standard deviation except for one (sample 3). Figure 14 displays the overview for the elongation at break.

Figure 14 illustrates that the observed elongation at break values also vary greatly across the individual test specimens of the respective filament samples, except for sample 3. For this reason, a high standard deviation is also seen here for four of the five filaments.

The results of the stress and strain at break clearly show variations within the filament specimens. The results of the test data are shown in Fig. 13 for stress at break and Fig. 14 for elongation at break. The high variations occur for both the recycled material samples and the virgin filament samples, so that an influence of the material is excluded. It is assumed that the reason for the high variations is due to the printing settings. The Z-seam, the point where the current layer ends and the subsequent layer starts, was randomly distributed across the sample. If these Z-seams are located in areas of pinching, the local fracture behavior of the material in that area will change. In order to confirm this hypothesis, further series of tests must be carried out that focus specifically on this issue.

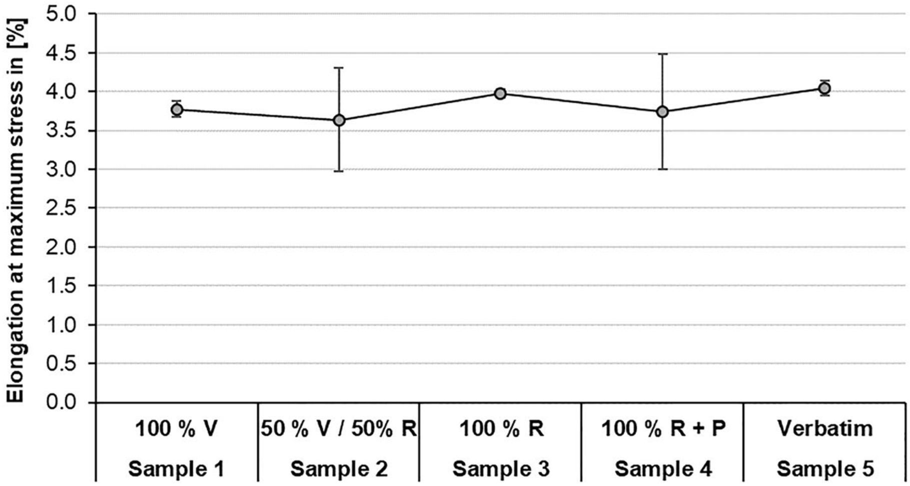

Fig. 12 Overview of elongation at maximum tensile strength for the different filament samples

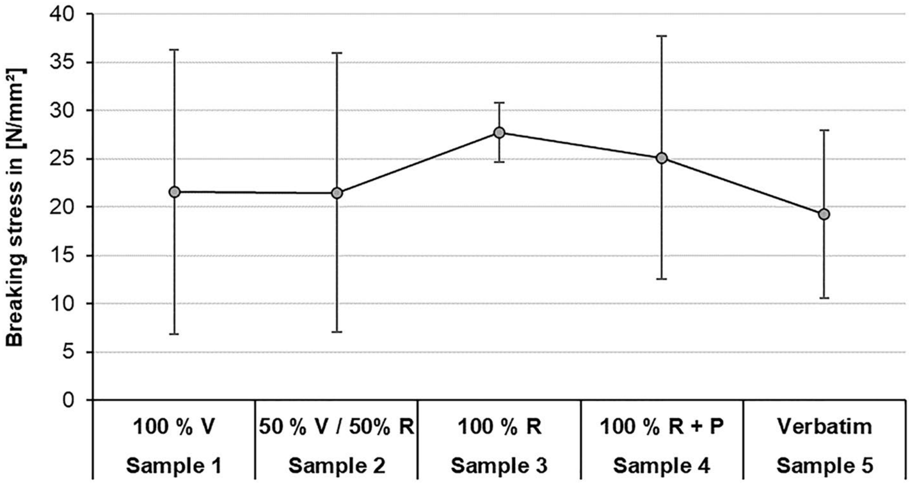

Fig. 13 Overview of the breaking stress for the different filament samples

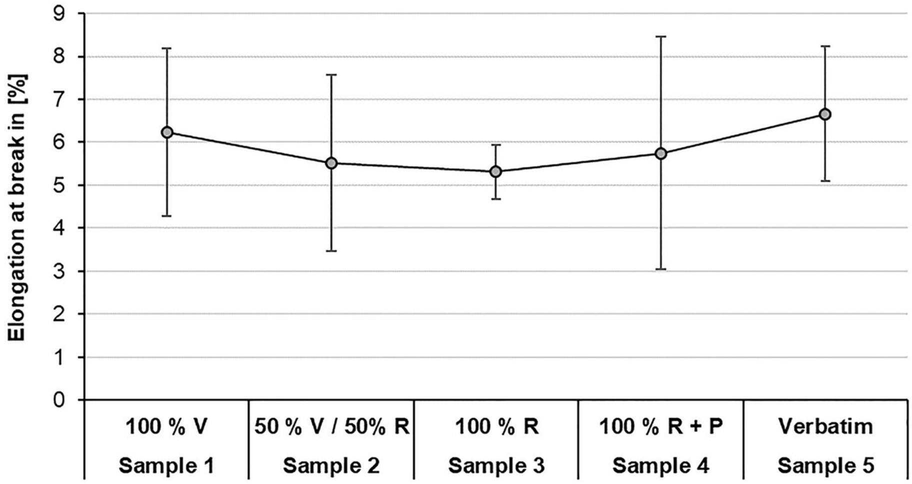

Fig. 14 Overview of elongation at break for the different filament samples

5 Conclusion

This feasibility study demonstrated that 3D printing waste and misprints from PETG plastic are suitable for material recycling and that the produced recycled granulate yields new filament for 3D printing. The filament should be manufactured using a granulate with a uniform shape and size. This has a positive effect on the filament diameter as well as on the mechanical properties of the plastic. The study showed that specimens made of uniform, recycled material have a slightly lower tensile strength than specimens made of conventional purchased material. The results also demonstrated that a mixture of virgin granules and recycled material at 50% each resulted in filaments whose tensile strength is at the same level as the tensile strength of the purchased material. This is especially important for recycling approaches in industrial companies, as resources can be saved and conserved by using the recycled material.

The results show that the execution of one recycling cycle leads to a weak decrease of mechanical properties. In further work the influence of the number of recycling cycles on the mechanical properties should be examined. Furthermore, the process parameters of filament production can be optimized on a laboratory scale. On the one hand, the process parameters can be adapted and on the other hand, the used equipment can be enhanced. An example would be an extruder screw with several heating sectors, so that the temperature along the screw can be controlled.

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Data availability The underlying data will be uploaded as supplementary data, if there is a reasonable request.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent to publish Not applicable.

Appendix

See Figs. 15, 16, 17 and 18.

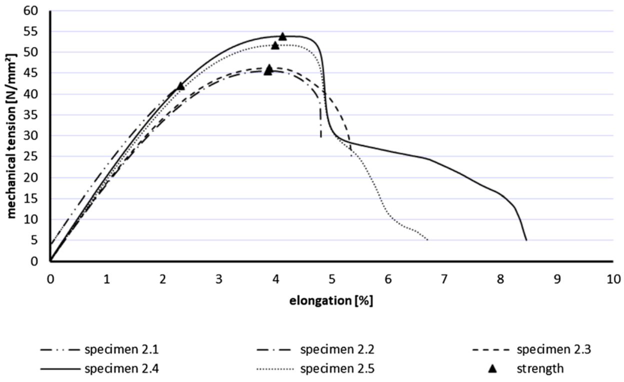

Fig. 15 Stress–strain diagram sample 2 (50% virgin material/50% recycled material)

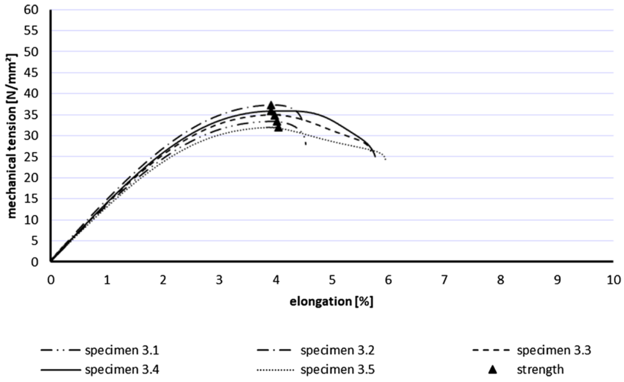

Fig. 16 Stress–strain diagram sample 3 (100% recycled material)

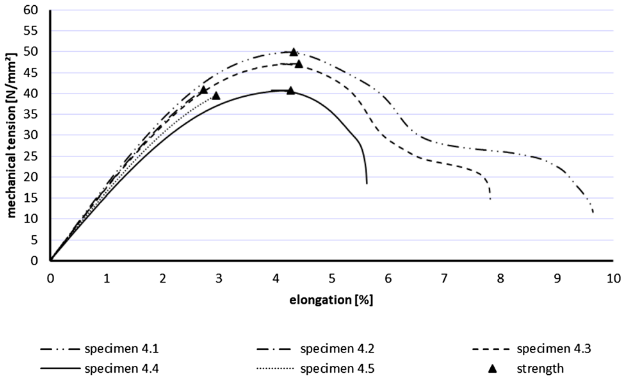

Fig. 17 Stress–strain diagram sample 4 (100% recycled pelletized material)

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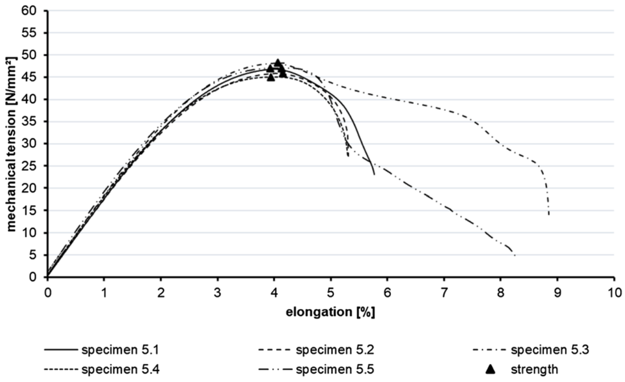

Fig. 18 Stress–strain diagram sample 5 (Verbatim material)

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