



Circular economy solutions for plastic waste: improving rheological properties of recycled polyethylene terephthalate (r-PET) for direct 3D printing

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Abstract

As global plastic production reaches unprecedented levels, the increasing amount of plastic entering our oceans poses serious environmental risks. The Circular Economy (CE) concept plays a key role in this shift, from linear to circular, by promoting waste reduction, improved recycling methods, and innovative technologies that convert waste into value-added products. Among waste polymers, poly (ethylene terephthalate) PET, known for its enhanced properties like chemical resistance and mechanical properties, which is widely used for water bottles and food containers, is a prime candidate for recycling efforts. Taking advantage of 3D printing and recycled PET as a feedstock emerged as one of the potential solutions to reuse waste PET. However, 3D printing recycled PET (r-PET) is challenging due to the deterioration of physical properties after recycling compared to virgin PET, like reduced viscosity and melt strength, as well as chain scission. To address these challenges and direct 3D printing of r-PET, this study, for the first time, modified r-PET using a proprietary additive, to make it compatible with 3D printing and enhance properties. Through analysis of flow behavior and examinations of thermal stability, chemical structures, and mechanical properties, it is found that 0.75% is the optimum amount of additive added to r-PET, which improves the printability of r-PET feedstock. After the addition of 0.75% additive, the complex viscosity of the modified r-PET increased from 200 Pa.s to around 1000 Pa.s, which meets the viscosity requirements for 3D printing. In addition, ultimate tensile strength of modified r-PET reached around 51 MPa which is comparable with commercial filaments like ABS, PETG and PLA. The findings of this study highlight the importance of using modifiers as additives to enhance the properties of recycled waste plastic, rendering them suitable for 3D printing. This facilitates the reprocessing and remanufacturing of new products within the framework of a circular economy with the aid of 3D printing.

Keywords Additive manufacturing · Waste plastic · Polyethylene terephthalate (PET) · Sustainable materials

1 Introduction

In modern life, polymers are inseparable parts of many industries, such as aerospace, automotive, packaging, and construction. To meet the huge demands of these industries, the worldwide rate of plastic production increased from 2 million metric tons in 1950 to 391 million metric tons in 2021. As a result of this high rate of production, each year, an estimated range of 4.8 million to 12.7 million

tons of plastic waste finds its way into the ocean [1–3]. It is projected that without intervention, the weight of plastic in the ocean will exceed that of fish by 2050. More importantly, one of the main objectives in the context of sustainable development goals (SDGs) is responsible consumption and production [4]. To prevent entering more plastic waste into the ocean, inefficient use of raw materials and reach the goal of circular economy in plastic production, it is imperative to use them for recycling and energy recovery [2]. Energy recovery involves extracting energy from plastic waste through processes like incineration or pyrolysis. This approach not only reduces the amount of plastic waste ending up in landfills or oceans but also harnesses the energy potential stored in these materials. The Circular Economy is a production system concept that aims to increase the value and use of materials by promoting their retention and

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restoration within the economy. This material retention can be achieved by reducing waste, increasing recycling rates, improving collection efficiency, enhancing recycling methods, or developing technologies for upcycling and downcycling [5].

Among industries using plastics, packaging is the primary end-user market for polymers, specifically polyethylene (PE), poly (ethylene terephthalate) (PET), and polypropylene (PP) [6]. PET is the most recycled thermoplastic in Canada and is widely recognized globally. It is commonly used in bottle manufacturing and various industries such as food, cosmetics, and healthcare. This semi-crystalline polyester offers excellent barrier properties, mechanical strength, ductility, and resilience to large deformations. [2, 7]. PET is traditionally manufactured by injection blow molding, which promotes rapid cooling rates and inhibits crystallization. This technology enables the manufacture of flexible and translucent PET packages and films [8–10]. PET can also be made using other technologies, including lamination, injection molding, thermoforming, or coextrusion [7].

In addition to the abovementioned traditional methods for manufacturing PET parts, the other method is reprocessing PET flakes or pellets into filaments via extrusion, which can be utilized as a feedstock for Fused Deposition Modeling (FDM) which is one of the additive manufacturing (AM) (also called 3D printing) techniques [11, 12]. A key benefit of AM is its reduced waste production in comparison to traditional manufacturing methods, thereby aligning with sustainability and economic objectives. Stratasys created the FDM method, the process of extruding filament material through a heated nozzle and depositing it layer by layer onto a substrate while it is still semisolid [13]. Among many 3D printing technologies, FDM has grown in popularity due to its low cost, accessibility, and adaptability with a wide range of materials [14, 15]. Over time, the range of 3D printable materials with FDM has been expanded to a variety of plastics, metal powders, ceramics, and composites, for use in the aerospace, medical, mold design, and automotive industries [16, 17].

However, the number of studies for developing filaments from recycled PET (r-PET) and subsequent FDM 3D printing is very limited [18–23]. The main challenge for making filaments from r-PET is its low intrinsic viscosity (IV) and melt strength, which makes it unsuitable for the extrusion process. Mechanical recycling methods for PET, such as heat-induced processes like extrusion, cause property degradation due to imposing high shear stress and temperature, leading to the reduction in IV by the formation of low molar mass PET. The intrinsic viscosity of PET serves as a crucial indicator of its printability and final product quality. In addition, parameters such as molecular weight, melting point, crystallinity, and tensile strength are significantly influenced by the IV of PET [24].

In the very first study by Zander et al. [25], they developed r-PET filament for FDM without additives using a twin-screw extruder. The filament was pelletized and re-extruded to achieve a consistent diameter. The study examined the effects of processing conditions, drying, and PET source on mechanical, rheological, and thermal properties. Crystallinity ranged from 12.2% for water-cooled filaments to 24.9% without active cooling. The tensile strength of printed parts was 35.1 ± 8 MPa, comparable to commercial polycarbonate-ABS filament, with an elongation to failure of 3.5%, similar to injection-molded parts. Three-point bending tests showed that parts made from recycled filament had equivalent loads at failure compared to those made from commercial filament." In another study by Voorde et al. [26], they studied how FDM and extrusion parameters affect the crystallinity and mechanical properties of recycled PET using a twin-screw extruder. Polymer degradation depended on extruder residence time, with 270 °C for 5 min being optimal. Extrusion conditions, such as barrel temperature and residence time, influenced filament crystallinity and mechanical properties. Optimal FDM printing temperatures were 250 °C for Ultimaker 3 and 260 °C for Prusa i3 MK3S. Fan cooling and the interaction between printing and build plate temperatures significantly affected the crystallinity and mechanical properties of printed parts. Tensile testing showed significant differences ($p < 0.05$) in tensile modulus between Ultimaker (2.65 ± 0.14 GPa) and Prusa (2.41 ± 0.04 GPa) printed components.

These two groups that worked on processing r-PET using FDM employed a certain grade to manufacture filament and print it, with no chemical change. Most studies have concentrated on optimizing process parameters rather than finding a technique to improve the properties of the main material feedstock with different grades and discover a practical strategy for employing r-PET for AM on a commercial scale. The primary challenge encountered when processing r-PET for FDM lies in the significant degradation of r-PET properties with different grades, produced from different sources, during their lifespan and recycling process. This degradation results in lowered viscosity and melt strength, rendering direct extrusion into filament forms unfeasible. More importantly, PET undergoes different processing methods for various applications, such as injection molding or blow molding, utilizing different grades. However, during recycling, these grades get mixed, creating a blend of different PET grades. Some of these streams of r-PET can be processable for extrusion and some of them not. Separating these grades proves challenging, prompting the use of chemical modification instead. The proposed approach in this study, by adding a suitable modifier, adjusts the rheological properties of the mixed PET grades and makes it extrudable. By modifying the chemical composition or structure, the mixed PET becomes suitable for processes like FDM. To this end,

in this study, r-PET flakes sourced from water bottle waste were procured and subjected to rheological analysis, revealing insufficient shear thinning behavior and viscosity for making filaments and 3D printing, due to chain scission during mechanical recycling. To address this issue, a reactive modification of r-PET was investigated using a proprietary additive (hereafter called PA), via a batch mixer, to modify the rheological property of r-PET and make it printable. Subsequently, the filament-making process was executed using a single-screw extruder (Filabot). Various concentrations of additives (0.5, 0.75, 1, and 1.5 wt %) were employed to modify r-PET viscosity. Following reactive modification, comprehensive investigations into thermal stability, chemical structures, rheology, and mechanical properties were conducted to determine the optimal additive concentration. As the showcase, the parts of a centrifugal pump was 3D printed successfully using the modified r-PET. Through a systematic approach, this study aimed to mitigate the inherent limitations of remanufacturing and reusing recycled PET using a low-cost desktop 3D printer, thereby enhancing reprocessing and remanufacturing waste plastics into new value-added products.

2 Experiment

2.1 Materials

Recycled PET flakes (r-PET), sourced from post-industrial water bottle waste, were purchased from Post Plastics Inc. Canada. The additive PA was supplied by Sigma-Aldrich in the form of white powders with 99% purity.

2.2 Reactive modification, filament making, and 3D printing

Reactive modification process of r-PET with PA additive was carried out in a Haake Rheomix 3000P (ThermoFisher Scientific; Waltham, MA) at a rotor speed and mixing temperature of 60 rpm and 260 °C, respectively. To prevent a hydrolysis reaction, r-PET flakes, and the PA powders were pre-dried for 12 h at 100 °C in an oven before the melting process. Dried flakes were melted and mixed for 4 min in the batch before the PA addition. PA contents were selected at 0, 0.5, 0.75, 1, 1.5 wt%. After adding the additive, the reaction process was continued for 6 min when the torque became stable. After that, samples were detached from the batch, grinded, and then dried for another 12 h prior to filament-making process. To make filaments, the granules were fed into a single-screw extruder (EX2, Filabot, Barre, USA), with one heating zone and air fans cooling system. The heating zone temperature and the nozzle diameter were adjusted to 245 °C and 1.75 mm, respectively. The screw and spooling speeds were adjusted to make

filaments with 1.75 ± 0.05 mm diameter, which is compatible with Prusa FDM 3D printer. After filament making, type V tensile test specimens based on ASTM D638 were printed by using a low-cost desktop Prusa i3 MK3S + 3D printer. The STL files of the specimens were converted to G-code files by using the Cura Slicer software. All printing parameters are represented in Table 1. The show case of centrifugal pump parts was printed with the same parameters in Table 1. In addition, the process schematic is presented in Fig. 1.

2.3 Thermal properties

2.3.1 Differential scanning calorimetry (DSC)

To investigate the thermal properties of r-PET modified with PA, a DSC test (Q20 instrument from TA Instruments in New Castle, DE, USA) was conducted. The experiments were implemented under the 50 mL/min nitrogen flow rate. The average weight of the samples was 6 mg. To eliminate the thermal history of the materials, 3 cycles, including heating, cooling, and reheating were conducted. Samples were heated up until 300 °C, followed by an isothermal hold at this temperature for 3 min. Subsequently, the cooling phase occurred at 10 °C/min down to 30 °C, succeeded by a second heating phase at 10 °C/min up to 300 °C. From the DSC test, melting temperature (T_m), cold crystallization temperature (T_{cc}), glass transition temperature (T_g) and the degree of the crystallinity of the samples X_C were extracted. The degree of crystallinity is calculated using Eq. (1), where ΔH_f is the fusion enthalpy, ΔH_{cc} is the cold crystallization enthalpy and ΔH_f^0 is the heat fusion of 100% crystalline PET (140 J/g) [27]:

$$X_C(\%) = \frac{\Delta H_f - \Delta H_c}{\Delta H_f^0} \times 100\% \quad (1)$$

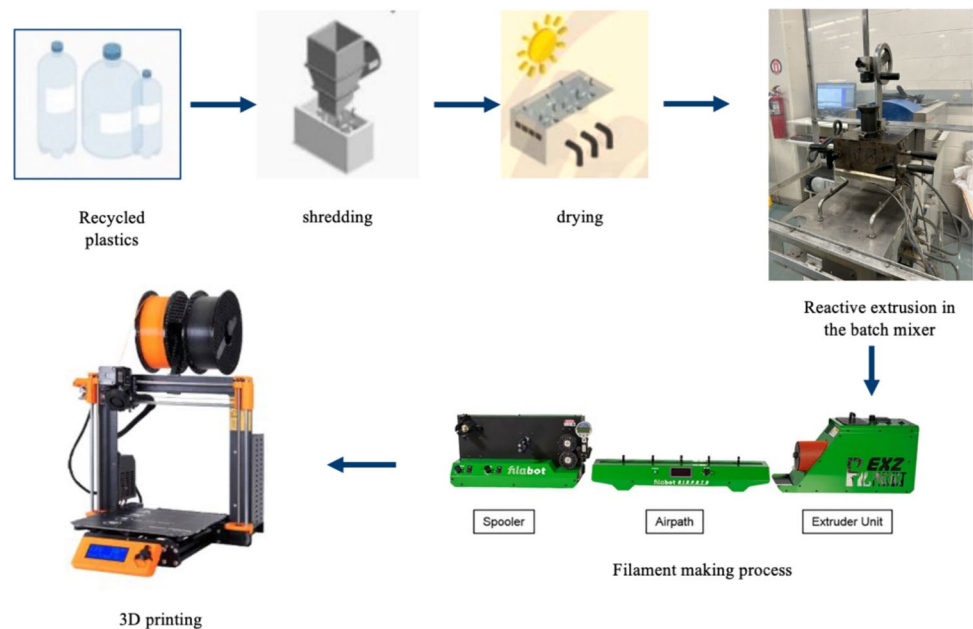
2.3.2 Thermal gravimetric analysis (TGA)

TGA test was conducted by utilizing a thermal gravimetric analyzer (Q50, TA Instruments, USA) to extract

Table 1 3D printing parameters of test samples

Printing parameters	
Nozzle temperature	260 °C
Bed temperature	80 °C
Flow rate	100%
Layer height	0.15 mm
Printing speed	20 mm/s
Infill pattern	45 degrees, lines
Infill density	100%
Nozzle diameter	0.4 mm

Fig. 1 Schematic of the process and equipment



decomposition temperature as well as additives content in r-PET samples. The sample's average weight was 5 mg. The process was carried out under a nitrogen-controlled atmosphere with a temperature range of 30–600 °C and 10 °C/min heating rate.

2.4 Fourier transform infrared spectroscopy (FTIR)

PerkinElmer Spectrum 100 FT-IR Spectrometer was used to determine the chemical structure of r-PET and the additive and indicate the chemical reactions.

2.5 Rheology

The melt viscosity of the samples at 260 °C was measured by using a parallel plate rheometer (DHR, TA Instruments, USA) with a 25 mm parallel plate and 1500 µm gap. The samples were prepared in the form of disks with 25 mm diameter and 2 mm thickness. The shear frequencies were set in a range between 1 and 100 rad/s with a constant strain rate of 5%, which is in the linear viscoelastic region.

2.6 Mechanical test

The tensile evaluation of the 3D-printed doge-bone-shaped samples (ASTM D638) was carried out utilizing a cutting-edge Universal Testing Machine (LS100 Plus, Lloyd, UK), boasting a remarkable load capacity of up to 100 kN. Each specimen was positioned between upper and lower flat support surfaces, ensuring alignment. In addition, the long axis of the specimen was carefully oriented along the central axis of the testing apparatus for optimal testing conditions.

The testing protocol was executed, maintaining a consistent speed of 5 mm/min throughout the evaluation process. This deliberate approach ensured uniformity and accuracy in the assessment of the mechanical properties. For each formulation, 3 samples were printed. Images of the printed samples and dimensions are represented in Fig. 2.

3 Results and discussion

3.1 DSC and TGA analysis

According to DSC results, shown in Fig. 3a, the melting temperature of modified r-PET samples with PA (0–1.5%) showed a decrease of around 3 °C in their melting point compared to neat r-PET. This decrease is attributed to the fact that steric hindrance is increased by adding the additive and changing the side chain from carbon-zero to carbon [25]. Thus, in these cases, a decrease in the melting point was caused by an increase in the amount of additive agents. The addition of PA increases branching in the PET chain, which results in a lower melting temperature due to changes in the size of the crystals and the length of the chain. Because the melting temperature depends on the size of the crystal, it drops as branching rises. The most significant changes were observed in the crystallization temperature by adding PA to r-PET in that T_c of all modified samples in Fig. 3b shifted to a higher temperature compared to unmodified r-PET. It appears that increasing the amount of additive that serve as uniform nucleation site leads to the formation of branch structures which increase the crystallization temperature [28, 29]. This results in an elevation of both the initial rate

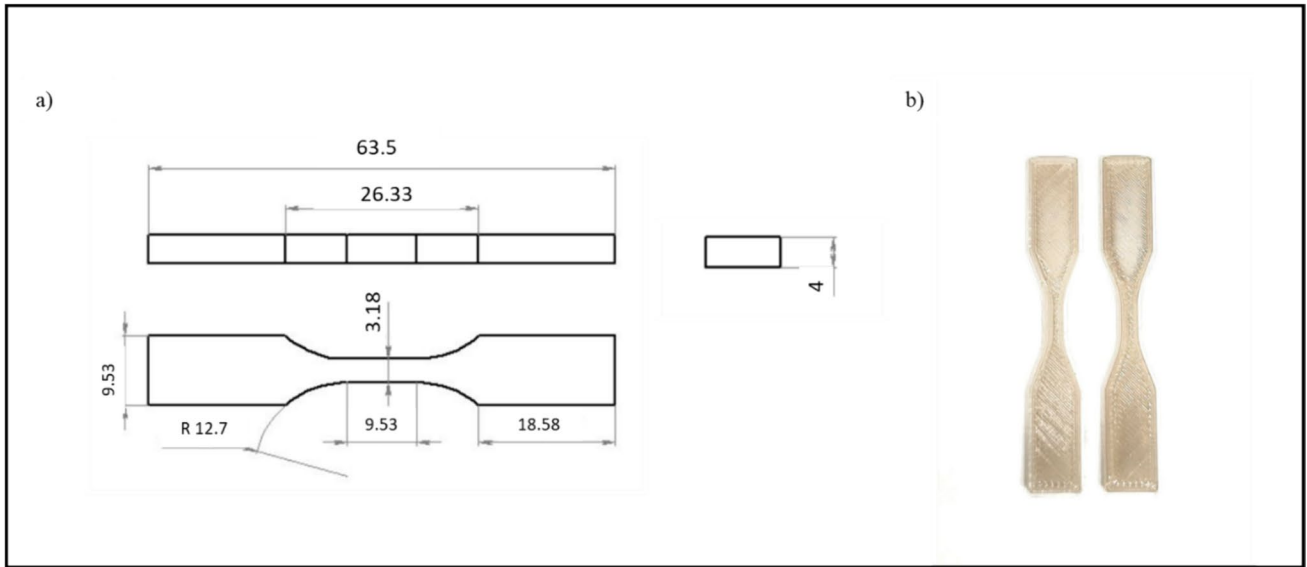


Fig. 2 Dimension of the tensile test sample according to ASTM D638, **b** example of printed samples

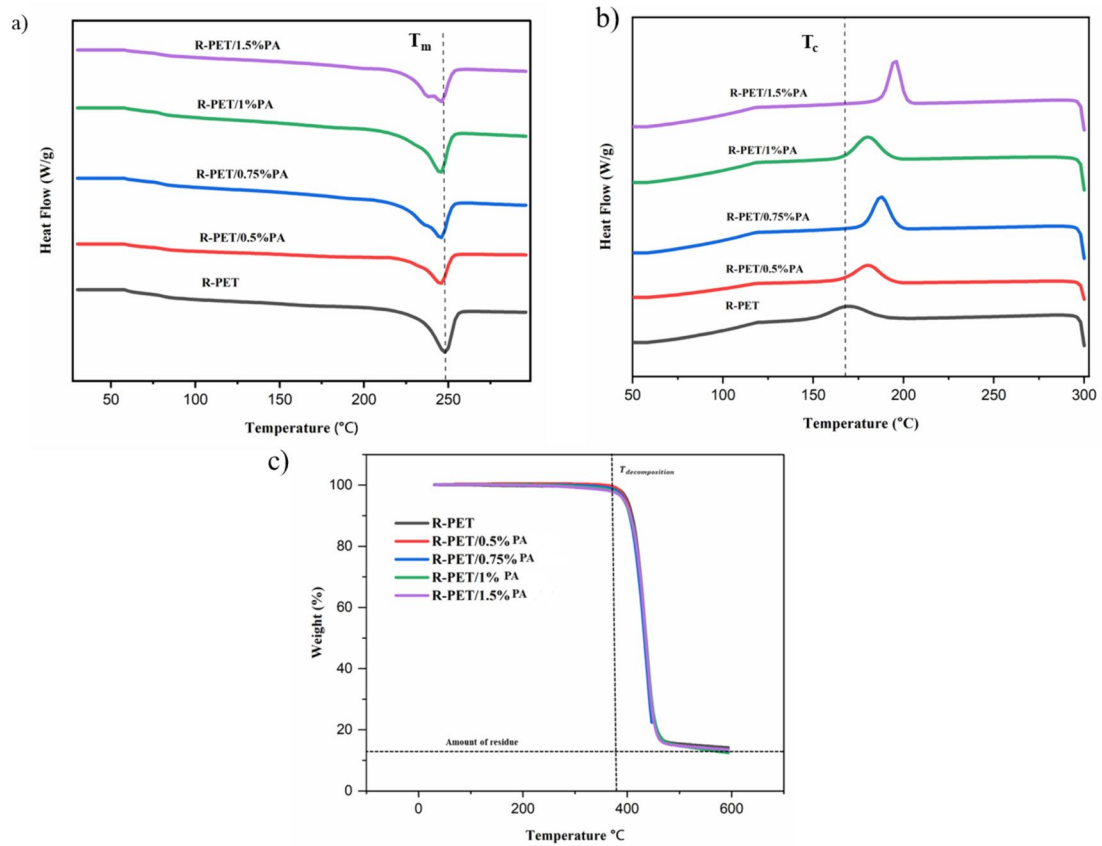


Fig. 3 **a** Heating cycle in DSC test, **b** cooling cycle in DSC test, **c** TGA test results

of crystallization and the crystallization temperature. In Table 2, the values of T_m , T_c , enthalpies, and degree of crystallization (calculated using Eq. 1) are illustrated. Regarding the degree of crystallinity, adding 0.5% PA led to a decrease, indicating that at this concentration, PA disrupted the crystallization process. However, when the concentration was increased to 0.75% and 1% PA, the degree of crystallinity improved. This suggests that these higher concentrations enhanced chain mobility and facilitated optimal crystallization, resulting in increased crystallinity.

In the TGA analysis shown in Fig. 3c, both decomposition temperature and the residue content of r-PET were investigated. The results indicated that r-PET typically leaves behind approximately 15% residue, which shows the small quantity of impurities or additives added by the producers or recycling center to r-PET. Another key parameter in TGA results is the decomposition temperature which tends to hover around 400 °C for r-PET (Fig. 3c). When additives were added, there was no notable alteration observed in the decomposition temperature compared to the neat r-PET. All sample decomposition temperatures were around 390.

3.2 Fourier transform infrared spectroscopy (FTIR)

Fourier transform infrared spectroscopy was done to analyze the chemical modifications that occurred after adding PA additive to r-PET. FTIR analysis provided insight into the chemical structure of pure as well as functionalized r-PET, Fig. 4. The PET spectra showed absorption bands at 725 cm^{-1} , 1015 cm^{-1} (aromatic bands), 1090 cm^{-1} (methylene), 1235 cm^{-1} (ester group), and 1720 cm^{-1} (ester carbonyl). In the FTIR spectra, double shoulder peaks from 1250 to 1050 cm^{-1} were associated with the vibration of C–O from carboxyl groups, and absorption bands at 1340 cm^{-1} and 1370 cm^{-1} were assigned to the wagging of the ethylene units. Absorption peaks in PA spectra indicate symmetric and asymmetric stretching of carbonyl groups at $1780\text{--}1763\text{ cm}^{-1}$. For comparative analysis, a graph was plotted for r-PET, PA and r-PET/0.75%PA. The intensity of these peaks at 1700 cm^{-1} and 1770 cm^{-1} was reduced in the r-PET/0.75%PA sample, indicating that the reactive modification was done completely [30].

Table 2 Crystallization temperature, enthalpy, crystallinity, and melting temperature from DSC test results

Sample	Crystallization temperature $T_c(^{\circ}\text{C})$	Crystallization enthalpy $\Delta H_c(\frac{\text{J}}{\text{g}})$	Melting temperature $T_m(^{\circ}\text{C})$	Melting enthalpy $\Delta H_m(\frac{\text{J}}{\text{g}})$	Degree of crystallinity (%)
r-PET	168.23	30.28	248.31	37.33	26.66
r-PET/0.5% PA	180.37	29.97	245.79	26.6	19
r-PET/0.75% PA	187.45	39.5	245.48	38.23	27.3
r-PET/1% PA	179.75	38.12	245.32	39.59	28.27
r-PET/1.5% PA	195.36	39.62	245.94	35.07	25.05

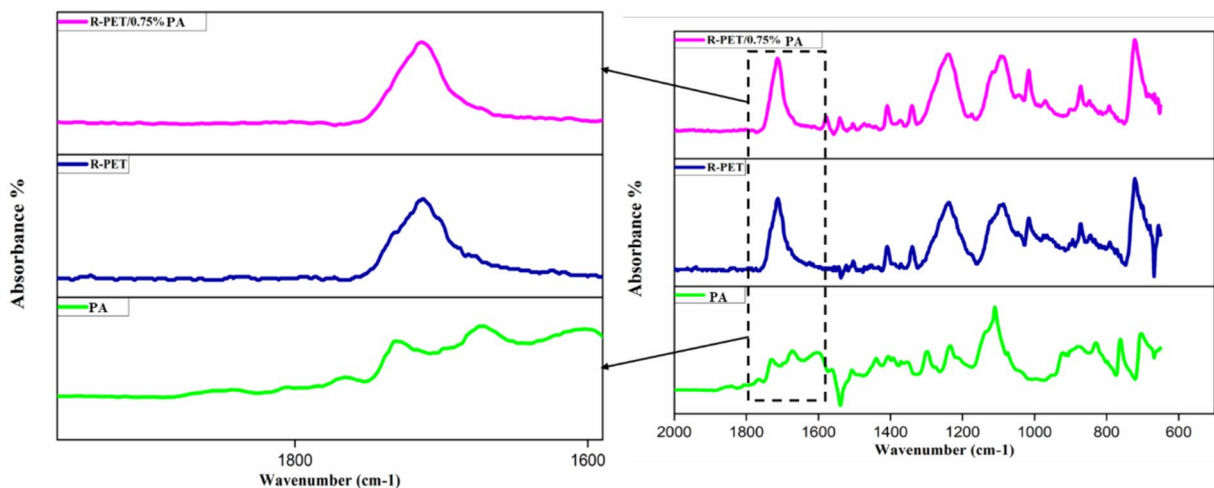


Fig. 4 FTIR results, showing the chemical reactions by addition PA to r-PET

3.3 Rheology analysis

In Fig. 5 a, b the storage and loss modulus of all samples represented. Similar trend to the complex viscosity results was observed here for all formulations. For PA-modified samples, the storage modulus significantly exceeded that of pure r-PET. It is attributed to the reason that increasing the number of entanglements enhances the material's capability to transfer external forces, resulting in improved melt elasticity and a consequent increase in the storage modulus [31, 32]. The storage modulus rises as frequency increases because, at low frequencies, there's ample time for chain relaxation, resulting in a lower number of contributing values to the storage modulus. Conversely, at higher frequencies, the chains lack sufficient time for relaxation, leading to an increase in the storage modulus. This increase in storage modulus which is representative of melt elasticity improves

filament-making process and makes it stable without any failure during the extrusion process. As for loss modulus, Fig. 5b, a similar trend to storage modulus is observed, overall, it is dominant to storage modulus, which illustrates that the material is more viscous rather than elastic.

The complex viscosity graphs of all samples are illustrated in Fig. 5c. In the neat sample, it is obvious that by increasing the frequency, no significant changes in viscosity were detected in the range of 1 to 100 rad/s. It shows that the neat r-PET flakes do not show shear thinning behavior, which is not favorable for material extrusion (both printing and filament-making process) and the complex viscosity was around 200 Pa.s in the linear region. However, in modified samples with PA, the behavior was different. PA-modified r-PET samples demonstrated higher viscosity compared to r-PET. This increasing trend in viscosity was continued until the PA amount of 0.75% (complex viscosity: around

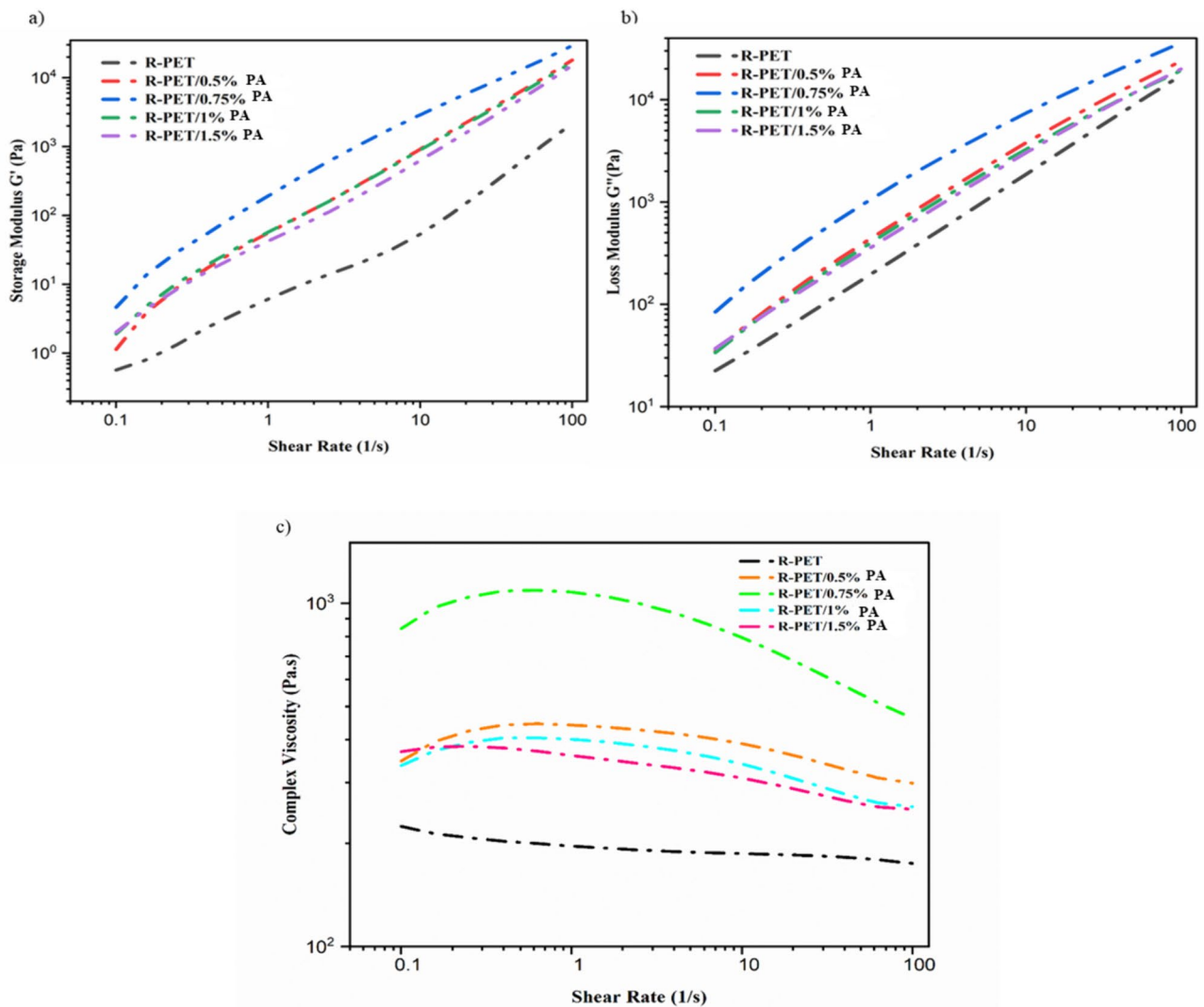
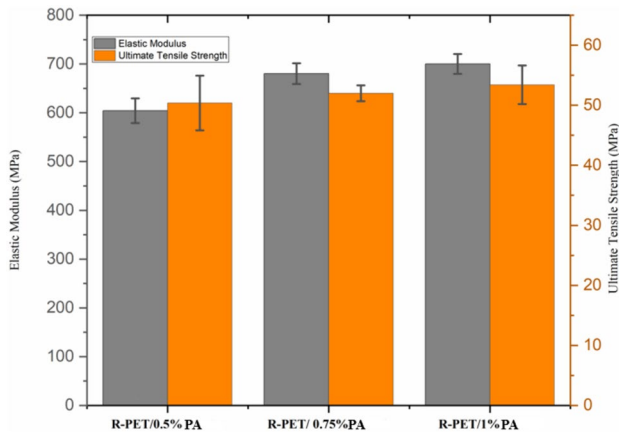


Fig. 5 a Storage modulus, b loss modulus c complex viscosity from rheology tests

Table 3 Summary of mechanical properties of 3D printed parts

Sample	Elastic modulus (MPa)	Ultimate tensile strength (MPa)	Elongation at break (%)
R-PET/0.5% PA	604.25 ± 25.46	50.37 ± 4.56	119.4 ± 10.24
R-PET/0.75% PA	680.26 ± 21.31	52 ± 1.32	75.65 ± 3.5
R-PET/1% PA	700.25 ± 20.32	53.4 ± 3.22	69.34 ± 2.84

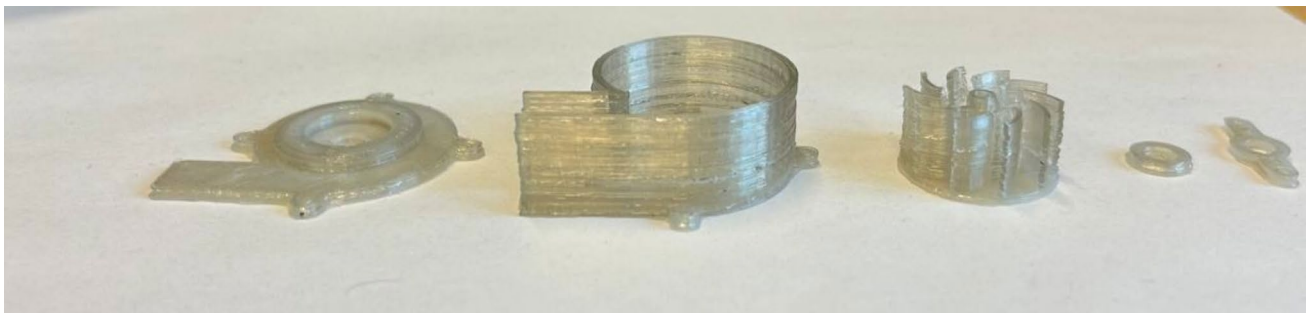
**Fig. 6** Trend of UTS and elastic modulus of 3D printed samples

1000 Pa.s); however, after increasing the PA content to 1% and 1.5%, the complex viscosity of the samples dropped to around 430 Pa.s in the linear region. The decline in complex viscosity could be attributed to the excessive addition of additive, which causes disruption to the reaction process. The other important point is that, by adding 0.75% PA, the shear thinning behavior of the material improved significantly, which is favorable for 3D printing. Shear thinning behavior enables the material to flow more readily under the high shear rates encountered during extrusion through the printer nozzle, promoting smoother extrusion and deposition. In addition, shear-thinning materials typically regain viscosity after deposition, which aids in preserving the shape and structural integrity of the deposited layers, thus promoting suitable interlayer adhesion. The PA additive which is

used falls under the category of anhydride additives. This additive functions by connecting polymer chains together, thereby creating longer branches that significantly increase the viscosity of the material.

3.4 Mechanical properties

Table 3 and Figs. 6, 7 represent the mechanical properties of samples containing varying PA concentrations (0.5%, 0.75%, and 1%). The ultimate tensile strength (UTS) values for all modified formulations display no significant difference, averaging 51 MPa. Comparative analysis with existing literature on 3D-printed recycled PET (r-PET), reveals UTS values ranging from 39 to 70 MPa. This disparity can be attributed to various production methodologies, including the use of twin-screw extruders or batch mixers, divergent mixing temperatures, and variations in recycled PET sources [23]. Regarding elastic modulus and elongation at break, samples with 1% and 0.75% PA exhibited diminished values compared to r-PET/0.5%PA, a trend validated by differential scanning calorimetry findings (Fig. 3b). These samples indicated higher degrees of crystallinity (27.3% and 28.27%, respectively), resulting in higher elastic modulus and reduced elongation at break. Conversely, the sample containing 0.5% PA displayed elevated elongation at break, attributable to a lower degree of crystallinity (19%). This underscores PA's role as a nucleating agent, enhancing crystallinity and consequently improving mechanical properties. In addition, in the previous studies by Zader et al., the printed r-PET ultimate tensile strength was 35 MPa, which is 15 MPa lower compared to our modified r-PET [25]. Crucially, when compared with widely used commercial

**Fig. 7** Parts of a centrifugal pump printed via r-PET/0.75% PA

feedstocks such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), and polyethylene terephthalate glycol (PETG), which exhibit average tensile strengths of 43 MPa, 59 MPa, and 53 MPa, respectively, it becomes evident that recycled PET modified by PA in this work presents a promising eco-friendly alternative for commercial feedstocks in 3D printing applications. This is noteworthy even though the PET used in this research is a recycled grade and typically would have lower properties compared to the mentioned virgin plastics [33].

As a proof of concept for this work, a centrifugal pump was 3D printed (FDM) using a selected formulation (r-PET/0.75 PA) that provided optimized properties. The successful printing of stable and fairly complex part shapes in this research showcases the effective use of our proprietary additive in recycled PET, making it suitable for 3D printing and enabling the successful reprocessing and remanufacturing of waste plastic.

4 Conclusion

This study aims to address the pressing issue of plastic waste management by exploring sustainable solutions within the framework of the Circular Economy (CE). In this study, the primary objective was to enhance the processability of recycled PET (r-PET), whose properties had deteriorated due to the recycling process, to make it suitable for 3D printing. This was achieved through the utilization of a proprietary additive (PA), to modify the recycled PET for 3D printing. Key findings revealed that:

- The optimal concentration of 0.75% PA significantly improved the complex viscosity of modified r-PET from 200 Pa·s to 1000 Pa·s, facilitating extrusion in FDM 3D printing.
- The introduction of PA led to beneficial changes in the thermal, crystallinity, and mechanical properties of r-PET. Differential scanning calorimetry showed a crystallinity of 27.3% and a crystallization temperature of 187.4 °C for samples with 0.75% PA. Fourier Transform Infrared Spectroscopy confirmed successful chemical modification, resulting in a branched structure that enhanced mechanical properties. Rheological assessments revealed a substantial increase in storage modulus, essential for stable filament production.
- As for mechanical properties, samples with 0.75% PA exhibited an ultimate tensile strength (UTS) of 51 MPa, while elongation at break was reduced by 75%, indicating improved structural integrity. The elastic modulus also increased with PA concentration, reaching 680.26 ± 21.31 MPa. The modified r-PET demonstrated tensile strengths comparable to conventional virgin mate-

rials like ABS, PLA, and PETG, despite using recycled grade PET. These findings support the potential of modified r-PET as a viable material for various applications in additive manufacturing, contributing to sustainable plastic waste management.

Future research should focus on optimizing the mechanical properties of r-PET to enhance its strength and uniformity, making it suitable for a broader range of applications. Experiments could explore different additives, compatibilizers, or processing approaches, such as using a twin-screw extruder to prepare feedstock for 3D printing. A detailed analysis of the material's impact, bending, and compressive strengths could reveal additional uses, like as a core for sandwich panels. Modeling efforts could simulate r-PET performance in real-world applications, such as load-bearing structures and stress analysis, guiding the development of new formulations. Based on the investigated properties, r-PET is suitable for producing plastic parts in the automotive and aerospace industries, including brackets, structural support, panel components, and as an affordable material for printing prototypes in research studies. In addition, it can be used for printing container and packages with specific geometry as well.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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