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Yazarlar (Authors): Musa Yilmaz*

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SUSTAINABLE RECYCLING PLA AND ABS MATERIALS IN ADDITIVE MANUFACTURING: EFFECTS ON STRENGTH, THERMAL STABILITY, AND ENVIRONMENTAL IMPACT

Musa Yilmaz[a]*

[a]Naci Topcuoğlu Vocational School, Gaziantep University, TÜRKİYE

* *Corresponding Author: msyilmaz@gantep.edu.tr*

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ABSTRACT

This study examines the impact of recycling on the thermal and mechanical properties of polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) filaments, as commonly used in additive manufacturing. Virgin and recycled PLA and ABS specimens were fabricated using an fused filament fabrication (FFF) type 3D printer. 3D printed specimens were evaluated using tensile and bending tests, as well as thermal analyses through differential scanning calorimetry (DSC) and scanning electron microscopy (SEM). Mechanical testing results showed minimal differences in tensile and bending strengths between virgin and recycled PLA samples, while in contrast recycled ABS demonstrated a more pronounced reduction in tensile strength. Thermal analysis revealed a slight decrease in the glass transition temperature for both materials, particularly in ABS, suggesting possible changes in layer bonding and structural stability. Overall, the recycled materials exhibited comparable mechanical properties to their virgin counterparts. This recycling approach not only lowers material costs but also enhances environmental sustainability within 3D printing applications. By reusing waste materials and reducing the dependency on virgin resources, this method supports a more sustainable manufacturing cycle, helping to reduce overall environmental impact in additive manufacturing.

Keywords: Additive Manufacturing, ABS Filaments, PLA Filaments, Recycling, Environmental Sustainability

1. INTRODUCTION

Plastics, synthetic polymers formed through the polymerization of monomers typically derived from petrochemicals, are widely used due to their lightweight nature, strength, durability, and versatile fabrication capabilities [1,2]. These properties and low manufacturing costs have made plastics integral to various sectors, including agriculture, construction, packaging, and medicine [3]. However, their short life cycle, especially in single-use products, has resulted in a significant accumulation of plastic waste in the environment. It is estimated that 6.3 billion tons of plastic waste were generated globally from 1950 to 2015, of which approximately 80% remains in natural ecosystems [4,5].

Plastic waste represents a significant environmental challenge because of its prolonged degradation period, which is estimated to range from 100 to 1000 years [6]. This has led to plastic fragmentation into macro, meso, micro, and nanoplastics, dispersed through various ecosystems, causing physical and chemical harm to numerous species [7,8]. Factors such as urbanization, economic growth, and population increase have contributed to the rise in plastic waste, which disproportionately affects developing regions that typically lack advanced waste management technologies and regulations [9,10].

As plastic waste continues to increase, the need for effective waste management and recycling strategies are becoming increasingly urgent. The management of plastic waste can be approached through reduced production, mindful consumption, and robust end-of-life processes, such as recycling [11]. However, recycling faces challenges due to high treatment costs and the complexities involved in

processing plastic waste without harming the environment [3,6]. Addressing these challenges is essential to reducing plastic's negative environmental impacts. Global organizations, such as the United Nations, have recognized plastic as a major environmental threat [12,13].

The challenges posed by plastic waste have driven global efforts to adopt sustainable practices in production, usage, and end-of-life management. In this context, the European Union (EU) has committed to advancing a circular economy model [14], with increased plastic recycling rates as a central goal. The EU's targets include recycling 50% of plastic packaging by 2025 and 55% by 2030, emphasizing the importance of innovative recycling methods alongside conventional approaches [15,16]. Achieving these targets would enable plastics to remain within the value chain longer, supporting their use in high-value applications and enhancing sustainability [17,18].

Additive manufacturing (AM) has grown rapidly in recent years, enabling quick and cost-effective production without the need for traditional machining or tooling [19]. With advances in AM technologies, particularly FFF, the use of 3D-printed polymers like PLA and ABS continues to expand [20,21]. However, FFF generates significant waste, including failed prints, support structures, and disposable prototypes. PLA, a biodegradable polymer derived from renewable sources, can be managed through recycling, combustion, composting, or landfill disposal [22]. Among these, recycling is considered the most sustainable approach due to its minimal environmental impact, while composting and combustion present challenges related to process complexity and carbon emissions, respectively [23,24].

Given the increasing application of 3D printing in various industries and the environmental impact of plastic waste, exploring sustainable management of waste generated from AM, particularly in materials like PLA and ABS, has become vital. Recycling presents a promising solution to the reduction of the environmental footprint of FFF-generated waste, yet the effects of recycling on the mechanical and thermal properties of these polymers require further examination. An understanding of how recycling impacts the performance and durability of 3D-printed materials is critical to enabling sustainable practices without compromising the functional quality of printed parts. This study assesses the mechanical and thermal behaviours of recycled PLA and ABS filaments to evaluate their suitability for reuse in FFF-based 3D printing applications. The findings aim to support sustainable recycling practices in AM. Mechanical properties, including tensile and bending strength, along with thermal properties, were analysed for both virgin and recycled samples to identify any changes in performance resulting from the recycling process. Additionally, SEM analysis was conducted to examine fracture surfaces, offering insights into structural integrity and layer adhesion.

2. EXPERIMENTAL PROCEDURES

2.1. Materials

This study focuses on PLA and ABS in both their virgin and recycled forms. The recycled materials were sourced from previously used 3D printing waste. Test specimens were created using virgin and recycled filaments, each with a nominal diameter of 1.75 mm.

2.2. Methods

The test specimens were fabricated using a Creality K1C 3D printer with a maximum build volume of 220 x 220 x 250 mm. The 3D printer used for specimen fabrication, operating with FFF technology (Figure 1a), offers a printing accuracy of 100 ± 0.1 mm. The AM process was carried out with four distinct filament types: virgin PLA (v-PLA), recycled PLA (r-PLA), virgin ABS (v-ABS), and recycled ABS (r-ABS). In order to isolate the effects of the recycling process on the mechanical and thermal properties of the polymers, all 3D printing parameters—including layer height, print speed, nozzle temperature, and infill density—were kept constant for both virgin and recycled samples. To ensure optimal printing conditions, the printing temperature was set to 220°C for PLA filaments and 250°C for ABS filaments. Correspondingly, the bed temperature was set to 50°C for PLA and 100°C for ABS to promote adhesion throughout the printing process. Each specimen was manufactured with a 100% infill density. The layer thickness was maintained at 0.28 mm, and the printing speed set to 50 mm/s. All other printing parameters, such as air gap, build

orientation, raster angle, printing velocity, contour width, and number of contours, followed the manufacturer's default settings and recommendations. All samples were fabricated using a flat build orientation along the XY plane to ensure a consistent printing direction throughout the study.

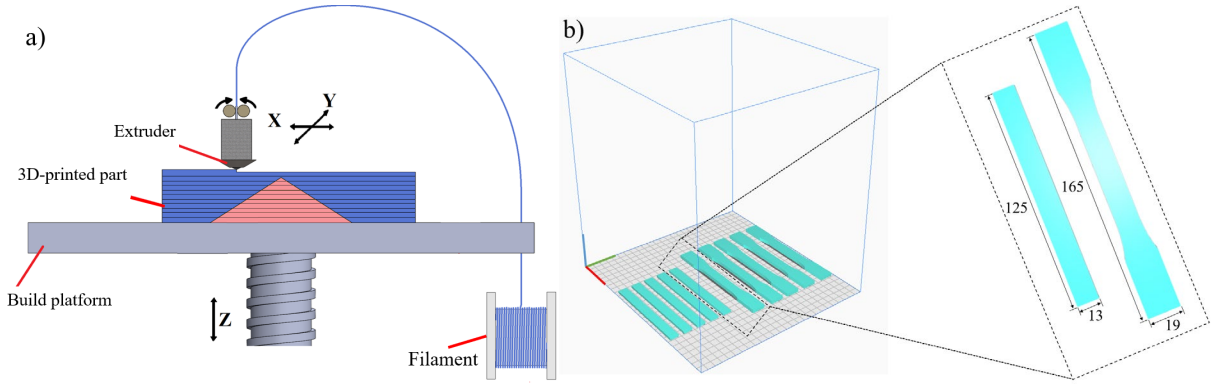

Figure 1. Schematic representation of (a) the FFF process and (b) the solid model of tensile/bending test samples with their building direction.

The recycling process for 3D printing materials begins with the collection of waste generated from previous 3D printing projects (Figure 2). These waste materials, often in the form of failed prints, support structures, or excess filament, are gathered and prepared for processing. The first step in the recycling workflow is the grinding phase, where the waste materials are fed into a grinder to be broken down into smaller particles or pellets. Once ground, the particles undergo an extrusion process. The particles are heated to their melting point during extrusion, creating a homogeneous molten polymer. This molten material is then extruded through a nozzle to form a continuous filament, which is cooled and spooled for easy handling and storage. The recycled filament is then loaded into a 3D printer, where it can be used to create new objects.

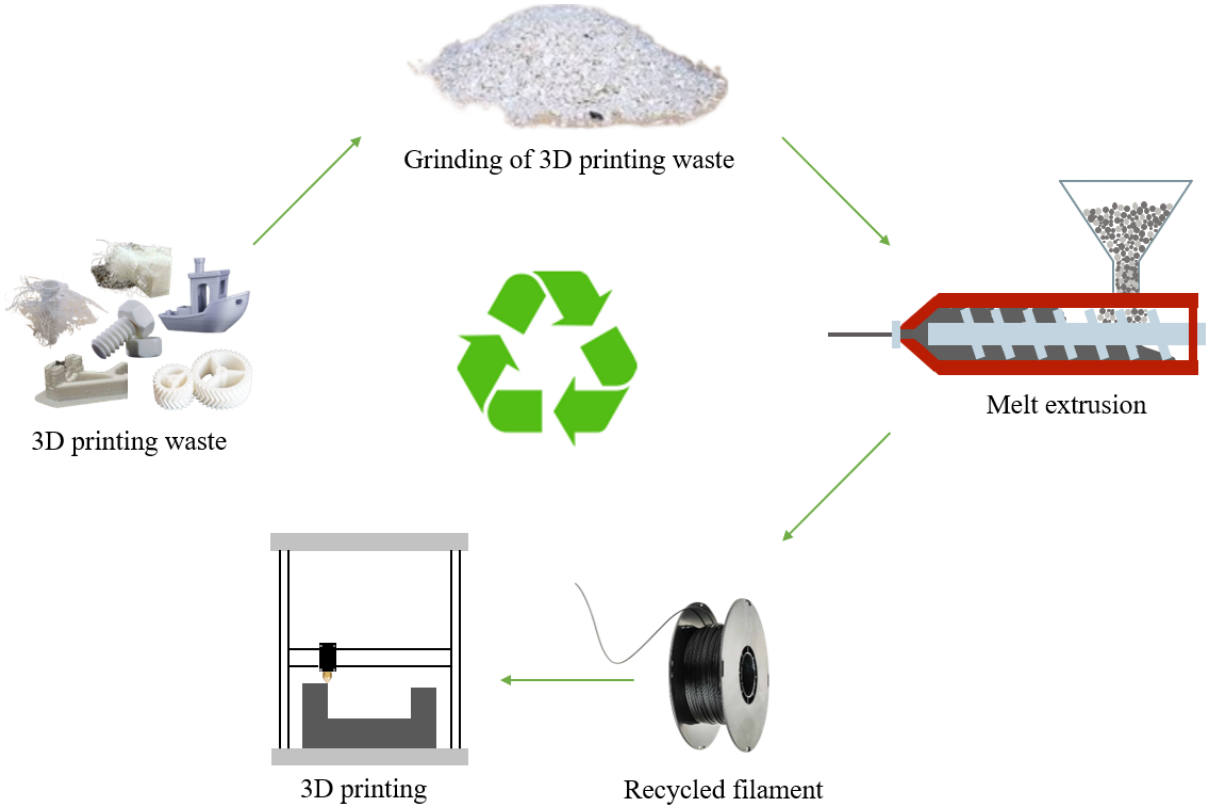

Figure 2. Recycling and filament production scheme for 3D printing materials

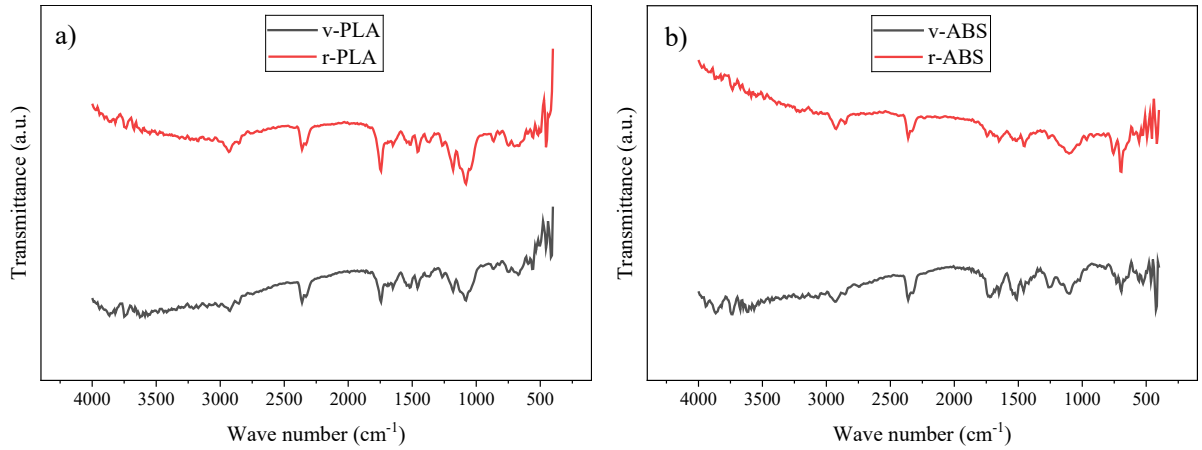

Figure 3. FTIR spectra of 3D-printed PLA and ABS samples

2.3. Characterization and Mechanical Testing

The chemical structure of the samples was analysed using fourier transform infrared (FTIR) spectroscopy using a Shimadzu IRTracer-100 spectrometer at room temperature. Spectral scans were conducted across the range of 4000 to 400 cm^{-1}, with a resolution of 4 cm^{-1}, for all specimens. DSC was used to analyse thermal transitions, including the glass transition and melting temperatures, with both heating and cooling rates set to 10°C/min on a Mettler-Toledo/700 DSC. Samples were placed in aluminium pans and initially heated from -50°C to 240°C at a rate of 10°C/min (first heating cycle). After reaching 240°C, the samples were again cooled to -50°C, then reheated from -50°C to 240°C at the same rate (second heating cycle). All measurements were performed in a nitrogen atmosphere. The thermograms obtained allowed for the identification of the glass transition temperature (Tg), cold crystallization temperature (Tcc), and melting temperature (Tm). SEM was used to capture detailed images of the surface morphology and microstructural characteristics of the specimens. A Zeiss Gemini 300 SEM was employed for sample preparation and imaging, with specimens coated in a thin layer of palladium/gold prior to analysis.

The mechanical properties were evaluated via tensile and bending tests following the ASTM D638 [25] and D790 [26] standards, respectively. Each test was conducted five times at room temperature using a Shimadzu AGX universal testing machine with a load capacity of 50 kN. The dimensions of the test samples are given in Figure 1b. The testing speeds were set to 5 mm/min for tensile tests and 1.56 mm/min for bending tests.

3. RESULTS AND DISCUSSION

3.1. FTIR Results

The FTIR spectra of the PLA and ABS samples used in the study are presented in the spectral region in Figure 3a and Figure 3b, respectively. There are no apparent differences between samples printed with virgin and recycled filament for both PLA and ABS. The presence of identical peaks indicates that the recycling process did not lead to any chemical changes in the samples. Additionally, the chemical structures of all the samples align with IR spectra reported in the literature, as confirmed by the FTIR spectra shown in Figure 3 [27–29]. In the IR spectra of PLA, a strong CO stretching vibration is observed at 1757 cm^{-1}, while bands corresponding to the $-CH_3$ C-H stretching vibrations are observed at 2996 cm^{-1} and 2945 cm^{-1}. Furthermore, bands associated with the characteristic absorption of ester CO stretching vibrations are observed at 1080 and 1187 cm^{-1} [30].

In the FTIR spectra of ABS polymer, characteristic absorption bands corresponding to each of its main components -acrylonitrile, butadiene, and styrene- can be identified. Aromatic C-H stretching vibrations from the styrene component are observed in the range 3200–3000 cm^{-1}, while C-H bending vibrations in the benzene ring can be observed at approximately 700 cm^{-1} and 760 cm^{-1} [31]. The absorption at 1638 cm^{-1} represents the stretching vibration of the C-C double bond from the butadiene units, while the stretching vibration of the aromatic ring from the styrene unit appears at 1495 cm^{-1} [32]. The deformation

of C-H for hydrogen atoms attached to alkenic carbons is observed at 967 cm^{-1} for 1,4-butadiene units and 911 cm^{-1} for 1,2-butadiene units [32]. These peaks confirm the presence and integrity of the ABS structure, and their alignment with equivalent spectra reported in the literature indicates that no significant chemical alteration has occurred to the samples due to processing.

3.2. DSC Results

The DSC analysis results for PLA samples, including heating and cooling cycles, are shown in Figure 4 and summarized in Table 1. Figure 4a and Figure 4b focus on the heating and cooling cycles to highlight the consistent thermal behaviour of both v-PLA and r-PLA, with minimal influence from external factors like cooling rate. In the first heating cycle, there is no significant difference between v-PLA and r-PLA, as can be seen in Figure 4c, with both showing similar thermal patterns. During the second heating cycle, the Tg for v-PLA was 63.34°C, while for r-PLA, it is slightly lower at 61.13°C. This small drop (~2°C) in Tg for the recycled sample suggests some minor effect from the recycling process, but this difference is too small to impact the material's overall mechanical and/or thermal performance significantly.

Table 1. Table of DSC results after the second heating cycle of PLA and ABS samples

Material	Tg - Glass transition (°C)	Tcc - Cold crystallization (°C)	Tm - Melting (°C)
v-PLA	63.34	118.87	153.07
r-PLA	61.13	117.99	149.88
v-ABS	107.63	-	-
r-ABS	103.68	-	-

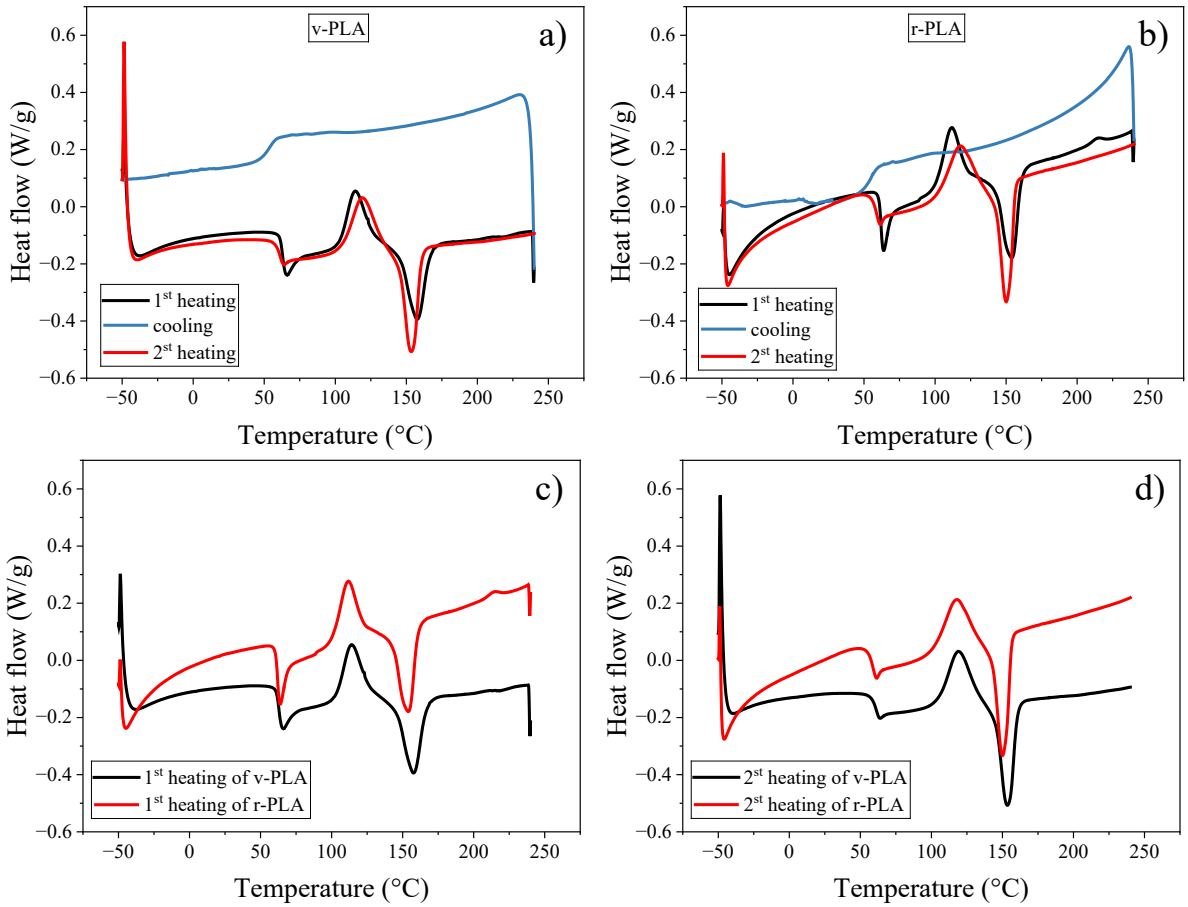

Figure 4. DSC plots showing: the heating and cooling cycles of a) v-PLA, and b) r-PLA, a comparison of c) first and d) second heating cycles

The cold crystallization temperature is also slightly lower for r-PLA, occurring at 117.99°C compared to 118.87°C for v-PLA. This indicates that r-PLA crystallizes just slightly earlier, but the difference (~1°C) is minimal and can be considered insignificant. Additionally, a decrease in melting temperature between the first and second heating cycles is noted for both materials, as shown in Figure 4c and Figure 4d. Therefore, the DSC results suggest that recycling causes only minor changes in the thermal properties of PLA. The recycled PLA maintains a similar thermal stability across both heating cycles, and the observed changes are very small, indicating that the recycling process has little effect on the polymer's stability.

The DSC analysis results for ABS samples, covering both heating and cooling cycles, are presented in Figure 5 and summarized in Table 1. Figure 5a and Figure 5b emphasize the heating and cooling cycles to demonstrate the stable thermal behaviour of both v-ABS and r-ABS, with minimal impact from external factors such as cooling rate. Due to the amorphous structure of ABS polymer, DSC analysis generally provides information only on the glass transition temperature. In amorphous polymers, a lack of a regular crystalline structure means that thermal transitions such as crystallization or melting temperatures cannot be observed [33]. Consequently, in Table 1, only the Tg of ABS filaments can be reported. In the heating cycles, no significant difference is observed between v-ABS and r-ABS, as shown in Figure 5c and Figure 5d, with both displaying a similar thermal profile. In the second heating cycle, the Tg for v-ABS is 107.63°C, while for r-ABS it is slightly lower, at 103.68°C. The slight decrease in the Tg suggests that the recycling process can cause minor changes at the molecular level. This reduction may be due to chain scission, lower molecular weight, or increased free volume within the polymer, which can enhance chain mobility. Additionally, impurities introduced during recycling could act as plasticizers, further lowering Tg. Despite this small change, the thermal properties of r-ABS remain close to those of v-ABS, indicating that recycled ABS retains sufficient thermal stability for similar applications.

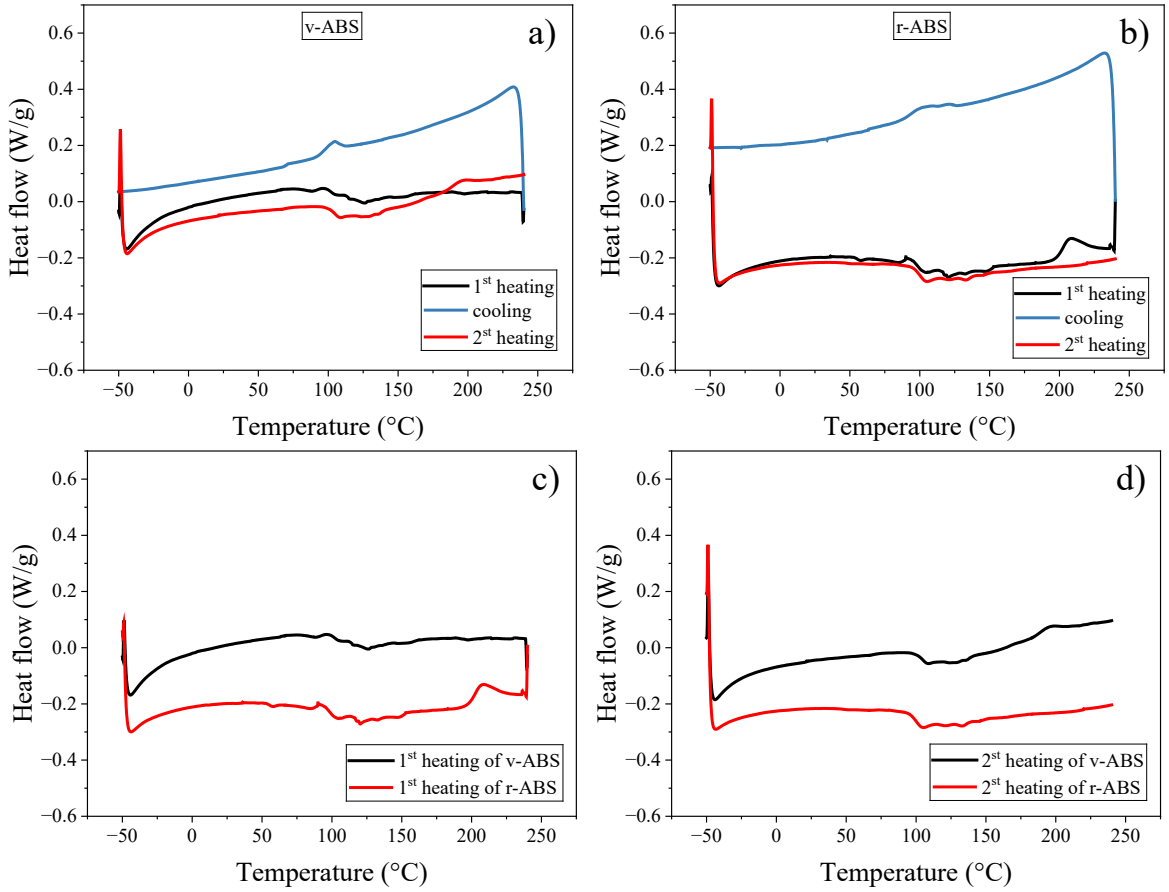

Figure 5. DSC plots showing: the heating and cooling cycles of a) v-ABS, and b) r-ABS, as compared for the c) first and d) second heating cycles

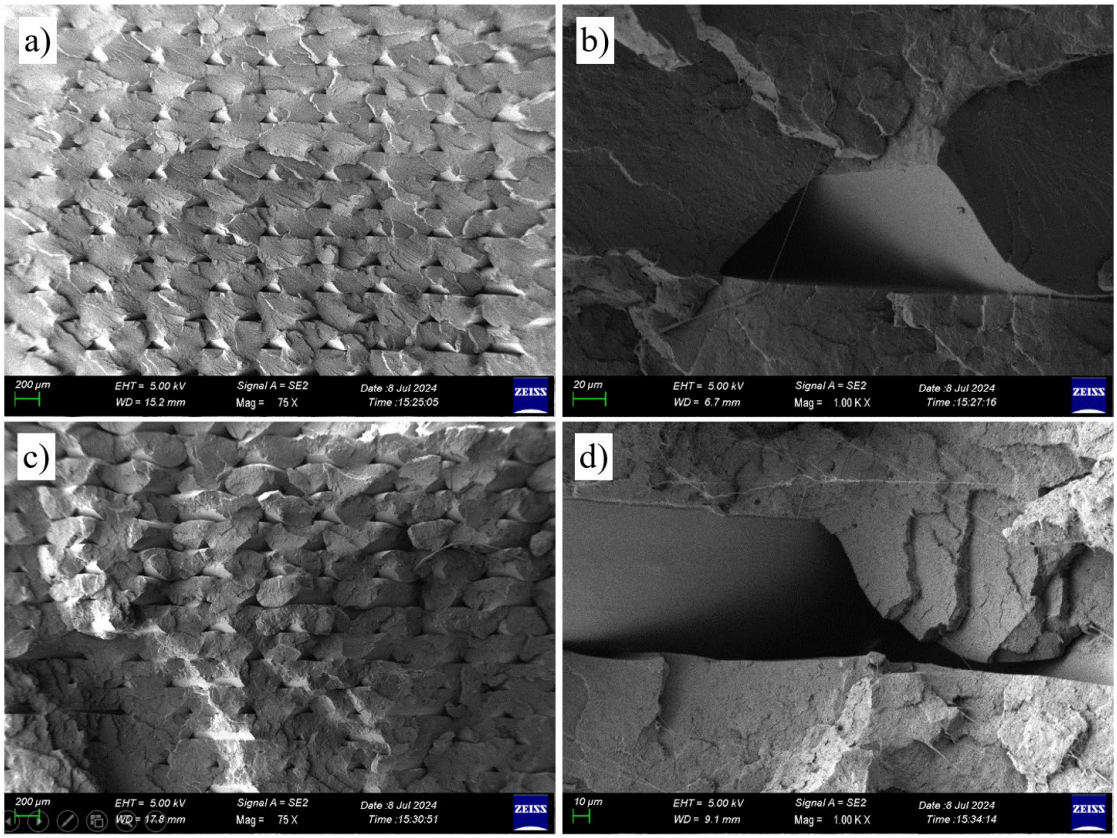

Figure 6. SEM images of the fractured surface of a) v-PLA at 75x, b) v-PLA at 1000x, c) r-PLA at 75x, and d) r-PLA at 1000x

3.3. SEM Results

In Figure 6 and Figure 7, SEM images illustrate the fracture surfaces of PLA and ABS samples, highlighting structural differences between the virgin and recycled materials. Figure 6a illustrates the fracture surface of the v-PLA sample, which shows a uniform appearance with the majority of fibres breaking along the fibre surfaces. In contrast, Figure 6c reveals that the r-PLA sample has a less uniform fracture surface, with more interfacial bond failure than seen in v-PLA. Additionally, the fibres in r-PLA appear to merge and smear each other, both at the interface and across individual fibre surfaces. This behaviour is thought to result from the reduction in Tg observed in the DSC analysis due to the recycling process. The lower Tg causes the recycled material to soften at a lower temperature, which may potentially allow fibres to bond more extensively. When examining Figure 6b and Figure 6d, although there are slight differences in fracture patterns, the fracture surfaces of each of the samples appear quite similar. Thus, the recycling process does not seem to cause any significant changes in the microstructure or fracture surface of the material. At lower magnifications (Figure 7a and Figure 7c), the v-ABS sample displays a smoother, more uniform surface, with fibres and layers distributed consistently across the structure. In contrast, the r-ABS sample shows clear smearing between layers, suggesting that the layers have bonded in a less uniform manner. Instead of fracturing evenly along each fibre, the r-ABS sample tends to break more along interlayer bond regions.

In Figure 7c and Figure 7d, a larger interlocking fibre structure can be observed in the recycled sample, where fibres merge and form a smeared structure. This increased smearing may result from the slight reduction in Tg, which causes the recycled material to soften earlier, potentially allowing the layers to bond more tightly. In Figure 7d, at higher magnifications, this smeared bonding between layers becomes even more apparent in r-ABS than it is in v-ABS.

For both the ABS and PLA samples, the SEM images revealed two main differences between virgin and recycled specimens. These differences include an increase in smearing and a higher rate of interfacial bond failure in the

recycled samples. Previous studies [21,34–36] have shown that an increase in interfacial bond failure generally reduces mechanical properties, as AM tends to produce stronger mechanical performance with fibre surface breakage, while interfacial regions are more likely to act as weak points. Therefore, the increased occurrence of interfacial bond failure in recycled samples is considered a negative outcome. However, the smearing observed between layers in the recycled samples may contribute to improved mechanical properties by creating a more integrated, cohesive structure. Provided that fibre smearing does not lead to dimensional shrinkage subsequent to production, it may enhance interfacial bonding and lead to more favourable mechanical properties.

3.4. Tensile Test Results

The stress-strain graphs obtained from the tensile test results for all samples are presented in Figure 8. These graphs show that there is generally little difference between the virgin and recycled samples, with the curves being quite close to each other and both samples for each material exhibiting similar tensile strengths. Furthermore, as stated in the literature, a comparison of the tensile strengths of PLA and ABS filaments reveals that PLA has the higher tensile strength. In accordance with ASTM standards, the repeated test results for each tensile test, along with their standard deviations, are presented in Table 2 and Table 3 for PLA and ABS, respectively, to allow for a more detailed analysis.

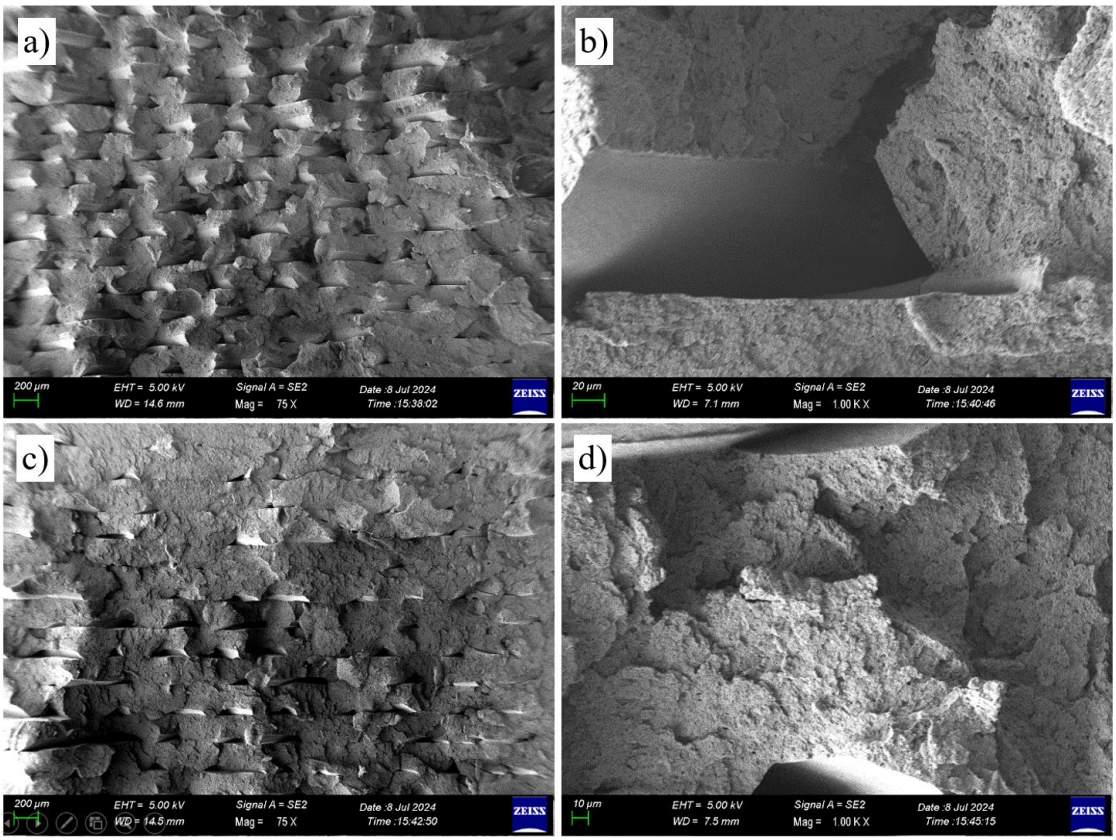

Figure 7. SEM images of the fractured surface of a) v-ABS at 75x, b) v-ABS at 1000x, c) r-ABS at 75x, and d) r-ABS at 1000x

Table 2. Results of tensile tests of samples produced with v-PLA and r-PLA

Material	Maximum stress (MPa)						
	1 st test	2 nd test	3 rd test	4 th test	5 th test	Mean	± S.D.
v-PLA	41.99	44.19	44.74	44.26	43.21	43.68	1.10
r-PLA	44.52	44.22	44.67	44.16	44.32	44.38	0.21

Material	Strain (%)						
	1 st test	2 nd test	3 rd test	4 th test	5 th test	Mean	± S.D.
v-PLA	1.76	1.85	1.88	1.86	1.80	1.83	0.05
r-PLA	2.02	2.08	2.12	2.01	2.11	2.07	0.05

Table 3. Results of tensile tests of samples produced with v-ABS and r-ABS

Material	Maximum stress (MPa)						
	1st test	2 nd test	3 rd test	4 th test	5 th test	Mean	± S.D.
v-ABS	29.40	28.58	30.13	29.56	29.24	29.38	0.56
r-ABS	26.27	23.80	22.34	25.20	23.56	24.23	1.53

Material	Strain (%)						
	1st test	2 nd test	3 rd test	4 th test	5 th test	Mean	± S.D.
v-ABS	1.63	1.56	1.65	1.62	1.59	1.61	0.04
r-ABS	1.51	1.21	1.15	1.44	1.19	1.30	0.16

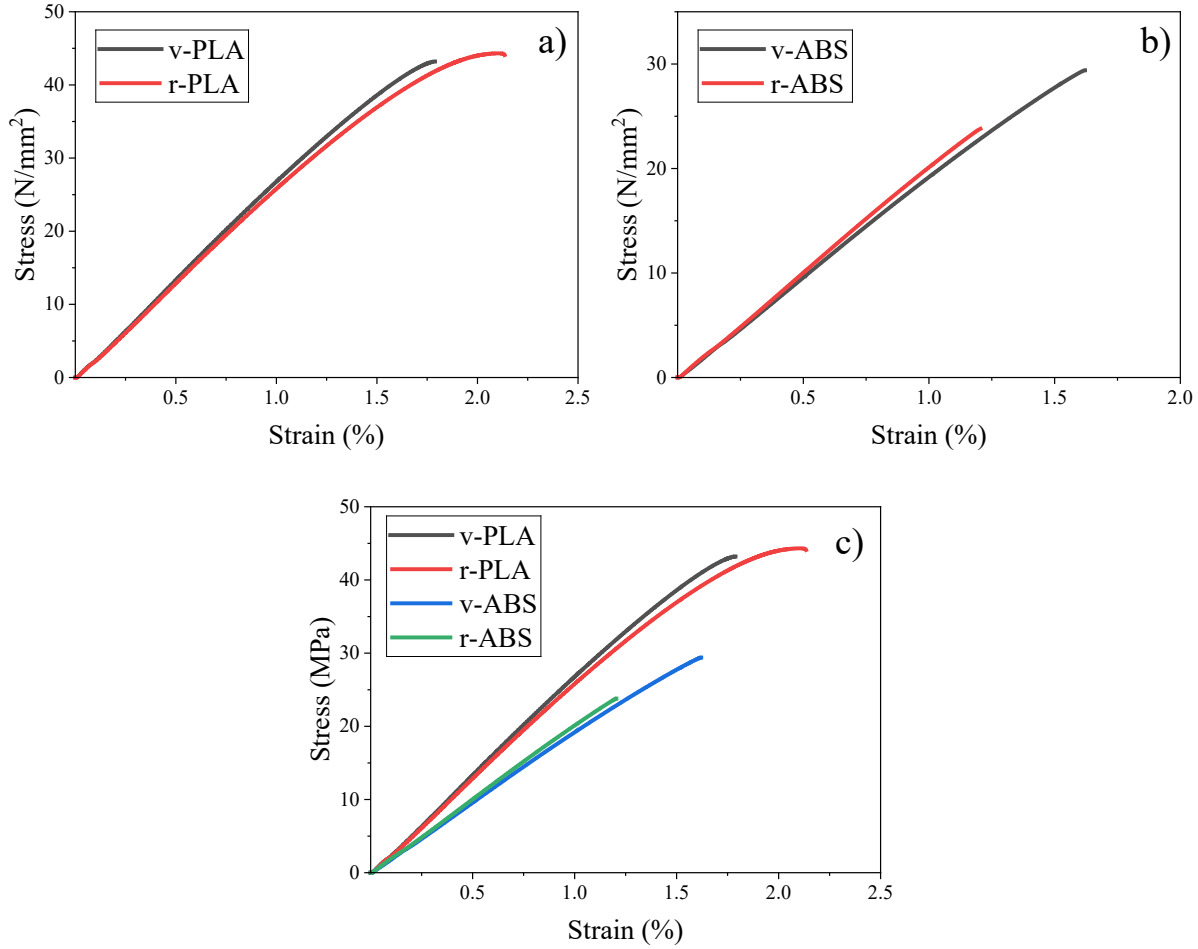

Figure 8. Stress-strain graphs of samples printed with; (a) PLA, (b) ABS, and (c) a comparison of the PLA and ABS samples

Table 2 shows that r-PLA samples had slightly higher tensile strengths. However, this difference is negligible, and cannot be considered significant when standard deviations are taken into account. The highest standard deviation, ±1.10 MPa, was observed for the v-PLA samples, which is sufficient to account for the strength difference between v-PLA and r-PLA. Therefore, it can be concluded that recycling does not have a significant effect on the tensile strength of PLA.

In Table 3, r-ABS samples show a relatively more pronounced decrease in tensile strength compared to PLA. v-ABS samples have a tensile strength of 29.38 MPa, while r-ABS samples exhibit an average tensile strength of 24.23 MPa. This indicates that ABS polymer is more strongly affected by the recycling process than PLA. Additionally, the low standard deviations observed for all samples suggest that the production process for specimens manufactured via AM is stable and consistent across repeated analyses. The low standard deviations in the mechanical tests indicate that

the production process for the specimens is stable and consistent, with the material properties showing a homogeneous structure and the test results being highly reliable. This suggests that the production parameters were themselves very consistent, thus minimizing environmental or measurement errors. Low standard deviation also implies that the material is likely to perform predictably in terms of mechanical properties, such as tensile strength, and is unlikely to exhibit unexpected variations in application. Therefore, the low standard deviations obtained for the current test results support the stability of the production process and the reliability of the mechanical performance of the materials.

3.5. Bending Test Results

Figure 9 presents the force-displacement curves obtained from the bending tests for all samples. Overall, the results indicate minimal differences between virgin and recycled specimens, with similar bending strengths observed across the groups. The curves are closely aligned, demonstrating comparable bending performance between samples. Detailed results for each bending test, following ASTM standards, as well as corresponding standard deviations, are listed in Table 4 and Table 5 for PLA and ABS samples, respectively, providing a comprehensive analysis.

In Table 4, the bending force results show that v-PLA samples exhibit slightly higher bending forces than r-PLA samples. The average bending force for the v-PLA samples is 139.95 N, compared to 129.75 N for r-PLA. However, this difference remains relatively insignificant, particularly when standard deviations are considered. The highest standard deviation of ±13.37 N was recorded for v-PLA samples, which offsets the minor difference between v-PLA and r-PLA. Therefore, it can be inferred that recycling does not significantly impact the bending strength of PLA materials.

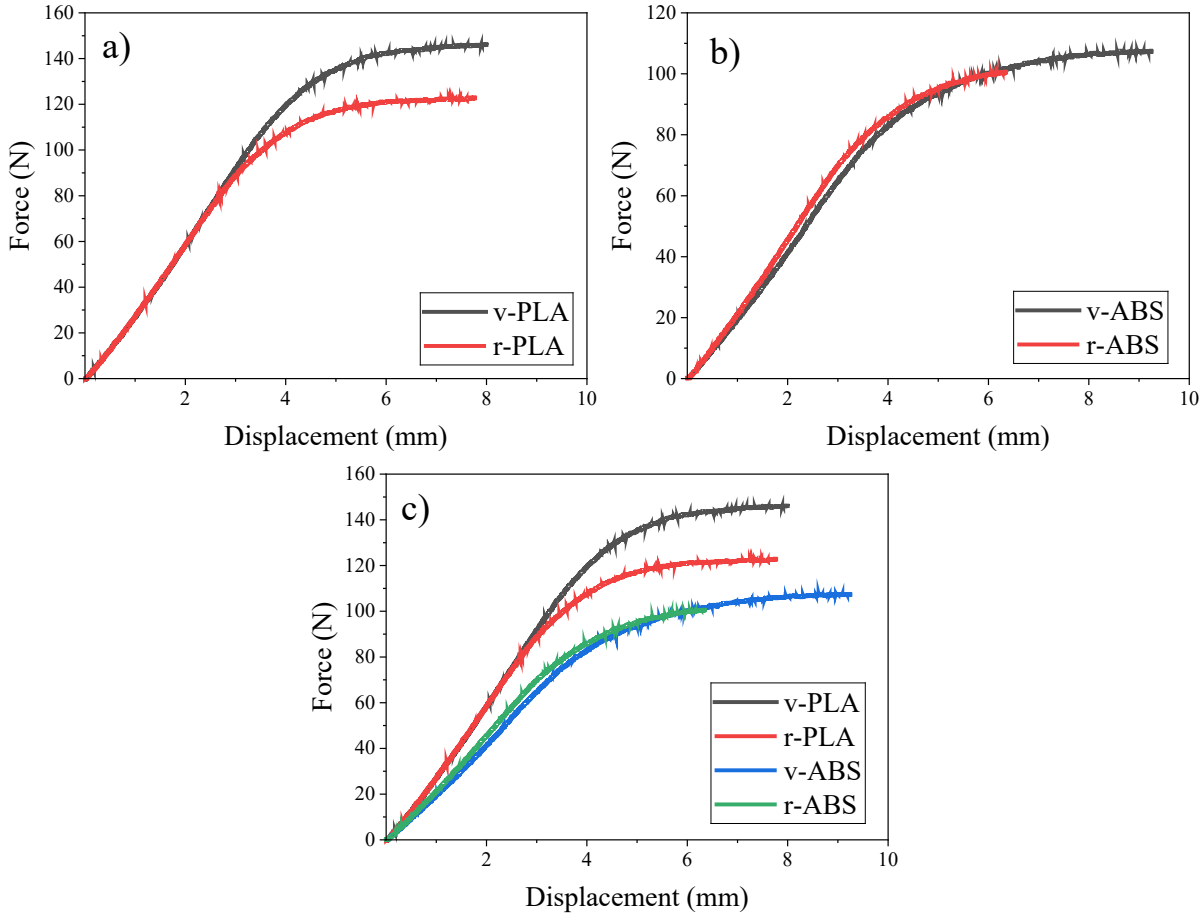

Figure 9. Bending force-displacement graphs of specimens produced with (a) PLA and (b) ABS, and (c) a comparison of PLA and ABS samples

Table 4. Results of bending test of samples produced with v-PLA and r-PLA

Material	Maximum bending force (N)						
	1st test	2 nd test	3 rd test	4 th test	5 th test	Mean	± S.D.
v-PLA	152.92	128.22	123.12	146.25	149.25	139.95	13.37
r-PLA	137.19	133.32	129.70	122.98	125.55	129.75	5.74

Material	Maximum displacement (mm)						
	1st test	2 nd test	3 rd test	4 th test	5 th test	Mean	± S.D.
v-PLA	8.37	8.33	8.32	7.99	8.06	8.21	0.18
r-PLA	8.13	7.33	7.18	7.76	7.91	7.66	0.40

Table 5 Results of bending test of samples produced with v-ABS and r-ABS

Material	Maximum bending force (N)						
	1st test	2 nd test	3 rd test	4 th test	5 th test	Mean	± S.D.
v-ABS	110.10	107.58	106.86	103.81	102.76	106.22	2.96
r-ABS	103.33	98.37	95.18	100.71	104.76	100.47	3.84

Material	Maximum displacement (mm)						
	1st test	2 nd test	3 rd test	4 th test	5 th test	Mean	± S.D.
v-ABS	9.37	9.24	9.62	8.45	8.74	9.08	0.48
r-ABS	6.88	6.32	6.62	6.34	6.57	6.55	0.23

As illustrated in Table 5, recycled ABS samples show a slightly reduced bending force compared to their virgin counterparts. The mean bending force for v-ABS is 106.22 N, whereas for r-ABS, it is 100.47 N, indicating a small reduction due to recycling. This suggests that ABS is relatively less impacted by the recycling process under bending loads compared to tensile loads, as seen in prior sections. The low standard deviations across all tests imply that the AM process was consistent and that the results are reliable. In terms of bending tests, the low standard deviations indicate that the material properties remain homogeneous and that the tests produced highly consistent results.

4. CONCLUSIONS

This study investigated the effects of recycling on the thermal and mechanical properties of PLA and ABS filaments, which are commonly used in AM. The results of mechanical tests, alongside thermal analyses, provided valuable observations regarding the structural stability and performance of virgin and recycled specimens. Thermal analysis showed a slight decrease in the Tg of both recycled PLA and ABS, which may facilitate increased layer bonding but could also influence their mechanical properties under stress. This reduction in Tg was more pronounced in recycled ABS, which aligns with its observed reduction in mechanical performance. The fracture surfaces revealed increased smearing and interfacial bond breaking in recycled samples, especially for ABS, which supports the hypothesis that ABS is more significantly affected by recycling in terms of layer adhesion and structural integrity. Mechanical tests indicated a minimal impact of recycling on the performance of both PLA and ABS samples. The recycled materials demonstrated comparable strengths to their virgin counterparts, indicating that the recycling process did not significantly degrade mechanical performance in either case. In the tensile tests, PLA showed only a 1.6% change, while ABS exhibited a greater decrease of 17.5%, indicating higher degradation susceptibility in the latter. Bending tests showed strength reductions of 7.3% in PLA and 5.4% in ABS, indicating a limited but more pronounced effect on ABS's properties. The similar mechanical strengths of recycled PLA and ABS suggest that recycled materials are suitable for applications where high strength is not critical, offering a cost-effective and sustainable alternative to the use of virgin materials. This closed-loop recycling system not only reduces waste but also minimizes the environmental impact associated with raw material production, enhancing the sustainability of 3D printing.

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