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Characterization of Mechanical and Thermal Properties of 100% Recycled 3D Printed ABS Samples

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ABSTRACT

Additive manufacturing enables rapid and cost-effective production of prototypes and final products, with Fused Deposition Modeling (FDM) being widely used due to its accessibility and low material costs. This study addresses a key research gap by analyzing the mechanical and thermal properties of 100% recycled ABS printed using an open-source FDM 3D printer. Unlike prior research focusing on blended materials or reinforcement techniques, this study evaluates the standalone performance of recycled ABS, offering insights into its viability for sustainable manufacturing. Recycled ABS filament was produced through mechanical recycling and used to fabricate test samples. Microstructural analysis of fractured samples in X, Y, and Z orientations revealed voids and pores in recycled ABS, while standard ABS exhibited air bubbles in specific orientations. Impact testing per ASTM D256 showed that recycled ABS had an impact strength of 154.67 J/m, significantly lower than the 383.31 J/m of standard ABS. Differential Scanning Calorimetry analysis indicated a glass transition temperature (Tg) of 100.14°C for recycled ABS, compared to 104.97°C for standard ABS, demonstrating relative thermal stability. While 100% recycled ABS exhibits reduced mechanical properties and impact strength, its thermal performance remains stable. This study comprehensively evaluates recycled ABS filament for FDM printing, highlighting its potential for sustainable manufacturing by minimizing material waste. The findings contribute valuable data on the feasibility of upcycling polymer waste for functional 3D-printed products, offering insights into the challenges and opportunities of integrating recycled ABS in green additive manufacturing.

Keywords: Fused deposition modeling; mechanical properties; thermal properties; recycle acrylonitrile butadiene styrene

INTRODUCTION

Additive Manufacturing (AM), particularly Fused Deposition Modeling (FDM), has transformed modern manufacturing by enabling low-cost, high-speed prototyping of complex geometries. Its wide adoption in the automotive, aerospace, and biomedical sectors stems from its ability to fabricate functional components with minimal material waste (Zander et al. 2018). For instance, in the automotive industry, FDM is used to create custom tooling, jigs, and prototypes, while in aerospace, it is utilized for manufacturing lightweight components such as air ducts and brackets. In the biomedical field, FDM has enabled the production of patient-specific implants, prosthetics, and anatomical models for pre-surgical planning. However, the increased use of thermoplastics in AM raises environmental concerns, especially regarding plastic waste accumulation, prompting the need for more sustainable 3D printing practices (A. Elsonbaty et al. 2024).

Acrylonitrile Butadiene Styrene (ABS) is among the most commonly used thermoplastics in FDM due to its strength, durability, and heat resistance (Ibrahim et al. 2024). Nonetheless, the reliance on virgin ABS contributes significantly to environmental pollution (Maraveas et al. 2024). Recycling ABS into filament offers a promising solution for reducing this impact and fostering a circular economy in AM. Despite this, fully recycled ABS faces challenges such as material degradation, poor interlayer adhesion, and reduced mechanical properties (Nguyen et al. 2023). Much of the existing research has explored recycled ABS blended with virgin materials or reinforced with additives (Domingo-Espin et al. 2015), with fewer studies focusing on the performance of 100% recycled ABS in open-source FDM systems (Zander et al. 2018). Understanding the mechanical and thermal characteristics of pure recycled ABS is critical to assessing its feasibility as a sustainable 3D printing material (Gomez-Kervin et al. 2018).

This study addresses this research gap by analyzing the mechanical and thermal properties of 100% recycled ABS filament. Using open-source FDM printing, we investigated the material's structural integrity through Scanning Electron Microscopy (SEM) in three build directions (X, Y, Z), assessed impact strength per ASTM D256, and performed Differential Scanning Calorimetry (DSC). The results highlight significant void formation and poor interlayer bonding, adversely affecting mechanical performance. Interestingly, a reduced glass transition temperature led to lower warping, indicating a potential benefit in print stability (Zander et al. 2018). Our findings underscore the implications of porosity and layer adhesion on print quality, offering valuable insight into optimizing recycled ABS for FDM applications. Unlike studies focused on novel composites or partially recycled blends, this research emphasizes the mechanical behavior and thermal performance of fully recycled ABS. The outcomes support sustainable AM by revealing how recycled polymers can be processed effectively without compromising key performance metrics.

Researchers have explored various recycled thermoplastics, including HDPE, PLA, PET, and PP, aiming to develop economical and eco-friendly FDM feedstocks (Prem Ananth & Jayram, 2024). ABS, with its impact resistance and processability, remains a primary focus. Nonetheless, thermal degradation, residual impurities, and inconsistent performance pose challenges (Mikula et al. 2021). While recyclability is a key advantage, these limitations can hinder the broader application of recycled ABS in engineering contexts (Mishra et al. 2023). Several studies have examined material degradation over recycling cycles. Charles et al. (2019) observed variations in tensile strength and thermal transitions with each recycle cycle, while Gomez-Kervin et al. (2018) demonstrated acceptable tensile strength and print quality for 100% recycled ABS filaments. Other researchers, such as Atakok et al. (2022), compared virgin and recycled filaments, emphasizing recycling's potential to reduce waste. V. Kumar et al. (2020) showed that twin-screw extrusion (TSE) improved the toughness of recycled ABS compared to non-TSE-processed counterparts. In this study, the following parameters were chosen for FDM printing: Raster angle of 45°, Printing speed of 60 mm/s, Layer thickness of 0.20 mm, Printing temperature of 230°C, and Bed temperature of 105°C (Nguyen et al. 2023).

Maidin et al. (2022) demonstrated enhancements in mechanical properties when applying ultrasonic vibration during 3D printing with recycled ABS. Cress et al. (2021) reported significant porosity and minor molecular degradation over multiple recycling rounds, emphasizing the need for improved processing methods. Marciniak et al. (2019) and Czyżewski et al. (2018) validated the feasibility of recycling ABS from electronic waste and failed 3D printer parts into functional FDM filaments. Pinho et al. (2020) found that while PLA loses strength upon recycling, ABS maintains its mechanical performance, although microstructural and thermal differences remain. This study contributes to the limited but growing body of knowledge on fully recycled ABS for FDM printing. It provides quantitative data on the degradation and performance of recycled ABS, identifies factors limiting its use, and outlines benefits like reduced warping. These insights are critical for developing greener 3D printing solutions and advancing the sustainable use of recycled polymers in additive manufacturing.

METHODOLOGY

This paper investigates the microstructure, impact strength, and thermal properties of 100% recycled ABS in open-source FDM 3D printing. Accordingly, test samples were designed to meet the standards of ASTM and were analyzed for impact strength and microstructure. FDM parameters were optimized based on a literature review. High-resolution images of the microstructure after tensile testing were provided by SEM analysis. Impact testing measured toughness by energy absorption. DSC analyzed the thermal behavior of both standard and recycled ABS. A comparative analysis was conducted to evaluate the performance of recycled ABS.

TEST SPECIMEN

Standard ASTM D638 Type 1 tensile test samples are used to conduct SEM analysis, focusing on the microstructure of the fractured cross-sectional area. This approach enabled a detailed examination of the internal structure and material properties of the recycled ABS after tensile testing. For impact testing, the samples were designed and printed according to the Izod impact test method by ASTM D256 (ASTM, 2023), which measures toughness due to the input of energy while impacting suddenly. These standardized methods assured consistent and reliable evaluation of both standard and recycled ABS materials for mechanical property testing according to ASTM 2019.

TEST SAMPLES FOR MICROSTRUCTURE ANALYSIS

The fractured areas of the different recycled ABS samples were analyzed using “dog bone” tensile test specimens fabricated according to ASTM D-638 Type 1 specifications (ASTM, 2022). These samples were subjected to tensile testing at a loading speed of 5 mm/min using a 20 kN load cell. The microstructural characteristics of the fractured cross-sections were examined to characterize the 100% recycled ABS material. Additionally, the tensile test samples were analyzed in X, Y, and Z build orientations. Figure 1 presents (a) the tensile test samples, (b) the fractured cross-sectional areas after tensile testing, and (c) the schematic illustration of X, Y, and Z build orientations adapted from Knoop & Schoeppner (2015).

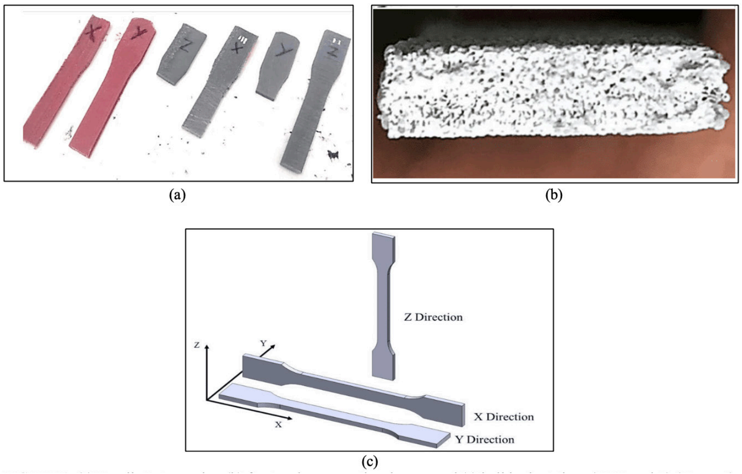


FIGURE 1. (a) Tensile test samples, (b) fractured cross-sectional areas, and (c) build orientations (X, Y, and Z) (Knoop & Schoeppner, 2015) for standard and 100% recycled ABS

TEST SAMPLES FOR IMPACT TEST

The impact test samples were designed using CATIA V5 according to the American Society for Testing and Materials (ASTM) standards, specifically ASTM D-256, commonly used for the impact testing of plastic materials. This standard was chosen because it is suitable for determining the Izod pendulum impact resistance of plastics and is a preferred design standard (Sandra Van Natta, n.d.). The dimensions of the test samples are 64 × 12.7 × 6.4 mm, as shown in Figure 2. The thickness of 6.4 mm was selected to prevent crushing and bending during testing. After the design was completed in CATIA, as illustrated in Figure 3(a), it was converted into an STL file. This STL file was then transferred to the FDM machine, which used optimized parameter settings for the printing process. Six test samples were printed for both standard and 100% recycled ABS filament, as shown in Figures 3(b) and 3(c), respectively.

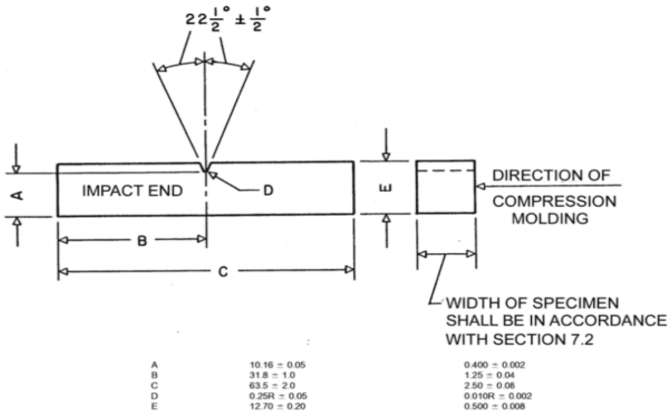
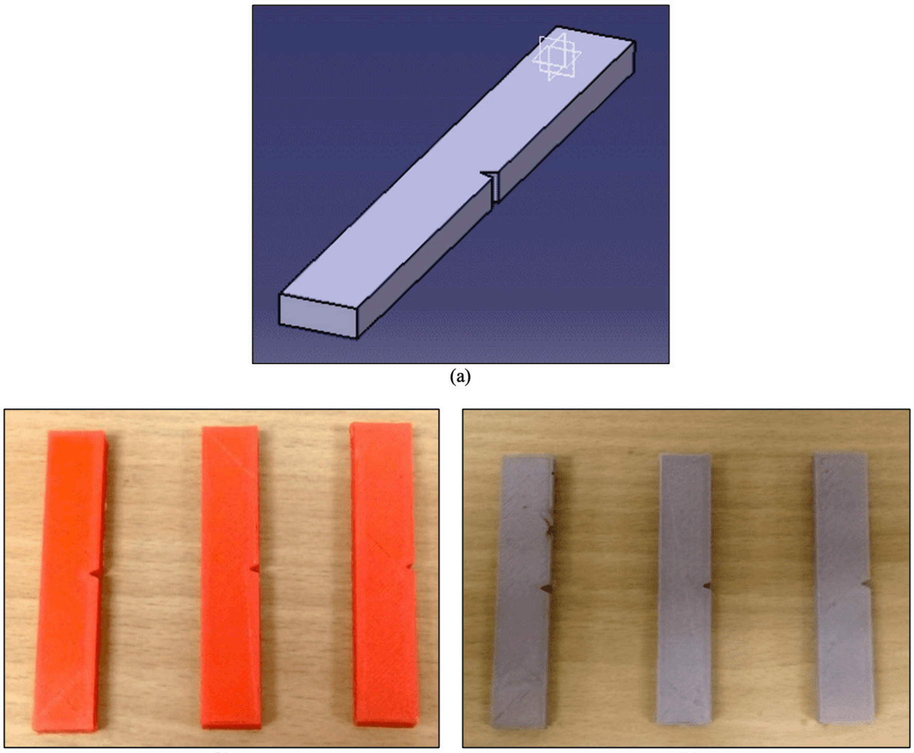


FIGURE 2. Dimension of the test samples in mm (ASTM D-526)



(a) (b) (c)

FIGURE 3. Impact test samples (a) (CAD model), (b) standard ABS, (c) 100% recycled ABS.

EXPERIMENTAL EQUIPMENT

This study begins with designing the test samples using CATIA V5. The designed samples were produced using an Odyssey X2 3D printer, which utilizes FDM technology. The Odyssey X2 used in this study is classified as a consumer-grade FDM printer. To prepare recycled ABS material, waste ABS is first crushed using a polymer crusher to reduce its size. The crushed ABS is then processed into recycled filament using a filament extruder. The study focuses on analyzing the microstructure of the recycled ABS by examining the cross-sectional area of tensile test samples to assess any degradation of the material. A SEM will be employed to observe the detailed microstructure of these samples.

Additionally, an impact tester will be used to evaluate the impact strength of the recycled ABS. At the same time, a DSC test provides insights into the recycled material's thermal properties, such as melting and glass transition temperatures. This detailed approach will enable a thorough understanding of the performance and characteristics of recycled ABS filaments.

RECYCLED ABS FILAMENT PREPARATION

Preparing the 100% recycled ABS filament involves a mechanical recycling process, which begins with crushing the waste ABS into pellet-sized pieces as in Figure 4 (a). These pellets are then subjected to an extrusion process to produce a filament with a precise diameter of 1.75 ± 0.05 mm (refer to Figure 4 (b). The waste ABS used in this process is sourced from failed printed parts collected in the lab.

The collected waste ABS material is crushed into small pellets to facilitate the extrusion process in a filament extruder. Since ABS is lightweight and elastic, the crushing process is repeated multiple times to achieve a small and uniform particle size. Specifically, the waste 3D printed ABS will be subjected to crushing five times to ensure the production of uniformly sized recycled pellets. This uniformity is crucial as it minimizes the time required for the material to melt in the extruder. The average size of recycled ABS pellets from 20 samples is $3.18 \times 3.07 \times 2.25$ mm.

POLYMER EXTRUDER

KE Rheomax OS polymer extruder produces 3D printer filaments from pelletized ABS material. As illustrated in Figure 4 (b), during this process, pelletized ABS is fed into a hopper and conveyed through a temperature-controlled heated zone using a drive screw. At the elevated temperature, the material softens and melts at a specific temperature and is then extruded through a nozzle of a defined diameter. The final filament diameter is controlled by the heat zone temperature, drive screw speed, size of the granules in the hopper, and nozzle diameter.

The extrusion temperature for ABS is set at 230°C to ensure a smooth surface and a round cross-sectional area of the filament, as shown in Figure 4 (c), which aligns with the characteristics of standard filaments.

The acceptable filament diameter is 1.75 ± 0.05 mm, and the conveyor speed significantly impacts this diameter. Table 1 presents filament diameter measurements of conveyor speed, with a speed of 1.0 providing the closest match to the desired diameter. The filament diameter is measured using a Digital Vernier Caliper, as illustrated in Figure 4 (d).

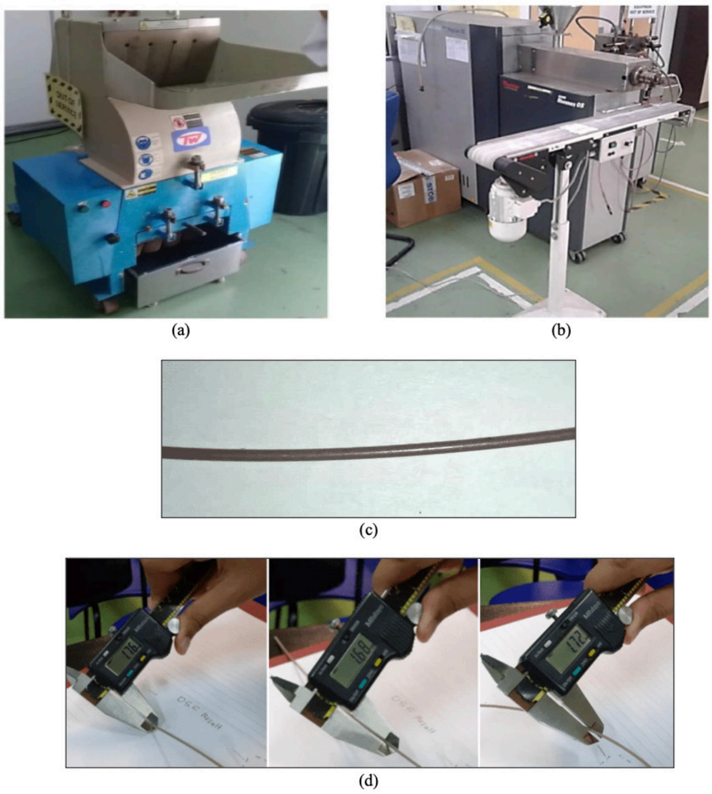


FIGURE 4. (a) Polymer crusher machine, (b) Polymer extruder HAAKE Rheomax OS with conveyor, (c) Smooth, round-shaped cross-sectional area of filament at a temperature of 230°C, (d) Filament diameter at a conveyor speed of 1.0.

TABLE 1. Speed of conveyor vs diameter of filament formed

Speed of conveyor	Diameter of recycled filament (mm)
0.0	2.32-2.50
0.5	1.86-2.02
1.0	1.62-1.80
1.5	1.30-1.58
2.0	0.98-1.36

FDM 3D PRINTING

This research utilizes the Odyssey X2 FDM printer for producing test samples, as detailed in Table 2. The printer settings have been optimized to work with recycled ABS material for the final test samples, as outlined in Table 3.

TABLE 2. Technical Specification of Odyssey X2 machine (*Odyssey X2 Series*, n.d.)

Specification	Dimension
Machine Dimensions (without filament spool attachment)	480 × 405 × 450mm (W×D×H)
Machine weight	12kg
Build Material	PLA, ABS, Flex (Tested and Supported)
Build volume	210mm(X) × 210mm(Y) × 240mm(Z) /10.5L
Machine resolution/ positional accuracy	X & Y: 0.025mm/25microns, Z: 0.005mm/5 microns
Printing accuracy (minimum recommend)	Wall thickness: 0.48mm/480 microns Layer thickness: 0.1mm/ 100 microns

TABLE 3. Parameters used in 3D Printer

Parameters	Recycled ABS material
Raster angle	45°
Printing speed (mm/s)	60
Layer thickness (mm)	0.20
Printing temperature (℃)	230
Bed temperature (°C)	105

For standard filament materials, the printer operates at a nozzle temperature of 230°C and a bed temperature of 105°C. However, adhesion issues can occur when using recycled ABS filament, although the bed temperature remains constant. Other printing parameters are adjusted to achieve the best results and address these issues. Additionally, acetone is used to prevent warping of the samples during the cooling phase, ensuring the samples' integrity and quality are maintained.

MICROSTRUCTURE ANALYSIS

This research employs an SEM to analyze and characterize the microstructure of standard and 100% recycled ABS materials. The analysis will focus on failure structures observed from tensile test samples, with observations conducted from three different orientations of the printed samples: X, Y, and Z.

SEM MACHINE

The SEM is selected for its high-resolution imaging capabilities, essential for analyzing microstructures across various materials, including non-conductive, wet, or volatile samples (Girão et al. 2017). It allows for detailed examination of grain size, porosity, cracks, and failure mechanisms, offering valuable insights into material characteristics and structural integrity.

IZOD IMPACT TEST

The Izod impact test method was used to evaluate the impact strength of standard and 100% recycled ABS materials. This test was conducted using ASTM D-256 standards to accurately assess the impact resistance of the samples (Patterson et al. 2021). The impact tester features a pendulum weight of approximately 144 grams, which is used to apply a controlled impact force to the test samples.

DIFFERENTIAL SCANNING CALORIMETER (DSC) MACHINE

The DSC analyzes 100% recycled ABS thermoplastic thermal. This instrument measures the heat flow associated with various thermal transitions, including the glass transition, melting point, and crystallization temperature (Blanco & Siracusa, 2021). In this research, the DSC will determine the heat flow of recycled ABS to investigate its thermal properties within the FDM system. Standard ABS will also be analyzed to provide a comparative baseline for assessing the thermal behavior of the recycled material.

RESULTS AND DISCUSSION

This section details the results from the microstructure and thermal analysis of 100% recycled ABS. Test samples were designed for impact testing following ASTM D-256 standards, and microstructure analysis was conducted on fractured dog bone-shaped samples using SEM. Impact resistance was measured using the Izod method, and thermal properties, including Tg and Tm, were assessed using small square samples. These results will be compared with standard ABS to evaluate the mechanical and thermal properties of the recycled ABS in FDM systems.

MICROSTRUCTURE ANALYSIS OF ABS SAMPLES

A scanning electron microscope (SEM) was used to examine the microstructure of 100% recycled and standard 3D-printed ABS samples. The analysis was performed at an acceleration voltage of 15 keV. Prior to imaging, the fractured surfaces were sputter-coated with a thin layer of gold and platinum to enhance image quality.

The SEM analysis across different print orientations (X, Y, and Z) revealed distinct differences between the recycled and standard ABS samples.

For the X orientation, the SEM images in Figures 5(a) and 5(b) show distinct differences between the 100% recycled and standard ABS samples. The 100% recycled ABS, shown in Figure 5(a), exhibits tiny pores and voids within the fractured areas, indicating reduced bonding quality between adjacent fused filaments, likely due to material degradation during recycling. In contrast, the standard ABS sample, shown in Figure 5(b), displays numerous irregularly shaped bubbles on the fracture surface but lacks significant voids, reflecting better filament bonding and greater material uniformity.

For the Y orientation, the SEM image in Figure 5(c) reveals the presence of voids at the interfacial bonding between adjacent raster's in the 100% recycled ABS samples, along with tiny pores on the filament surfaces. In contrast, Figure 5(d) shows that the standard ABS samples exhibit no pores on the filament surfaces, and the air voids between bonded filaments are smaller compared to the recycled ABS. Additionally, no bubbles were observed on the fractured surface of the standard ABS in the Y orientation, unlike in the X and Z orientations.

For the Z orientation, Figures 5(e) and (f) reveal a high density of air bubbles in both recycled and standard ABS samples. However, the 100% recycled ABS samples exhibit more voids and tiny pores within the failure region, indicating poorer filament bonding and greater defect formation. Additionally, more air bubble defects were observed in the Z orientation compared to the X and Y orientations, especially for the recycled ABS. In contrast, standard ABS samples demonstrate fewer voids and smaller bubbles, reflecting better overall material quality and more consistent bonding.

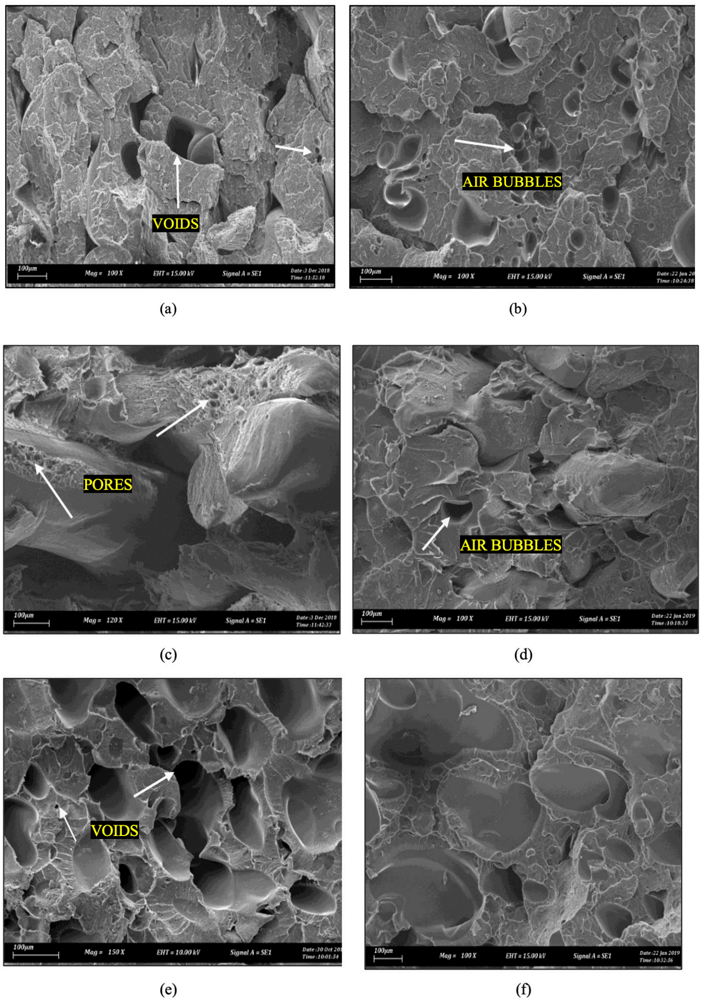


FIGURE 5. Micrographs of fractured surfaces for standard and 100% recycled ABS samples: (a) 100% recycled ABS (X orientation), (b) standard ABS (X orientation), (c) 100% recycled ABS (Y orientation), (d) standard ABS (Y orientation), (e) 100% recycled ABS (Z orientation), (f) standard ABS (Z orientation).

COMPARISON OF THE MICROGRAPH OF STANDARD ABS AND 100% RECYCLED ABS SAMPLES

Table 4 demonstrates voids in the fractured area of 100% recycled ABS samples in the Z orientation, indicating weaker layer adhesion. As shown in Figure 6, found that the Z orientation has the lowest tensile strength due to printing vibrations, with recycled ABS showing a 52% decrease in strength compared to standard ABS (Maidin et al. 2022). This reduction is linked to weaker adhesion bonds in the recycled ABS, leading to lower strength and compromised mechanical properties.

Additionally, both standard and recycled ABS samples contain air bubbles, likely due to moisture absorption, as ABS is highly sensitive to humidity. Conversely, the tiny pores in the recycled ABS are attributed to degradation during reprocessing, resulting in lower strength and weaker mechanical properties than standard ABS. Figure 7 further shows that fractures in the Z orientation occur at the interface between stacked filament layers, while in the X and Y orientations, fractures require breaking through multiple extruded plastic fibers. Consequently, samples in the Z orientation exhibit lower strength than those in the X and Y orientations.

TABLE 4. Comparison between the 100% recycled ABS with standard ABS in different build orientations.

Comparison of standard and 100% recycled ABS samples	Voids between the bonding of fused filament	Air bubbles formed	Small pores formed in the filament
X orientation	Present on recycled ABS	Present on standard ABS	Formed on recycled ABS
Y orientation	Present on recycled ABS	No air bubbles	Formed on recycled ABS
Z orientation	Present on recycled ABS	Present in standard ABS with 100% recycled ABS	Formed on recycled ABS

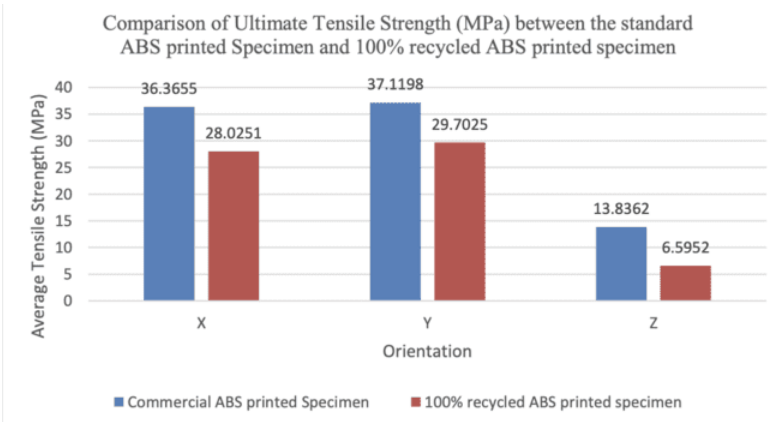


FIGURE 6. Histogram of comparison of ultimate tensile strength between standard ABS with 100% recycled ABS (Maidin et al. 2022)

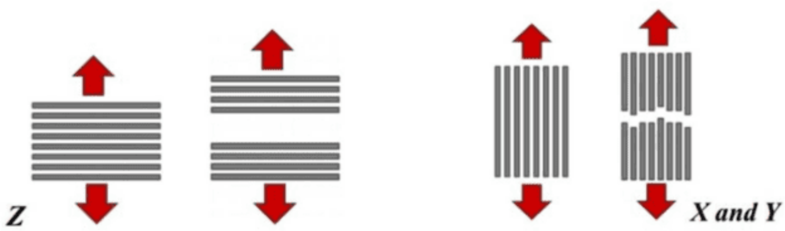


FIGURE 7. Break behavior of different build orientations
(Alejandro Benítez De la Riva & Jackson O'Connell, 2024)

IMPACT TEST AND IMPACT STRENGTH SPECIMENS

The impact test was conducted at room temperature following ASTM D256 standards, using six test samples: three fabricated from standard ABS filament and three from 100% recycled ABS filament. Each sample was individually tested, and the average result was calculated for improved accuracy. As illustrated in Figure 8(a), the samples fractured upon impact from the pendulum, which struck the notched area and absorbed energy, particularly where defects were present.

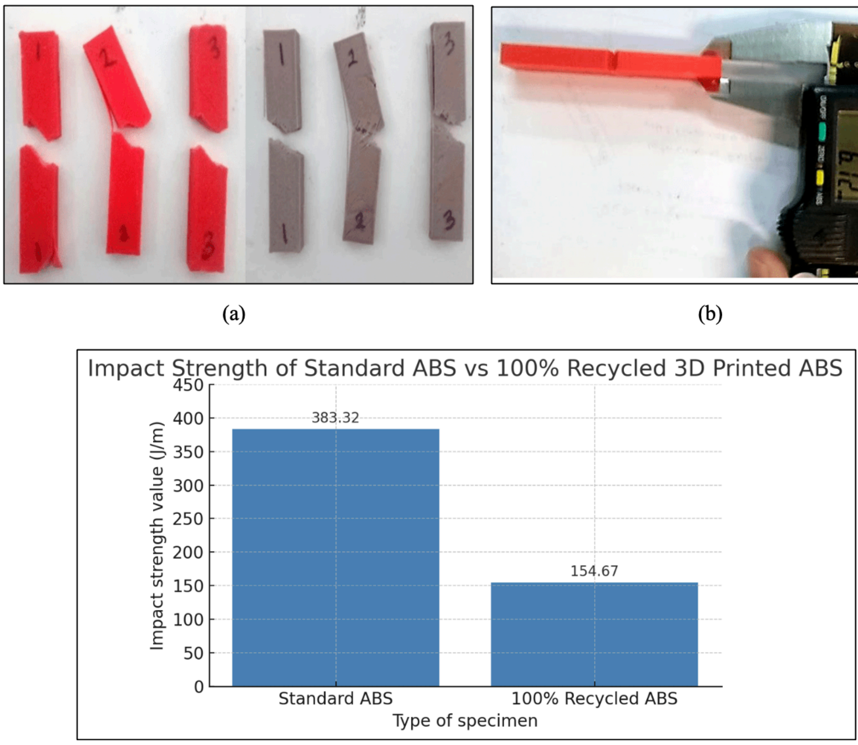
The energy absorbed by each sample during the impact test, detailed in Table 5, was determined by comparing the initial pendulum reading (taken without a specimen) to the reading after striking the sample. Sample thickness, measured using a Vernier caliper as shown in Figure 8(b), varied slightly due to bed adherence and printer settings. The impact strength was calculated by dividing the absorbed energy by the measured thickness, with results presented in Table 6.

The average impact strength recorded for standard ABS samples was 383.31 J/m, whereas for 100% recycled ABS samples it was significantly lower at 154.67 J/m, as illustrated in 8(c).

The impact test results show that standard ABS samples exhibit higher impact strength and toughness than 100% recycled ABS, with a 59.65% greater impact strength for standard ABS. This difference is due to the lower stress concentration in standard ABS filaments during printing, leading to better layer bonding and reduced internal defects.

The highest toughness is achieved in the zero-degree (Y) orientation, where consistent layer alignment without alternating orientations enhances impact resistance. ANOVA testing also confirms that raster gaps and scaffolding angles significantly affect impact strength, with specific orientations providing better structural support and energy absorption.

The decreased impact strength of 100% recycled ABS samples is linked to the quality of the printed parts, including increased stress concentrations. Degradation during the recycling process reduces the toughness of the extruded material. This degradation affects the adhesion between filament layers, leading to higher stress concentrations, voids, and porosities and altered thermal properties, such as changes in the glass transition temperature. Repeated reprocessing of filaments significantly reduces material strength, maximum strain, and toughness. Nevertheless, incorporating virgin pellets into the recycled material can enhance its performance.



(a) (b) (c)

FIGURE 8. (a) Test samples after running the impact test for standard ABS (left) and 100% recycled ABS (right), (b) Measurement of sample thickness and (c) Bar chart of impact strength of standard ABS versus 100% recycled ABS samples at room temperature.

TABLE 5. Result of Izod impact value of standard ABS and 100% recycled ABS specimen.

No	Type of Specimen	Initial reading (Without specimen), K1 (J)				Final reading (With specimen), K2	Amount of energy absorbed, K=K2-K1 (J)
		1	2	3	Mean		
1	Standard ABS	5.50	5.25	5.25	5.33	7.70	2.17
2	Standard ABS	5.25	5.00	5.50	5.25	7.50	2.25
3	Standard ABS	5.50	5.50	5.00	5.33	8.25	2.92
4	100% recycled ABS	5.00	5.00	5.00	5.00	6.00	1.00
5	100% recycled ABS	5.25	5.00	5.00	5.08	6.00	0.92
6	100% recycled ABS	5.00	5.25	5.25	5.17	5.75	0.58

TABLE 6. Result of Izod impact strength of standard ABS and 100% recycled ABS specimen

No	Type of Specimen	Thickness, t(m)	Amount of energy absorbed, K(J)	Izod impact strength, K/t (J/m)	Average Izod impact strength, (J/m)
1	Standard ABS	0.00615	2.17	352.85	
2	Standard ABS	0.00614	2.25	366.45	383.31
3	Standard ABS	0.00620	2.67	430.65	
4	100% recycled ABS	0.00618	1.00	161.81	
5	100% recycled ABS	0.00482	0.92	190.87	154.67
6	100% recycled ABS	0.00521	0.58	111.32	

DSC ANALYSIS

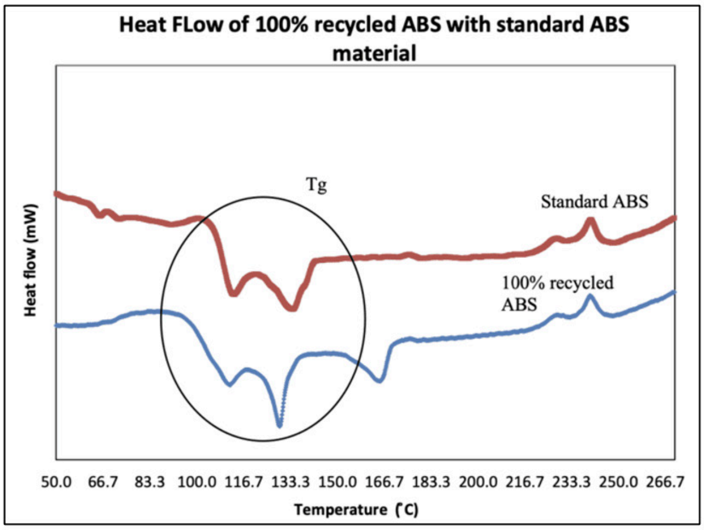
DSC analysis considers the thermal behavior of 100% recycled ABS material within the FDM system. The glass transition temperature (Tg) of the 100% recycled 3D printed ABS is crucial for optimizing the print platform temperature, or bed temperature, to enhance print quality.

Table 7 presents the Tg values for the 100% recycled ABS and standard ABS samples, determined using the DSC method, and shows that the glass transition temperature (Tg) of the 3D printed material decreases following mechanical recycling. Specifically, the average Tg of standard ABS samples is 104.97°C, while the average Tg of 100% recycled ABS samples is 100.14°C. This represents a 4.6% reduction in Tg for the recycled ABS, reflecting slight degradation in material properties, such as the formation of pores observed in SEM images. Despite this decrease, the Tg of 100% recycled ABS remains within a range that does not significantly impact the optimal bed temperature settings for 3D printing. However, the reduced Tg results in lower bonding strength between filament layers, affecting the material's toughness and increasing its tendency to shrink upon solidification. Consequently, the lower Tg contributes to decreased toughness in 100% recycled ABS, as evidenced by the impact strength analysis.

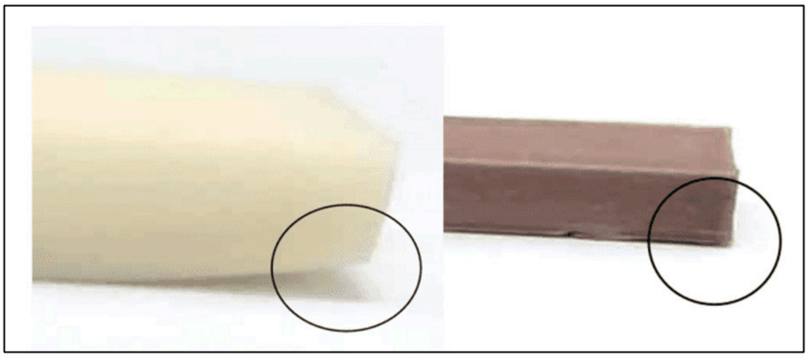
TABLE 7. Result of Tg samples

Type of specimen	Mass of sample (mg)	Glass transition temperature, Tg (C̊)	Average Tg (C̊)
Standard ABS	5.38	104.74	104.97
Standard ABS	6.20	105.19	
100% recycled ABS	5.48	98.51	100.14
100% recycled ABS	5.57	101.77	

Figure 9(a) shows an endothermic peak between 150-170°C in the 100% recycled ABS specimen, likely due to impurities introduced during the filament extrusion. Despite this, no warping was observed in the 100% recycled ABS samples during printing, unlike the standard ABS samples, as illustrated in Figure 9(b). This suggests that the lower glass transition temperature (Tg) of the recycled ABS helps reduce warping during the printing process. A lower Tg correlates with a reduced coefficient of thermal expansion (CTE), causing the material to soften more quickly when heated and to cool and stiffen sooner. Consequently, maintaining a bed temperature above Tg and significantly higher than room temperature is recommended to minimize warping and thermal stress during printing.



(a)



(b)

FIGURE 9. (a) Graph of DSC analysis, (b) Warping defect on standard ABS sample (left) and no warping on recycled ABS sample (right)

CONCLUSION

The results of this study offer valuable insights for advancing sustainable additive manufacturing using 100% recycled ABS. While the mechanical performance of recycled ABS particularly its tensile and impact strength was found to be significantly reduced compared to standard ABS, several pathways exist to optimize this material for practical use in FDM 3D printing.

One key observation from the microstructural analysis was the formation of voids, pores, and air bubbles, which directly contributed to mechanical degradation. This indicates that the extrusion process of recycled ABS filament plays a crucial role in determining final part quality. Therefore, improving extrusion conditions, such as controlling temperature, increasing filtration to remove residual contaminants, and optimizing cooling rates, can help reduce internal defects and improve interlayer adhesion. Additionally, drying the recycled granules thoroughly before extrusion can minimize moisture absorption, which otherwise contributes to bubble formation and polymer chain scission. The use of multi-pass extrusion with homogenization zones may also enhance filament consistency and reduce porosity.

Another promising approach is process parameter optimization during 3D printing. Adjustments to print speed, nozzle temperature, layer height, and cooling fan settings can be fine-tuned to enhance bonding between layers and reduce the effects of microstructural weaknesses. For example, printing at slightly higher nozzle temperatures than standard ABS can improve interlayer fusion for recycled filament. The study's finding that recycled ABS has a lower glass transition temperature (Tg) can also be leveraged positively. Lower Tg contributes to reduced warping, a common defect in ABS prints, thereby increasing the reliability of printing complex geometries with recycled material. This property could be particularly advantageous for applications that prioritize dimensional stability over high-impact resistance. Finally, hybrid recycling strategies, such as blending recycled ABS with a small percentage of virgin ABS or incorporating eco-friendly reinforcing agents (e.g., natural fibers, nanoparticles), may help recover mechanical strength while maintaining a high degree of sustainability.

In conclusion, although 100% recycled ABS exhibits reduced toughness and strength due to processing-related microstructural defects, its lower thermal warping behavior and potential for improvement through filament and print parameter optimization make it a viable candidate for sustainable, cost-effective FDM printing applications. This research supports ongoing efforts to close the loop in plastic waste management and opens up new avenues for designing high-performance recycled materials in additive manufacturing.

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DECLARATION OF COMPETING INTEREST

None.

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