Evaluation of the mechanical behavior of ABS/HIPS blends from WEEE by single screw extrusion

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Abstract: Waste electrical and electronic equipment (WEEE) has seen its useful life significantly shortened due to rapid technological development and innovation, growing commercial demand for updated equipment, and increasingly broad applications. To avoid the accumulation of waste in waste facilities, new recycling methods for this material have been studied. In this regard, this study aimed to optimize the composition and processing method of thermoplastic blends (ABS/HIPS) using polymers from the mechanical recycling of WEEE. This blend was then used to produce filaments for 3D printers. It also aimed to evaluate the effect of six recycling cycles on the mechanical properties of these blends, always comparing them to commercial, virgin ABS. To this end, the materials, primarily derived from discarded air conditioning housings, were processed in a single-screw extruder, where the blends underwent six successive processing cycles. The test specimens were obtained through the injection molding process, sectioned at the end of each extrusion cycle, thus separating them into samples ranging from zero to five processes, and studied via uniaxial tensile testing and impact strength testing. The results show that regarding mechanical tensile performance, the consecutive reprocessing may have slightly influenced the blend's properties, although they remained acceptable consistency. This was also true for impact strength values, although they appear to have less influence on this property, i.e., better reprocessing tolerance. Overall, the results are promising and suggest the possibility of recycling the ABS/HIPS blend without significant changes resulting from the degradation process; the new application simply requires mechanical stresses within the limits that the recycled blend can meet. Furthermore, the blend did not exhibit inferior properties to the filament used in printing during printing and is considered suitable as a raw material.

Keywords: Single screw. Blends. WEEE. HIPS. ABS.

Abbreviations: WEEE, Waste electrical and electronic equipment. ABS, Acrylonitrile Butadiene Styrene. HIPS, High Impact Polystyrene.

1. Introduction

Rapid technological evolution and the growing demand for electronic devices have intensified the generation of waste electrical and electronic equipment (WEEE), which represents one of the fastest-growing waste streams worldwide. This waste is a complex source of materials, including metals, plastics, glass, and hazardous chemicals, requiring effective management strategies to minimize its environmental impact [1]. The lack of adequate infrastructure for the treatment and recycling of this waste in many countries contributes to landfill accumulation and environmental contamination [2].

In this context, polymer recycling has emerged as a sustainable solution, not only for reducing waste volume but also for recovering valuable materials for reuse. ABS (Acrylonitrile Butadiene Styrene) and HIPS (High Impact Polystyrene) plastics are widely used in electronic products due to their mechanical properties, impact resistance, and ease of processing [3,4,5,6]. However, the short life cycle of many electronic devices leads to premature disposal of these materials, highlighting the need for effective recycling processes [6].

Mechanical recycling is a viable technique for reusing plastics, converting waste into new products through grinding, extrusion, and molding processes. This method is particularly advantageous because it does not require the use of harsh chemicals and can be implemented with low operating costs [5,6]. Studies indicate that the use of recycled ABS and HIPS blends can maintain physical and mechanical properties comparable to those of virgin materials, allowing their use in demanding applications, such as 3D printing [4,7].

Additive manufacturing, or 3D printing, represents a disruptive innovation in industrial production, offering versatility in the rapid and efficient manufacture of complex components [4]. The use of recycled filaments not only aligns 3D printing with sustainable practices but also presents an economic opportunity to reduce costs and dependence on virgin raw materials [7]. The integration of recycled materials into 3D printing can contribute to a more robust circular economy, encouraging the development of technologies that minimize waste and maximize resource efficiency [4].

The results are expected to demonstrate the technical and economic viability of mechanical recycling as a sustainable source of HIPS/ABS blends for additive manufacturing, since the proportion of polymers found in WEEE is predominantly HIPS and ABS, especially in air conditioners [8].

2. Methodology

To produce the blends, both ABS and HIPS were sourced from different types and brands of damaged or obsolete air conditioner housings, donated by the Assets Division (DIPATRI) affiliated with the Department of Material Resources (DRM/PROAD) at the Federal University of Sergipe. After collection, the material was disassembled, separated into polymeric parts, cleaned, and combined in a knife mill.

2.1. Blend Preparation by Extrusion

The blend was initially obtained using an AX Plastics single-screw extruder with a screw diameter of 16 mm and a L/D ratio of 26, located in the Polymer Rheology and Processing Laboratory of the Materials Engineering Department at the Federal University of Rio Grande do Norte. The machine's operating conditions for the various cycles are listed in Table 1.

Tabela 1: Parâmetros da extrusão das blendas HIPS/ABS. Fonte Autoral.

PARÂMETRO		V_0	V_1	V_2	V_3	V_4	V_5
Velocidade de Rotação (rpm)		100	100	100	100	100	100
Temperatura da extrusora (°C)	Zona 1	190	189	190	189	190	188
	Zona 2	210	210	209	210	210	210
	Zona 3	220	219	220	219	220	219
	Zona 4	200	221	221	219	221	220
	Zona 5	220	219	219	222	220	220
Temperatura da Massa (°C)	Zona 4	225	226	226	224	226	225
	Zona 5	221	220	220	223	221	220
Pressão da Massa (bar)	Zona 4	50	54	52	52	53	53

Once the blend was finished, a sample (V_0) was collected, and the remainder was reprocessed five times, with samples collected from each process, as shown in Table 2. It is worth noting that after each extrusion, the material was dried in a SOLAB oven (model SL 102/408) at 90°C for four hours.

Tabela 2: Codificação das amostras. Fonte Autoral.

Ciclo	V_0	V_1	V_2	V_3	V_4	V_5
Quantidade de Processamentos	1	2	3	4	5	6

2.2. Preparation of test specimens

The test specimens were manufactured in accordance with ASTM D-638 type I. The injection molding process was used on an Arbug All Rounder 270S 400-100 injection molding machine at the Rheology and Polymer Processing Laboratory (LabPol) of the Federal University of Rio Grande do Norte. The injection molding processing conditions are shown in Table 3.

Tabela 3: Parâmetros de Injeção. Fonte Autoral.

Parâmetro	Valor
Perfil de Temperatura	190/200/210/220/210° C
Temperatura do Molde	40 °C
Velocidade de Injeção	20 cm^3/s
Pressão de Recalque	100 bar
Tempo de Recalque	4 s
Volume de dosagem	32 cm^3

2.3. Mechanical Tests

2.3.1. Impact Tests

The impact test was conducted in accordance with ISO 180, using an Izod pendulum device. The notches were previously made using a notching machine. The cross-sectional width and thickness measurements of the specimens were obtained using a micrometer and used to obtain impact toughness results. That is, the energy required for complete rupture of the specimens was measured, resulting in a measurement of energy per area (J/mm2).

2.3.2. Tensile Tests

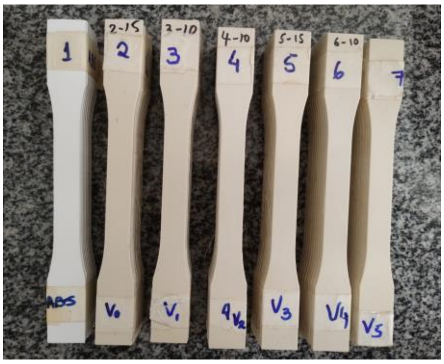
These tests were conducted in accordance with ASTM D256 to analyze the modulus of elasticity and tensile strength at break. The specimens were tested in the mechanical testing laboratory (DCEM) of the Federal University of Sergipe on an INSTRON model 3367 universal mechanical testing machine, operating at a speed of 5 mm/min and a grip distance of 115 mm. The data were processed and graphed for subsequent analysis and comparison.

3. Results and discussion

3.1. Appearance of samples

As Figure 1 shows a photograph of all the test specimens obtained after each extrusion cycle. By observing the images, it is possible to identify a change in visual appearance, especially in color. There is a loss of appearance, from a glossy white (in virgin ABS), to a light beige tone.

Figure 1. Photograph of test specimens produced from pure ABS and reprocessed WEEE casings (V_0 to V_5).



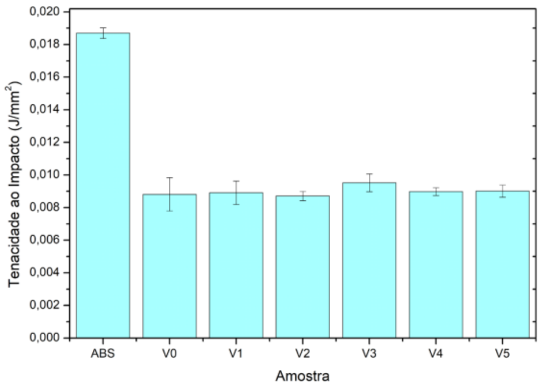
ABS, Acrylonitrile Butadiene Styrene. WEEE, Waste electrical and electronic equipment. V_0, sample with 1 reprocessing. V_1, sample with 2 reprocessing. V_2, sample with 3 reprocessing. V_3, sample with 4 reprocessing. V_4, sample with 5 reprocessing. V_5, sample with 6 reprocessing.

This change is believed to be due to the presence of various contaminants, which cannot be completely separated. These include metallic components and even other polymers in small quantities. Another determining factor in the decline in optical properties is the degradation of the blend, since, after several extrusion cycles, the rupture of some of the constituent polymer chains is inevitable.

3.2. Impact assay

The Graphic 1 shows a comparison of the average impact strength values and their respective standard deviations for virgin ABS and ABS/HIPS blends after successive extrusion cycles. Observing this figure, two findings are clear: A priori, the recycled ABS/HIPS blends presented mechanical performance approximately half that of pure ABS, implying that the blends are mechanically more fragile than the virgin filament material. On the other hand, this property remains consistent throughout the blends reprocessing cycles.

Graphic 1. Average impact toughness (J/mm2), with standard deviation obtained by the Izod impact test, ISO 180 standard.

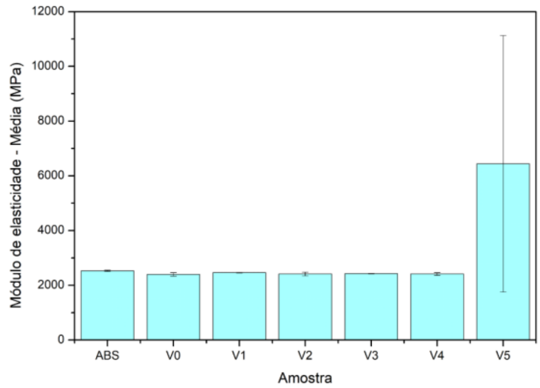


Therefore, this greater fragility of the recycled blends was expected, given that all samples had a useful life, such as air conditioning equipment, before disposal. That is, at the time of product conception, the product initially underwent an injection process, its lifespan was established and was ultimately discarded. Furthermore, after disposal, it underwent at least two more heating cycles. In the case of V0, it underwent another extrusion cycle to prepare the blend and another injection cycle to prepare the test specimens, with the others undergoing a subsequent, progressively increasing stage. Thus, the poor performance compared to virgin ABS can be associated with the degradation of the polybutadiene segments that occurs during the material's reprocessing, since, during the reprocessing of polymers grafted with tough rubbers, degradation occurs preferentially in the rubber phase, with chain scission and cross-linking. This is consistent with recent studies in the literature [9,10]. The constancy of this property after multiple reprocessing supports the ideals of sustainable additive manufacturing, since products generated through 3D printing can be recycled multiple times without significantly reducing the property in question. It's important to note that manufactured products must fit within the range of applications for which the determined impact resistance value is acceptable. It's important to emphasize that when we say, "recycle multiple times," there's still a limit. Six reprocessing were performed in this project, and therefore, this is the known limit. Further claims are not possible until further testing is conducted within this line of research.

3.3. Tensile assay

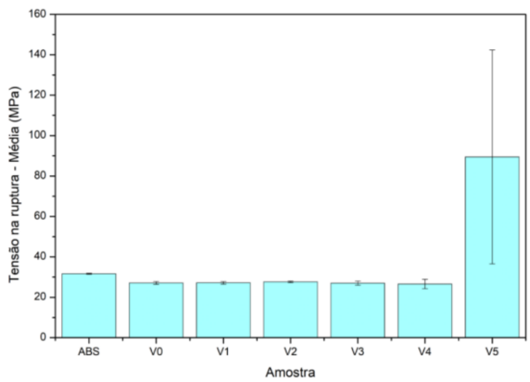
The Graph 2 shows a comparison of the elastic modulus values obtained from the tensile test for virgin ABS and the ABS/HIPS blends after the various reprocessing processes. The reprocessed samples presented similar elastic modulus values, indicating that the various recycling cycles did not significantly alter this property. However, sample V_5 presented a different value with a standard deviation outside the proposed statistical range, thus requiring this test to be repeated for this sample. Regarding the commercial ABS sample, which exhibits a slightly higher average elastic modulus than the reprocessed samples, based on the standard deviation, it is plausible to assume that the stiffness of only sample V_5 is not within the range of that of pure ABS, requiring a repeat test for this sample. Thus, the modulus variation for all samples was small, and therefore, the reprocessed ABS/HIPS blend presents a stiffness similar to that of the filament material.

Graphic 2. A Average modulus of elasticity (MPa), with standard deviation, of virgin ABS and HIPS/ABS blends under successive reprocessing.



The Graphic 3 shows the average tensile stress values at break obtained from the tensile test of virgin commercial ABS samples and recycled ABS/HIPS blends. The commercial ABS sample exhibits a slightly higher average value for this property than the other samples, corroborating the elastic modulus data.

Graphic 3. Mean tensile strength (MPa), with standard deviation, of virgin ABS and HIPS/ABS blends after successive reprocessing.



Furthermore, in order to meet the main objective of this study, which was to primarily evaluate the effect of consecutive reprocessing on the mechanical properties of ABS/HIPS blends from

WEEE, we observed that the mechanical properties of the blends did not vary significantly when the extrusion rate was increased. However, for V5, the experiment needed to be repeated due to the large standard deviation; that is, there were no statistically significant changes in the evaluated properties. This maintenance of properties guarantees the usability of these blends, even after six processing cycles, in the manufacture of 3D printing filaments.

3. Conclusion

Regarding the preparation of ABS/HIPS blends from WEEE, using a single-screw extruder, simulating recycling cycles through successive extrusions, the aim was to demonstrate the feasibility of using these blends in the production of 3D printing filaments. The study concluded that:

After several extrusion cycles, a change in the visual appearance of the test specimens was observed, especially in color, going from a glossy white to a light beige tone.

Regarding impact strength, the recycled ABS/HIPS blends presented an average value, equivalent to approximately half the performance of virgin commercial ABS. On the other hand, a consistency in this property is evident throughout the blends' reprocessing.

The modulus of elasticity values was similar, indicating that the various recycling cycles did not cause significant changes in this property, and this behavior was similar in terms of tensile strength.

Thus, the mechanical properties remained virtually constant throughout the reprocessing cycles. The decline in properties, compared to virgin ABS, was also not significant.

In summary, the results were very promising and the idea of using the HIPS/ABS blend from WEEE in the production of 3D printing filaments proves viable in terms of mechanical requirements. However, it would be beneficial to continue the project, through thermal and rheological characterization of the material, to confirm the quality of the final product.

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