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Conference Article

Evaluating Combination of Solvent-Based Recycling and Mechanical Recycling of ABS Materials for Mitigating Plastic Pollution and Promoting Environmental Consciousness

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Abstract

Plastics continue to transform everyday life with their versatility, lightweight, and durability, although the escalating issue of plastic pollution necessitates urgent action. The surge in single-use plastics and a disposable culture worsens this problem, emphasizing the need to reduce plastic production, establish circular material models, and phase out single-use plastic products.

Addressing the environmental impact of plastics requires the development of technologies enabling more efficient recycling solutions, converting waste plastics into harmless substances. Recycling methods, combining solvent-based recycling and mechanical recycling, are pivotal in this context.

This study specifically focuses on the solvent-based and mechanical recycling of ABS materials. Wiring devices are prepared using a blend of 70% virgin ABS material and 30% recycled ABS (rABS) material, with this loop repeated three times. The aim is to evaluate the quality and acceptability of products derived from the blend of virgin and recycled ABS material after three *times of cycle. Wiring devices, manufactured from mechanically ground broken ABS, undergo rigorous testing in each cycle. The experiments aim to assess the suitability and performance of recycled ABS material for mass production, facilitating an in-depth analysis of the material's life cycle. The mechanical test results demonstrate favorable outcomes for the recycled acrylonitrile butadiene styrene (rABS) materials, indicating comparable performance to the reference ABS virgin grade. While a marginal reduction in impact strength and tensile strength is observed when juxtaposed with the reference ABS virgin grade, the overall mechanical characteristics of rABS, remain consistent through successive recycling loops. These findings underscore the viability and resilience of rABS materials, positioning them as promising candidates for sustainable and environmentally conscious applications within the realm of polymer engineering. Through these efforts, the study contributes to sustainable plastic management practices, aligning with the broader goal of mitigating plastic pollution and promoting a more environmentally conscious approach.*

Keywords: Recycling of Plastics, ABS, Electric Frames, Sustainable Plastic.

1. Introduction

The invention of new plastics in the 19th century marked the beginning of the history of plastic use. Leo Baekeland's creation of Bakelite, the first wholly synthetic material in history, in 1907, was a momentous milestone in the history of polymers. With this development, a vast array of entirely synthetic materials that are now known as contemporary plastics were first created. Since then, plastics have developed into a material that is widely used in contemporary society and offers a wide range of advantageous qualities. This versatile substance, a thermosetting plastic, was extremely strong and heat-resistant, making it appropriate for a number of uses, including electrical insulation [1]. Furthermore, the processing and performance properties of the plastics, like rheological, mechanical, thermal, structural, morphologic, and optical properties were highly enhanced [2].

In both domestic and engineering applications, ABS is one of the widely used and popular polymers. ABS thermoplastics are of special interest since they are used for making outer bodies of almost every household equipment like telephones, televisions, mobile phones, laptops, air conditioners, piping and industrial applications for example; automobile and aircraft interior, medical equipment etc. The extensive use of ABS is due to its low price, high mechanical strength and excellent electrical insulation properties [3,4].

Acrylonitrile-Butadiene-Styrene (ABS) is a terpolymer made by polymerizing styrene and acrylonitrile in the presence of polybutadiene. The proportions can vary from 15 to 35 % acrylonitrile, 5 to 30 % butadiene and 40 to 60 % styrene. It possesses excellent toughness, good dimensional and geometrical stability, easy processing ability, chemical resistance, and cheapness. Typically, ABS is a product of systematic polymerization of monomers, namely, acrylonitrile, butadiene, and styrene as shown in Figure 1. [5].

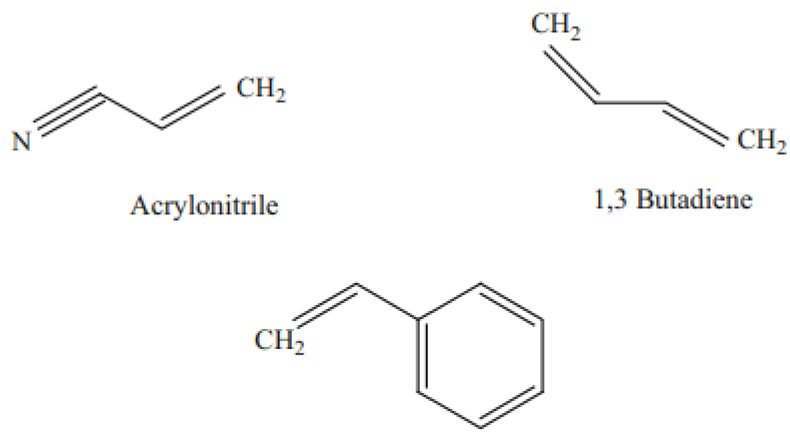

Figure 1: Monomer units of ABS.

Main properties of ABS plastic are density (ϱ) 0,9$g/cm3$ - 1.53 $g/cm3$, glass transformation ~105 °C. ABS is amorphous and therefore has no true melting point, however 230 °C is the standard for printing [6].

All these advantages make plastic usage higher in everyday life. According to OECD 2022 report; the annual production of plastics has doubled, soaring from 234 million tonnes (Mt) in 2000 to 460 Mt in 2019 globally [7]. Despite an anticipated surge in plastics consumption and waste, there is an expected rise in the utilization of recycled plastic in manufacturing new goods. Technological advances and sectoral economic shifts are also projected to result in an estimated 16% decrease by 2060 in the amount of plastic needed to generate USD 1 of economic output [8]. Global plastics use is projected to almost triple between 2019 and 2060 in the Baseline scenario, increasing from 460 million tonnes to 1 231 Mt yearly million tonnes [9]. In 2018, 35,680 million tons of municipal solid garbage were produced worldwide, just from plastic [10]. Plastic waste generated annually per person varies from 221 kg in the United States and 114 kg in European OECD countries to 69 kg, on average, for Japan and Korea. Most plastic pollution comes from inadequate collection and disposal of larger plastic debris known as macroplastics, but leakage of microplastics (synthetic polymers smaller than 5 mm in diameter) from things like industrial plastic pellets, synthetic textiles, road markings and tyre wear are also a serious concern [11].

The swift proliferation of plastic waste is a consequence of global industrial development and population growth, giving rise to both biodegradable and non-biodegradable waste from various human and natural sources. Recognizing the environmental impact, governmental bodies, social communities, and local authorities have implemented diverse measures and legislative frameworks to guide proper plastic waste disposal post-utilization [12].

The principal origin of macroplastic leakage stems from mismanaged plastic waste. In the year 2019 alone, the environment experienced an influx of 22 million metric tons of plastic materials. Macroplastics constitute 88% of this plastic leakage, predominantly attributable to deficiencies in the processes of collection and disposal. Microplastics, characterized by a diameter smaller than 5 mm, constitute the remaining 12% and emanate from diverse sources including tire abrasion, brake wear, and textile washing. The documented presence of these minute particles in freshwater and terrestrial ecosystems, as well as within various food and beverage channels, indicates a significant contribution of microplastics to the exposure of ecosystems and human populations to the consequences associated with leaked plastics [13].

Improper management of post-use plastics can lead to detrimental effects on the environment and human health. Non-biodegradability and inadequate waste disposal practices pose significant risks, including environmental hazards, safety concerns, and the obstruction of drainage systems in urban and industrial areas. Effective plastic waste management is crucial to mitigate these adverse consequences [14]. Waste management strategies, such as recycling, incineration, bioremediation, and landfills are usually scientifically based. These methods are established to have a clean environment and good plastic waste disposal [15,16].

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In 80's, recycling and incineration were introduced as alternative plastic waste management methods, but still globally a significant portion (56% in 2015, decreasing slowly every year) either goes to the landfill or escapes into the environment [17].
Mechanically recycled plastics face stiff competition against virgin plastics due to issues like inadequate quality, regulatory constraints, and pricing challenges. Additionally, certain post-consumer plastics, collected and sorted with varying degrees of mixing and contamination for mechanical recycling, are predominantly utilized in the manufacturing of new, lower-quality products, given the current limitations of processing technologies [18].
The plastic recycling industry employs five environmentally sustainable and financially viable options:
Reuse involves directly integrating recycled components into the production of new vehicles. **Remanufacturing** is a process of repairing and restoring plastic parts. **Mechanical recycling** entails reheating automotive plastic parts and transforming them into new products of similar materials. **Chemical recycling** involves converting plastic materials into monomers, allowing them to be repolymerized to create virgin resins or their corresponding petrochemicals, typically in liquid or gas forms. **Energy recovery** involves burning plastic waste to generate energy in the form of heat, steam, and electricity. As per recent studies, mechanical recycling is the most reasonable and advantageous method of plastic recycling when considering the economy, environment, and technology [19].
The plastic recycling process using solvent extraction involves three key steps: removal of impurities, dissolution of polymers in solvents, and selective crystallization. The ideal solvent is one that can dissolve only the target polymer or all polymers except the desired one, ensuring a selective dissolution [20].
Combining solvent extraction and mechanical recycling in waste management offers comprehensive material recovery, contaminant removal, and selective recovery. This synergy improves the processing of complex materials, enhances the quality of recycled materials, and promotes energy efficiency. The approach minimizes waste, ensures economic viability, and provides a versatile recycling strategy adaptable to various waste streams. However, success depends on considering specific waste characteristics, cost factors, and environmental impacts in the recycling process design [21,22,23].

2. Materials and Methods

2.1. Materials

The most commonly used materials in wiring devices are plastic materials. Wiring devices are electrical components designed to connect and control the flow of electrical power to appliances, lighting fixtures, and other electrical devices. These devices are available in a variety of types and configurations, including plugs, outlets, switches, and connectors [24].

ABS is mostly preferred polymer for wiring devices because the butadiene-styrene copolymers contribute to increased impact resistance, while acrylonitrile exhibits an inclination to form chemical bonds with external components. The butadiene component is uniformly dispersed within a matrix of acrylonitrile and styrene. Its notable attributes include good stability, toughness, ease of processing, chemical inertness and widespread availability. [25,26,27].

In the solvent-based recycling of coated plastic components, specific solvents from the CreaSolv® process developed at Fraunhofer IVV have been utilized. The recycled ABS utilized in this study was procured from Fraunhofer IVV (Freising, Germany. The remaining raw materials consist of the chemicals currently employed in frames at Panasonic Electric Works Türkiye (İstanbul, Türkiye).

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2.2. Methods

The removal process plays a crucial role in facilitating the efficient recycling of plastics [28]. Several techniques have been investigated for the removal of paint from plastic materials. Among these methods, solvent-based removal processes, aimed at separating plastics from the paint on their surfaces, are widely favored by the plastic recycling industry due to their ability to maintain good surface quality, cost-effectiveness, and high efficiency [29-30].
Solvent extraction has demonstrated effectiveness in the recovery and purification of plastics [31]. The fundamental principle behind solvent extraction involves selective dissolution, wherein a target polymer or all other polymers except the target polymer are dissolved [32]. Mechanical recycling finds application in large-scale commercialized processes [33]. Therefore, CreaSolv was used to removal process the paint from the surface. After the removal process, frames were produced by mechanical recycling of the recycled rABS.

2.2.1. Preparation of samples

The ABS electric frames were produced through injection molding at PANASONIC facilities (Figure 2).

Figure 2: Injection molding of plastic ABS façade prototypes manufactured at PANASONIC facilities.

The solvents were used to achieve a targeted dissolution or delamination of the coating to allow the recovery of a clean substrate material for reprocessing.

First, the samples were shredded in a cutting mill to a size of <0,5 cm. The shredded samples were fed into the solvent-based recycling process where, depending on the type of coating, the solvents are used to dissolve or delaminate the coating, while the substrate remains undissolved. The substrate material was cleaned from the removed coating, possible impurities on the material can be removed in that step as well. The solvent was removed from the cleaned substrate material in a subsequent drying process and reused in the process. After drying the product was recovered in granulate form.

These granules were further subjected to a melt spinning process to use in injection moulding applications.

As an outcome of the trials performed in the mechanical recycling line, a total amount of material sample of 5.5 kg ABS recyclate pellets produced with the intent of carry out the characterization of mechanical properties.

In order to evaluate usability of recycled material in standard manufacturing process, frames were produced with a ratio of 70% raw ABS material and 30% recycled ABS material mixture in three loops.

In the first loop, the recycled material was oven-dried at 80°C for two hours. A ratio of 70% raw ABS material and 30% recycled ABS material (rABS) were blended together and used in the standard injection process. The resulting frames were then ground into small particles to be used in the next loop as recycled material.

In the second loop, the recycled material was again oven-dried at 80°C for two hours. A ratio of 70% raw ABS material and 30% recycled material (obtained from the first loop's product) were blended together and used in the standard injection process. The resulting frames were again ground into small particles to be used in the next loop as recycled material.

In the third loop, the recycled material was once again oven-dried at 80°C for two hours. A ratio of 70% raw ABS material and 30% recycled material (obtained from the second loop's product) were blended together and used in the standard injection process. The resulting frames were then sent to a test laboratory to evaluate their quality standards.

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3. Result

3.1. Analysis on Results of ABS Samples

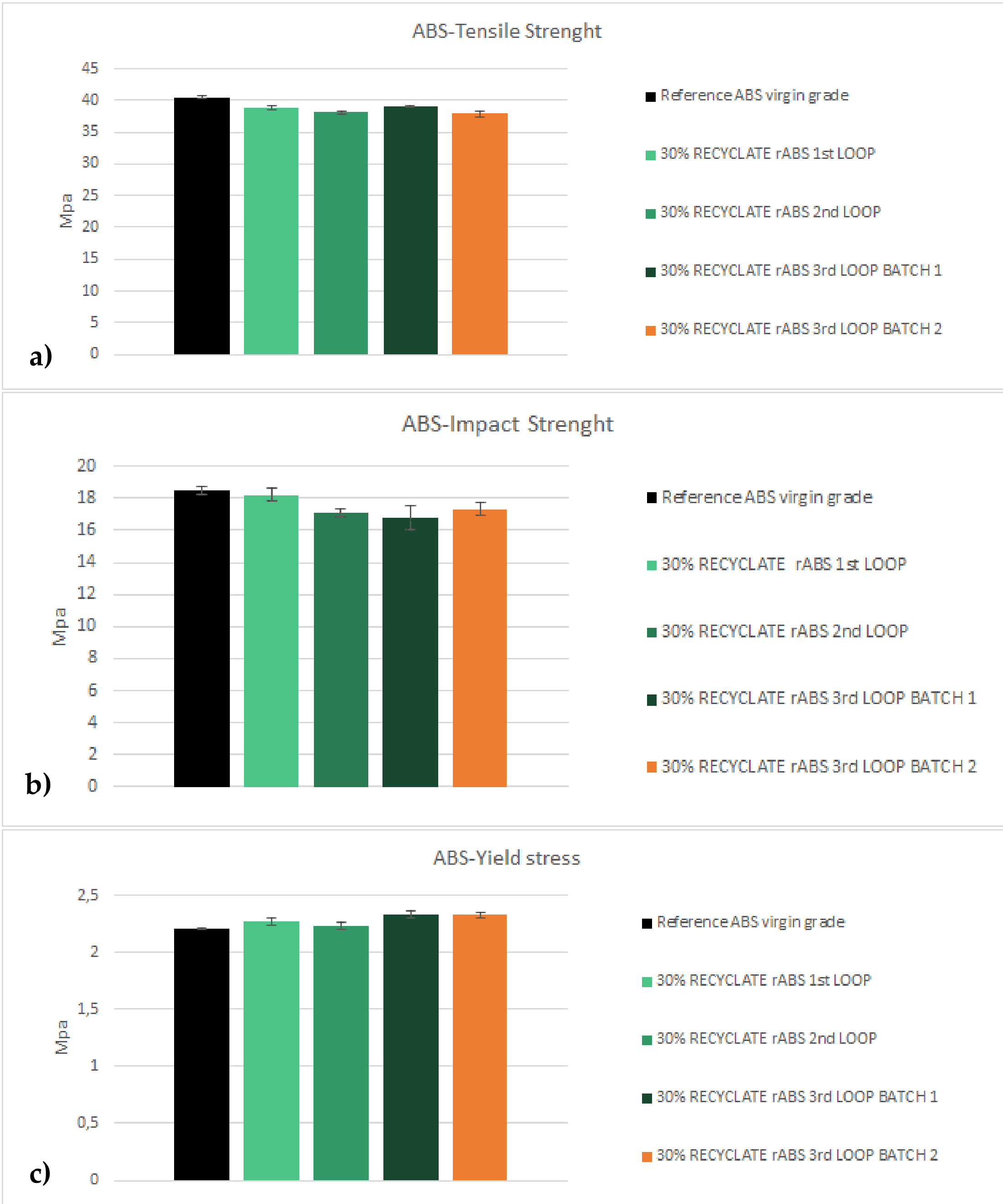
The adoption of recycled materials in industrial manufacturing processes is increasingly pivotal in the context of sustainable production [34]. In line with growing environmental concerns and the imperative to conserve resources, companies such as Panasonic are at the forefront of efforts to incorporate recycled materials into their manufacturing practices. This transition necessitates the implementation of robust evaluation methodologies to determine the suitability and performance of these recycled materials.

Several physicochemical characterizations were conducted to assess the properties of the rABS plastic. A comparative analysis was carried out between the ABS products recovered and the original ABS in the plastic electric frames. In this context, rABS pellet samples were molded to perform the initial cycle of mechanical recycling to produce test specimens to characterize the mechanical properties of the material. After the mechanical characterization of specimens produced with rABS, ball pressure tests and glow wire tests were conducted. These tests are essential for evaluating the material properties that must meet the standards required for the safe and effective production. The test sample is shown in Figure 3.

Figure 3: The test sample.

3.2. Mechanical Properties Characterization

After completing each loop of recycling, samples of rABS pellets were molded to produce test specimens for the characterization of mechanical properties. The following charts (Figure 4) present a comparative study of the rABS compound obtained after each recycling cycle, as compared to the reference virgin ABS grade.


ABS-Tensile Strenght
Mpa
0
5
10
15
20
25
30
35
40
45
Reference ABS virgin grade
30% RECYCLATE rABS 1st LOOP
30% RECYCLATE rABS 2nd LOOP
30% RECYCLATE rABS 3rd LOOP BATCH 1
30% RECYCLATE rABS 3rd LOOP BATCH 2
a)
ABS-Impact Strenght
Mpa
0
2
4
6
8
10
12
14
16
18
20
Reference ABS virgin grade
30% RECYCLATE rABS 1st LOOP
30% RECYCLATE rABS 2nd LOOP
30% RECYCLATE rABS 3rd LOOP BATCH 1
30% RECYCLATE rABS 3rd LOOP BATCH 2
b)
ABS-Yield stress
Mpa
0
0,5
1
1,5
2
2,5
Reference ABS virgin grade
30% RECYCLATE rABS 1st LOOP
30% RECYCLATE rABS 2nd LOOP
30% RECYCLATE rABS 3rd LOOP BATCH 1
30% RECYCLATE rABS 3rd LOOP BATCH 2
c)

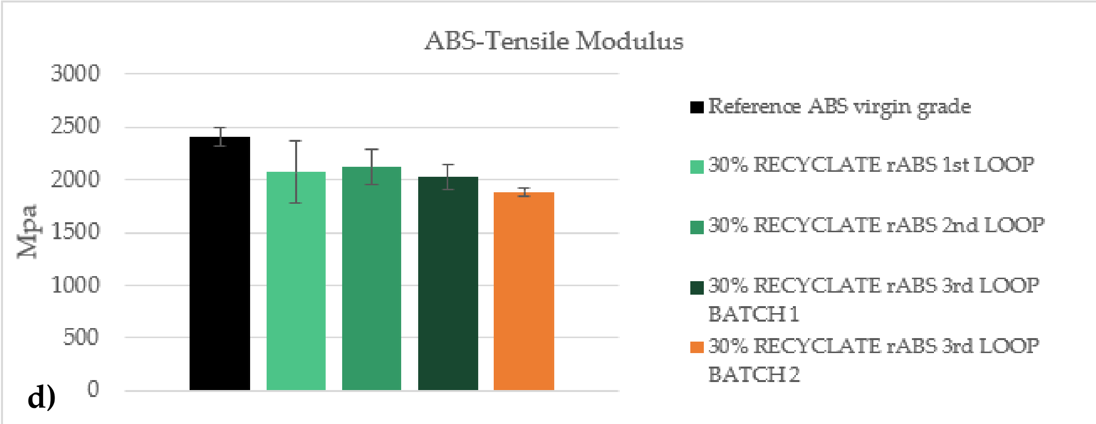


Figure 4: Test result of the characterization of mechanical properties of test samples.

a) Tensile Strength b) Impact Strength c) Yield Stress d) Tensile Modulus

The results of the mechanical testing are quite encouraging. Although rABS shows a slight decrease in the tensile strength (Figure 4. a) and impact strength (Figure 4. b) when compared to the reference ABS virgin grade, the rABS shows similar mechanical performance to the reference ABS virgin grade. The yield stress (Figure 4. c) shows more variability and a slight increase in average value for the rABS compared to the reference ABS virgin grade. The tensile modulus (Figure 4. d) property shows more variability and more noticeable decrease down to 15-20% for the rABS recyclates compared to the reference ABS virgin grade. This fact reinforces the suitability of the upcycling strategy incorporating an impact strength additive to the recyclate compounds and allows to increase the percentage of rABS above 30% in further developments.

In conclusion, the test results confirm the viability of utilizing rABS as a material for manufacturing plastic parts, following each loop of mechanical recycling. The mechanical properties characterization reveals that, while there is a minor decrease in impact strength and tensile strength compared to the reference virgin ABS grade, the rABS demonstrates commendable mechanical performance.

3.3. Resistance to Heat (Ball Pressure Test)

The ball pressure test is applied to electrical and electronic products and their components, including lighting equipment, low-voltage electrical appliances, household appliances, machine tool electrical appliances, motors, electronic appliances, information technology equipment, and electrical work equipment. Resistance to heat (ball pressure test) was performed on the ball pressure test machine at Panasonic Laboratory. This test was carried out according to the standard IEC 60884-1. The test sample and test machine are shown in Figure 5.

Figure 5: Test machine and test sample.

Table 1 presents the results of the ball pressure test, which measures the indentation size caused by a steel ball on a specimen under specific pressure and temperature conditions.

Table 1: The results of the ball pressure test.

Sample	Cycle No	Test Parameters	Observations	Verdict
Electrical frame made of raw ABS plastic	Reference	Samples are kept at 70°C for 1h Diameter of the ball impression shall not exceed 2mm. (Samples are kept at ambient temperature with a 60% relative humidity for 24h before the test.)	Diameter of the ball impression: 0,90 mm	Pass
Electrical frame made of different percentage rABS material	1		Diameter of the ball impression: 0,94 mm	Pass
	2		Diameter of the ball impression: 0,95 mm	Pass
	3		Diameter of the ball impression: 0,97 mm	Pass

According to the standard for test compliance, the sample must not exhibit any signs of flaming. In the event of flaming, it must be promptly extinguished within 30 seconds after the removal of the glow-wire. Additionally, there should be no ignition of tissue paper or scorching of the board. An assessment of the glow wire test was conducted on samples manufactured with varying amounts of rABS. Encouragingly, none of the test samples displayed combustion at a temperature of 650 degrees. All samples successfully met the specified standard.

3.4. Glow Wire Test

Glow wire test is an electrical safety test used to determine how flame-resistant plastic materials used in electrical equipment are. Its purpose is to prevent fires caused by overheated or electrically charged elements that could ignite plastic material. Glow wire test was performed on the glow wire test machine made by Zhilitong Electromechanical Co.,Ltd. at Panasonic Laboratory. The test is subject to the procedure IEC 60884-1. The test sample and test machine are shown in Figure 6.

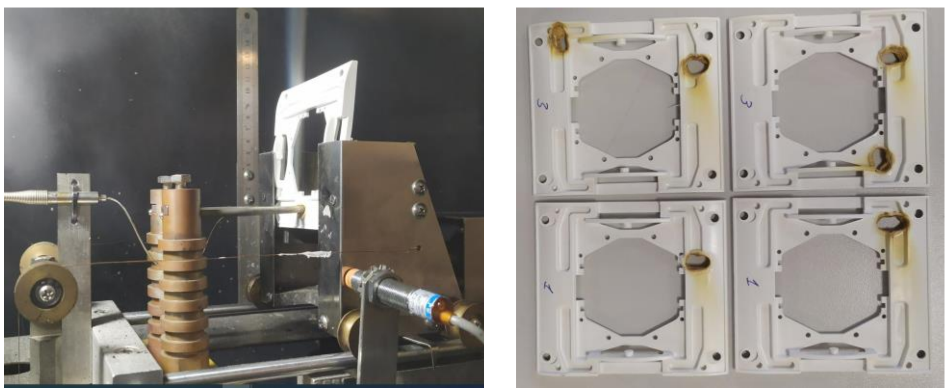


Figure 6: Test machine and test sample.

The results of the glowing wire test performed under 30 seconds at 650°C are given in the Table 2.

Table 2: The results of the wire glow test.

Sample	Cycle No	Test Parameters	Observations	Verdict
Electrical frame made of raw ABS plastic	Reference	Glow wire at 650°C for 30s. Sample shall not flame, if it flames it shall extinguish within 30 s after removal of the glow-wire. There shall be no ignition of the tissue paper or scorching of the board.	No flame was observed at 650°C.	Pass
Electrical frame made of different percentage rABS material	1		No flame was observed at 650°C.	Pass
	2		No flame was observed at 650°C.	Pass
	3		No flame was observed at 650°C.	Pass

According to standard, to pass the test, the sample should not flame. If it flames, it should be extinguished within 30 seconds after removing the glow-wire. There will be no ignition of tissue paper or scorching of the board. Glow wire test of the sample produced with different amount rABS was evaluated. None of the test samples exhibited combustion at a temperature of 650 degrees. All samples were successfully completed according to the standard.

3.5. Life Cycle Assessment

The LCA for the electric ABS frame coated with a painted layer based on styrene-acrylic emulsion with aluminium. The debonding technology modelled in the LCA was the solvent based recycling process and the quality degradation was modelled as 19% following data input from CTAG (Centro Tecnolóxico de Automoción de Galicia). Recycling to a market-acceptable quality is achieved with a blend of 30% recovered recycled ABS. Life Cycle Assessment data table is presented in Table 3.

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Table 3: Life Cycle Assessment data.

	Total impact
EF 3.0 Acidification [Mole of H+ eq.]	4,40E-02
EF 3.0 Climate Change - total [kg CO2 eq.]	1,33E+01
EF 3.0 Climate Change, biogenic [kg CO2 eq.]	5,75E-02
EF 3.0 Climate Change, fossil [kg CO2 eq.]	1,32E+01
EF 3.0 Climate Change, land use and land use change [kg CO2 eq.]	1,54E-02
EF 3.0 Ecotoxicity, freshwater - total [CTUe]	1,66E+02
EF 3.0 Eutrophication, freshwater [kg P eq.]	7,06E-03
EF 3.0 Eutrophication, marine [kg N eq.]	9,51E-03
EF 3.0 Eutrophication, terrestrial [Mole of N eq.]	8,88E-02
EF 3.0 Human toxicity, cancer - total [CTUh]	3,35E-09
EF 3.0 Human toxicity, non-cancer - total [CTUh]	1,31E-07
EF 3.0 Ionising radiation, human health [kBq U235 eq.]	1,27E+00
EF 3.0 Land Use [Pt]	3,45E+01
EF 3.0 Ozone depletion [kg CFC-11 eq.]	6,49E-07
EF 3.0 Particulate matter [Disease incidences]	4,33E-07
EF 3.0 Photochemical ozone formation, human health [kg NMVOC eq.]	2,86E-02
EF 3.0 Resource use, fossils [MJ]	2,12E+02
EF 3.0 Resource use, mineral and metals [kg Sb eq.]	1,85E-05
EF 3.0 Water use [m^3 world equiv.]	4,91E+00

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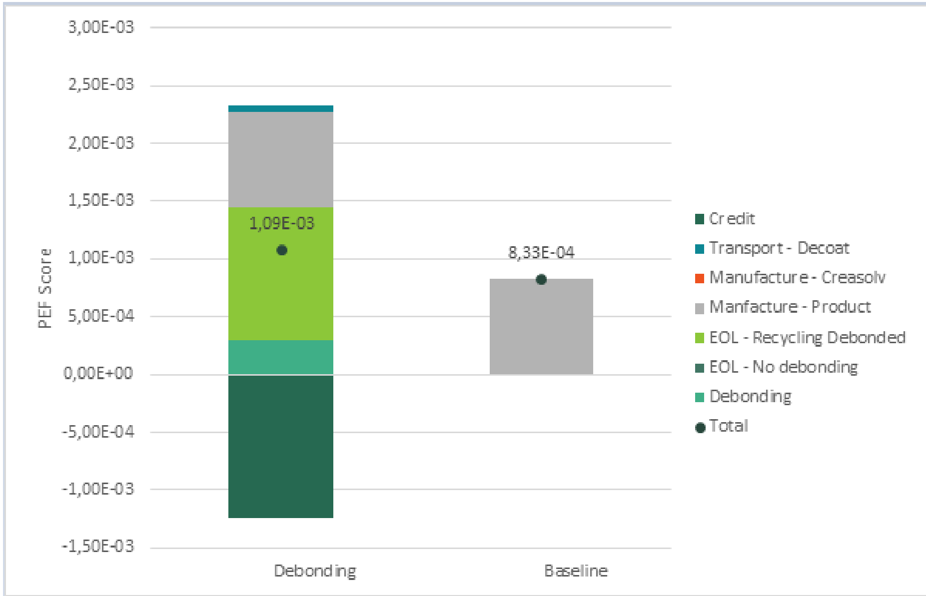

Figure 7: rABS Samples Environmental Footprint (PEF) Score for the Debonding and Baseline.

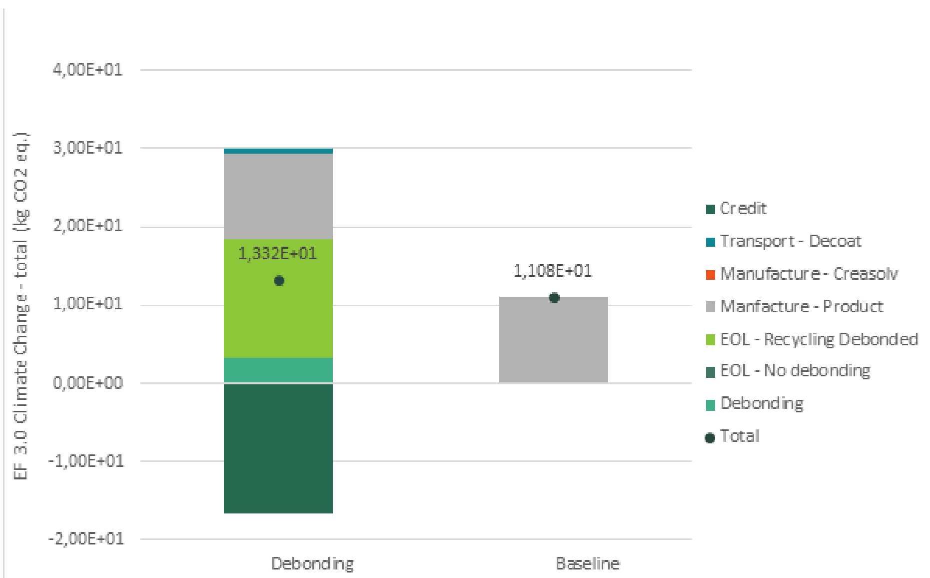

Figure 8: rABS Samples total Carbon Footprint of the Debonding scenario and the Baseline scenario with no debonding.

The Environmental Footprint (PEF) Score for the Debonding and Baseline shown in Figure 7 and Carbon Footprint of the Debonding scenario and the Baseline scenario with no debonding shown in Figure 8. The results of the LCA show that, debonding scenario has a higher Carbon Footprint and Product Environment Footprint than the baseline scenario (+20% and +31% respectively). Within the baseline scenario (no debonding) the

EOL processes account for only 1% of the total Carbon Footprint, however in the Debonding scenario the additional steps required for the debonding and recycling of the recovered substrate (EOL) contributes 61% to the total Carbon Footprint. The chemical solvent itself has negligible impact on the environmental impact. The sensitivity analyses indicate that if total electricity usage during debonding reduced to 25% of current levels, or if the percentage of recycled recovered content used in the production of the new product increases from 30% to 70%, then the Carbon Footprint of the debonding scenario would be at the same level as the baseline scenario.

3.6. Life Cycle Costing

For the rABS, the Life Cycle Cost Assessment was performed on solvent-based recycling of the coated ABS substrate. The LCC assessment included the following cost categories: the cost of raw materials, manufacturing and waste management cost, end-of-life treatment cost and cost of recycling of the substrate. The functional unit is defined as "1 kg of debonded substrate". The LCC results are shown in units "€/FU". Table 4 refers the total LCC of the included processes (shredding and solvent-based recycling) in the value chain of the coated ABS substrate.

Table 4: LCC, Data sourcing and TRL on additional processes of shredding and solvent-based recycling.

Process	LCC (€/kg)	Data source	TRL
Shredding	0.52	Primary	6
Solvent-based recycling	1.14	Estimated	7-8

The LCC of the ABS plastic debonding is higher by 2.16 times compared to the baseline, where the end-of-life is considered as incineration. The additional processes of shredding and solvent-based recycling are increasing the total cost of the final product by approx. 29% and 55%, respectively. Credits for the avoided content of virgin material is calculated at 46%.

4. Discussion and Conclusion

This study investigated the use of recycled ABS material in the remanufacturing of lighting frames, which has not been investigated in the previous literature. The main purpose of the study was to examine whether the proportional addition of recycled ABS material would change the mechanical properties of the frame produced. At the end of the study, the targeted production could be achieved and through tests performed on the output products, it was observed that adding rABS material did not adversely affect the mechanical properties of the ABS polymer and that it passed all the tests required for production.

The outcomes from the mechanical tests are quite promising. Although there is a slight decrease in impact strength and tensile strength when compared to the reference ABS virgin grade, the rABS generally exhibit similar mechanical performance both to the reference ABS virgin grade and after each recycling loop. This fact reinforces the suitability of the upcycling strategy incorporating impact strength additive to the recyclate compounds and allows to increase the percentage of rABS above 30% in further developments. Only the tensile modulus property show more variability and more noticeable decrease down to 15-20% for the rABS recyclates compared to the reference ABS virgin grade.

The result of the life cycle assessment shows that the debonding scenario has a higher Carbon Footprint and Product Environmental Footprint than the baseline scenario (+20% and +31% respectively).

The LCC of the ABS plastic debonding is higher by 2.16 times compared to the baseline, where the end-of-life is considered as incineration. The additional processes of shredding and solvent-based recycling are increasing the total cost of the final product by approx. 29% and 55%, respectively. Credits for the avoided content of virgin material is calculated at 46%.

Although promising results are obtained in terms of mechanical aspects, it is recommended to make improvements in these areas in future studies based on Life Cycle Cost (LCC) and Life Cycle Assessment (LCA) evaluations.

5. Acknowledge

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