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EVALUATION OF MECHANICAL PROPERTIES OF MIXTURES OF VIRGIN AND RECYCLED HIGH-DENSITY POLYETHYLENE
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Abstract: *The application of polymers in several sectors of the global economy has progressively grown in recent decades, especially in the development of novel products, owing to their high strength, low weight and low cost. Nevertheless, most polymers are traditionally obtained from naphtha, a colourless and volatile compound derived from the oil refining process, with deep environmental impacts. High-Density Polyethylene (HDPE) is one of the most used naphtha-derived polymers in industrial applications, and, thus, a large amount of this material is inappropriately discarded. However, HDPE recycling has been used as an effective alternative method to reduce the environmental impacts caused by the continuous extraction and indiscriminate use of oil. However, the recycling process degrades the mechanical properties of the polymer due to contamination, prior exposure to harsh environments, and the breakage of polymeric chains. This study evaluates the mechanical properties of polymeric mixtures composed of different virgin/recycled HDPE mass fractions: 100/0, 75/25, 50/50, 25/75 and 0/100. The materials were melted at 130°C, using a recycled mono-screw extruder, built from parts of disabled machines and scrap (metal sheets and bars), and the specimens were made using the thermo-pressing technique. The samples were tested under tensile loads using a universal testing machine (EMIC DL-20000). The mechanical properties investigated were the modulus of elasticity, yield strength, tensile strength, strength and elongation to failure and tensile toughness. The results reveal that the incorporation of 25% in mass fraction of recycled HDPE does not significantly reduce the mechanical properties of the virgin polymer, with a decrease ranging from 1.26% (in yield strength) to 6.31% (in toughness), which represents a reduction in costs of 4.51%. These findings corroborate the available literature and highlight the potential of this manufacturing strategy to produce sustainable materials with good mechanical properties. Therefore, recycling is a viable, sustainable strategy to reduce the volume of inappropriate material disposal and environmental impacts, reduce production costs, and preserve natural resources.*

Keywords: *HDPE, Sustainability, Recycling, Tensile mechanical properties.*

1. INTRODUCTION

Over the last century, polymers emerged as alternative multifunctional materials, revolutionising several sectors of the global economy. Plastics, rubbers and synthetic fibres have played a central role in the technological revolution of the 20th and 21st centuries. Owing to their technological importance, it would not be an exaggeration to designate this period as the "Polymers Age" compared to previous ones such as the Stone, Bronze and Copper Ages (NUNES & LOPES, 2012).

Synthetic polymers are the building blocks for a wide variety of products, from packages, plastic containers and adhesives to structures in civil, naval and aeronautic industries, where plastics with enhanced physical and mechanical properties, the so-called "engineering plastics", provide superior stiffness as well as impact, heat and abrasion resistance (CORRÊA, 2012). Additional advantages are resistance to deterioration by decomposition and attack of microorganisms, resilience, low specific weight, ease of processing and low maintenance cost (CANDIAN, 2007).

Synthetic polymers, however, are non-biodegradable and derived from non-renewable resources, such as petroleum. The scarcity of natural resources and the concern for next generations and their quality of life call for new solutions to environmental problems. In this context, recycling may offer an environmentally friendly and profitable alternative route, reducing fabrication costs and creating new jobs. For example, the recycling industry in Brazil obtained a turnover of R$ 2.4 billion, and 10,656 jobs were generated in the processed plastic sector in 2018 (ABIPLAST, 2020).

High-Density Polyethylene (HDPE) is one of the most used - and thus most inappropriately discarded polymers for industrial applications, which poses a severe environmental issue. The thermoplastic nature of HDPE allows for its remoulding and recycling. However, the recycled material suffers the degradation of its properties due to contamination, prior exposure to harsh environments and breakage of polymeric chains (PARENTE, 2006).

RAMOS *et al.* (2015) studied the mechanical properties of virgin (HD7600U) and recycled HDPE obtained from post-consumer packagings. Samples were fabricated by injection moulding using granules of virgin material and extruded molten recycled HDPE. The samples were tested under tensile and impact loadings. Results revealed that the mechanical properties of recycled HDPE were practically the same as those for the virgin material, except for impact strength.

VARGAS *et al.* (2005) investigated the molecular weight, structural (FTIR and X-ray diffraction), thermal (differential scanning calorimetry) and mechanical properties (elongation at break, tensile modulus and strength) of virgin/post-consumer HDPE blends. The recycled material was obtained from urban plastic waste and processed by water-cleansing/grinding and extrusion/pelletisation to remove contaminants. The authors report that 70/30 mixtures of virgin/grounded and 50/50 blends of virgin/pelletised recycled HDPE presented mechanical properties similar to the virgin material. In addition, compatibilisers (such as EVA, LDPE and antioxidants), used to improve the mechanical properties of the recycled material at higher fractions (50 and 70%), also provided similar mechanical properties relative to the virgin polymer.

HAWORTH *et al.* (2016) investigated the effects of rubber crumb addition into recycled HDPE and its composites reinforced by continuous glass fibres on acoustic, thermal and flexural properties. Samples were fabricated by injection or compression moulding of the HDPE/rubber blend obtained by twin-screw extrusion, using up to 20% in mass of rubber crumb. The recycled rubber improved the acoustic absorption of HDPE in the 2-6 kHz frequency range and slightly increased the crystallinity levels of HDPE, determined through differential scanning calorimetry. In addition, the flexural modulus and strength monotonically decreased for higher mass fractions of rubber.

This work evaluates the tensile mechanical properties of polymeric mixtures composed of different virgin/recycled HDPE mass fractions: 100/0, 75/25, 50/50, 25/75 and 0/100: modulus of elasticity, yield strength, tensile strength, strength and elongation to failure and tensile toughness.

Table 1. Main resins consumed in Brazil. Source: Adapted from ABIPLAST (2020).

Material	Consume (%)
Polypropylene (PP)	21
Polyvinyl Chloride (PVC)	13,6
High Density Polyethylene (HDPE)	12,7
Linear Low Density Polyethylene (LLDPE)	11,8
Recycled Plastic	10,6
Low Density Polyethylene (LDPE)	8,8
Engineering Plastic	6,9
Polystyrene (PS)	6
Polyethylene Terephthalate (PET)	5,4
Expanded Polystyrene (EPS)	2,1
Ethyl Vinyl Acetate (EVA)	1

2. MATERIAL AND METHODS

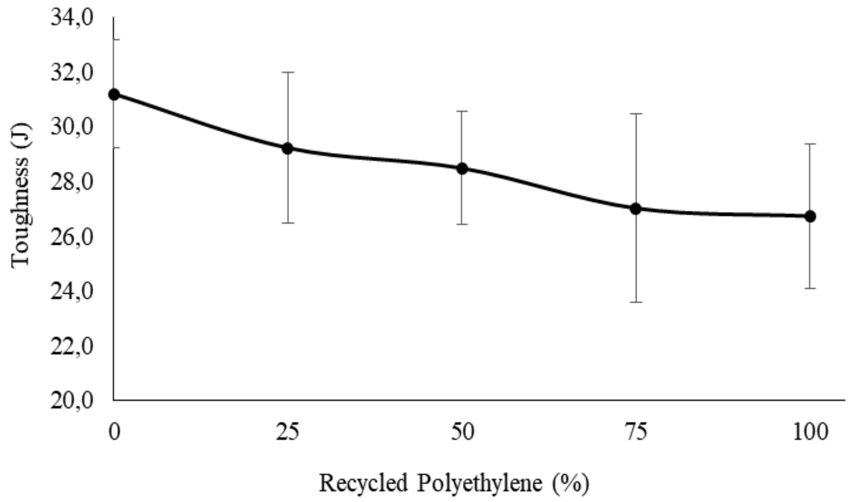
For the present study, mixtures of recycled HDPE, provided by Tergo Plásticos (Brazil), and virgin HDPE (HD7600U) supplied by Braskem (Brazil) were prepared – both in granules form. The specifications of the virgin HDPE were the following: index of fluidity 0.3g/10min; density 0.954g/cm³ and softening temperature 128ºC. The virgin/recycled HDPE mixtures were manually homogenised in the proportions of 100/0, 75/25, 50/50, 25/75 and 0/100 and processed using a mono-screw extruder built on reused parts of scrap extruders. The mixture was extruded at 130°C at an extrusion speed of 30 rpm. The extruded filaments were cooled in a bath of water at room temperature and then pelleted (particles of length 3.5 mm and diameter 3mm) to produce 2mm-thick plates using the thermo-pressing technique at 140ºC and 1.3 MPa for 5 min. The plates were air-cooled at room temperature. The 25 specimens (5 for each different virgin/recycled HDPE mass fractions) were finally cut by stamping according to type V dimensions described in the ASTM D638-14 standard.

Tensile tests were performed for all specimens (including the virgin HDPE) according to the standard in an EMIC DL-2000 universal testing machine equipped with a 200N load cell at a crosshead speed of 10 mm/min.

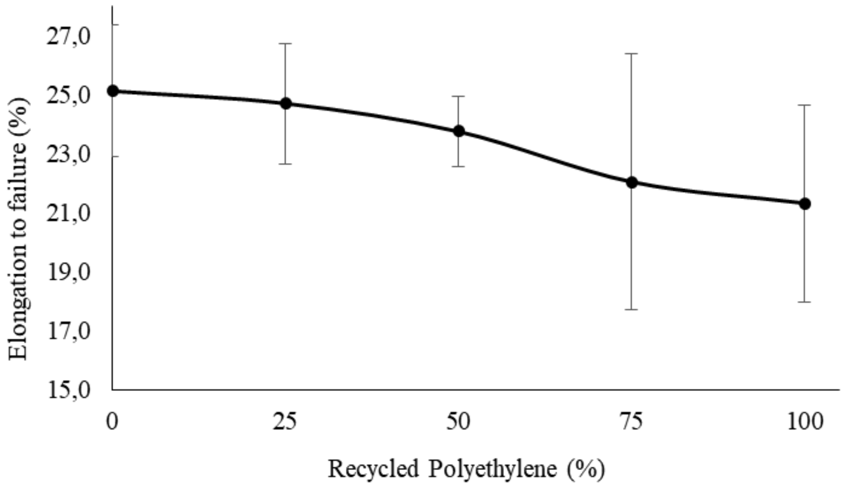
3. RESULTS AND DISCUSSION

3.1. Toughness, strength and elongation to failure

The toughness (Fig. 1a) and elongation to failure (Fig. 1b) presented a declining tendency as higher mass fractions of recycled HDPE were added into the polymeric mixture. The difference between 0/100 and 100/0 specimens was 4.45 J, a decrease of 14.30% in toughness. On the other hand, the difference in elongation to failure was 3.8, which corresponds to a loss of 15.1%, as shown in figure 1 (b). The averages are, however, equivalent, considering error bars.



(a)



(b)

Figure 1. (a) Toughness and elongation to failure (b) of virgin-recycled polymeric mixtures. Lines are a guide to the eye.

As shown in Fig. 2, an increase in recycled polyethylene dramatically reduces the strength to failure. The loss of 36.33% between 0/100 and 100/0 levels may be related to the breakage of polymeric chains during the recycling process (PARENTE, 2006). This result is corroborated by Ramos *et al.* (2015), who found a 33% reduction in strength to failure.

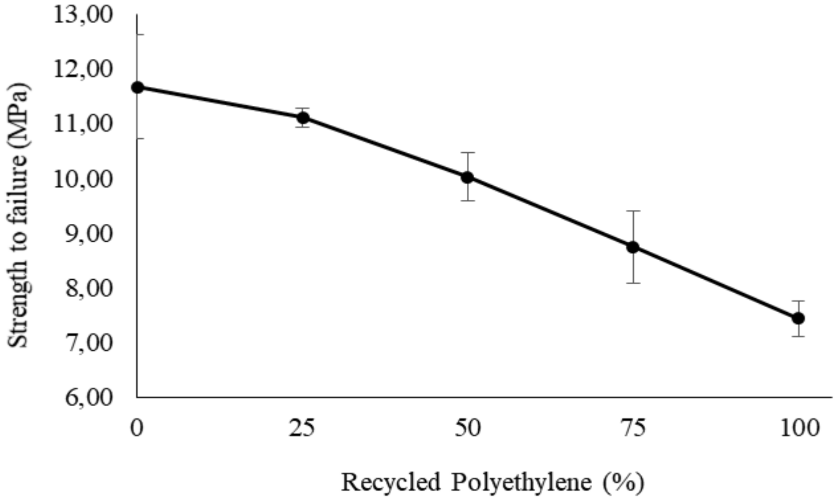
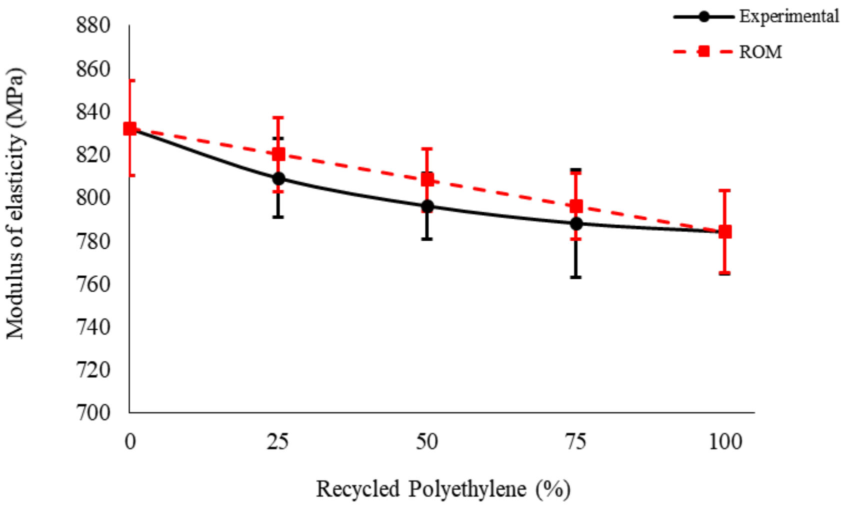


Figure 2. Dramatic reduction of the strength to failure upon the incorporation of recycled polyethylene. The line is a guide to the eye.

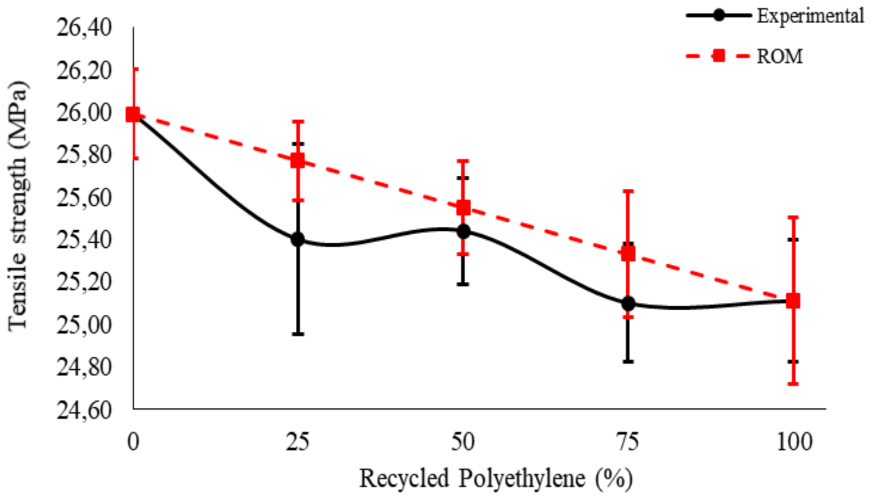
3.2. Tensile strength, yield strength and modulus of elasticity

The recycled HDPE decreases the modulus of elasticity (Fig. 3 (a)) and tensile strength (Fig. 3 (b)) of the virgin material, even though the reduction in modulus (5.76%) and tensile strength (3.38%) are much smaller relative to the decrease in strength to failure. The yield strength suffers a similar reduction of 5% (Fig. 4).

The Rule of Mixtures (RoM) has been evoked in the literature to account for the tensile elastic modulus and yield strength of polymeric blends (STRAPASSON *et al.*). The material investigated in this work is solely composed of HDPE. However, the recycled HDPE carries contaminants and is partially degraded due to the breakage of polymeric bonds. It is reasonable thus to consider that the material investigated is formed by the mixture of two phases: the pure HDPE and the recycled, impure and degraded HDPE. In this sense, Figures 3 and 4 also display the predicted behaviour of the respective mechanical property determined by the Rule of Mixtures (RoM). RoM assumes a perfect interface between phases (SILVA *et al.*, 2012). However, even though the discrepancy between the experimental and predicted values is small (≤ 1.5%), the results imply that the interface between virgin and recycled HDPE particles is not perfect, which may be explained by the presence of contaminants.



(a)



(b)

Figure 3. Tensile modulus (a) and strength (b) of virgin-recycled polymeric mixtures. Lines are a guide to the eye.

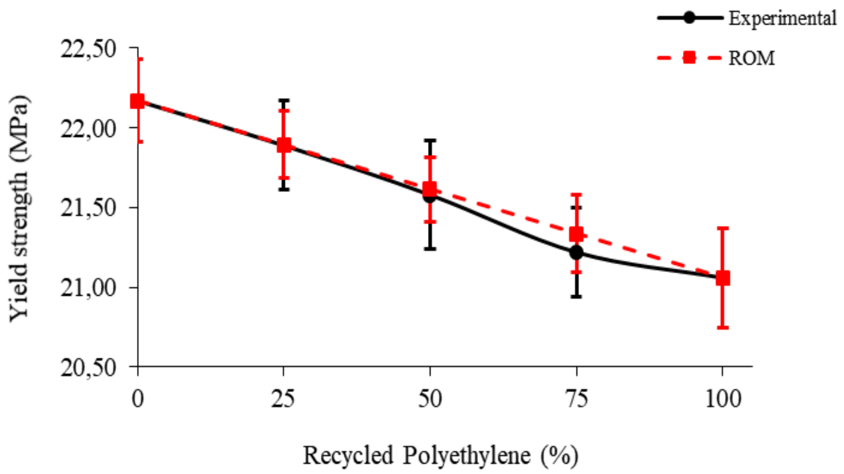


Figure 4. Reduction in yield strength of virgin-recycled polymeric HDPE mixtures. Lines are a guide to the eye.

4. CONCLUSIONS

The recycling process degrades the mechanical properties of HDPE due to contamination, prior exposure to harsh environments and the breakage of polymeric chains. This study, however, reveals that the reduction in tensile mechanical properties of the recycled HDPE is low, except for strength to failure (33.36% lower), as corroborated by the literature (Vargas *et al.* (2005); Ramos *et al.* (2015)). In particular, results reveal that the addition of 25% mass fraction recycled HDPE reduces only slightly the mechanical properties of virgin HDPE, with a decrease ranging from 1.26% (in yield strength) to 6.31% (in toughness). In addition, according to the Plastics Recycling Update (2020), it represents a reduction in costs of 4.51% (R$ 0.43/kg). Therefore, recycling is a viable, sustainable strategy to reduce the volume of inappropriate material disposal and environmental impacts, reduce production costs, and preserve natural resources.

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6. RESPONSIBILITY NOTICE

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