Analysis of the use of recycled plastics

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Abstract

There are significant environmental and public health concerns with the overuse and prolonged accumulation of solid plastic waste. Efforts to tackle this issue usually rely on Circular Economy theories and strategies. For this reason, this work aimed to review literature not only on the environmental issue caused by solid plastic waste, but also on the theoretical background of Circular Economy and its applications. Based on Circular Economy strategies, a simple methodology to perform mechanical characterization of unknown recovered ocean plastic was then developed. Widespread industrial use of mechanically recycled plastics with unknown composition would not only present a sustainable source of material, but also mitigate the pollution issue. The methodology developed consisted of mechanically characterize specimens made of different mixtures of recovered ocean plastic waste, and their virgin counterparts, through tensile testing. Although the manufacturing of the test specimens, by means of a heat press, hindered the results that could be obtained, it also highlighted the importance of using a high-standard manufacturing process, such as extrusion. An appropriate manufacturing process will allow for detail in comparing virgin and recycled materials and for more reliability in increasing amounts of recycled percentages in plastic products (without significant loss of the materials' or parts' properties). In the future, appropriate manufacturing and virgin materials should be used to replicate different percentage mixtures and evaluate their mechanical properties and how well they compare to the virgin counterparts.

Keywords: solid plastic waste, Circular Economy, mechanical recycling, tensile testing

1. Introduction

Plastic production has increased almost tenfold since large-scale production began around 1950. This happened mainly due to the replacement of reusable containers for single-use packaging (Geyer, Jambeck, and Law 2017), which currently makes up for almost 40 percent of European demand by application (PlasticsEurope 2019). This trend is expected to continue, with predictions of a two-fold increase in plastic production over the next twenty-years (World Economic Forum 2016).

Manufacturing of plastic products, which are in their majority non-biodegradable, leads to the accumulation of mismanaged plastic waste (Ritchie and Roser 2018). This issue is especially relevant for ocean plastic waste as not only are there few ways of effectively monitoring this problem (Barnes et al. 2009), but also due to the extensive degradation of plastic exposed to the elements (Welden and Cowie 2017). This degradation causes significant environmental impacts, including but not exclusively, for public health (Thompson et al. 2009). In its largest scale, plastic pollution affects the most occurring photosynthetic marine bacteria (*Prochlorococcus*), reducing its ability to produce oxygen. This issue is especially relevant considering this type of bacteria is believed to be responsible for up to 10% of global oxygen production (Tetu et al. 2019).

The total plastic amount in the oceans is estimated to be over 500 million tonnes. In a way to turn ocean plastic waste into a valuable resource stream and decrease the use of natural reserves of materials, Circular Economy (CE) presents several strategies. One of them is mechanical recycling. Finding mechanical properties for unknown source recovered polymers is a starting point to define appropriate mixture amounts of virgin polymers required and subsequent suitable applications.

The main objective of this work is to develop a simple methodology to perform mechanical characterization of mixtures of different percentages of unknown recovered ocean plastics and their virgin counterparts.

This methodology will be based on:

1) A literature review on Circular Economy (CE) for ocean plastic valorization
2) Mechanical characterization of plastics through tensile testing

2. State of the Art

The review of literature was done based on the diagram of Figure 1.

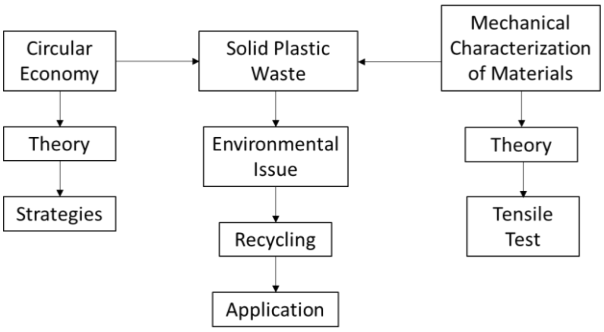


Figure 1 - Work structure considering CE strategies and mechanical characterization to mitigate the SPW's environmental issue

First, the solid plastic waste (SPW) problem was analyzed, focusing on the environmental issue it poses. Afterwards, Circular Economy (CE) principles and strategies were evaluated in order to reach a possible solution, which comes as the use of mechanically recycled plastic. Finally, an analysis of tensile testing of plastics was done in order to understand mechanical characterization of these materials.

2.1. Environmental issue

From all the plastic produced since 1950 to 201, just over seven percent has been recycled. Notably, as mentioned before, only about 30% of plastic produced is still in-use, supporting the conclusion that most plastic products have relatively short lifespans when comparing to other materials like metals and ceramics (Lebreton et al. 2018). Over half of plastic produced is "discarded", which is a general term to explain that it has leaked into land or ocean.

Concerning the environmental impact caused by plastic, production and even "acceptable" disposal methods like energy recovery and landfills, pose risks for human and animal health, as well as for the environment (Talsness et al. 2009). Landfill can have long term environmental effects like contamination of soil and groundwater by additives and byproducts of the breakdown of plastics. Incineration presents health and environmental risks because of the possibility of releasing hazardous substances into the atmosphere (Hopewell, Dvorak, and Kosior 2009), as well as CO2 emissions (Eriksen 2019).

SPW in the ocean is a concern because it breaks down due to weathering effects. Not only does it turn into ingestible-size pieces, but also into microscopic ones. It is then incorporated by wildlife into food chains, eventually reaching humans. Some studies point to 250 thousand tons of plastic debris floating in the oceans (Eriksen et al. 2014) and an annual leakage of about 8 million tons (Magnier et al., 2019), while others estimate that make up to 80% of waste found on land, shorelines, ocean surface and seabeds (Auta at al., 2017), making it the most significant source of marine pollution and contamination. The Ellen MacArthur Foundation gauges there will be more plastic than fish in the ocean (by weight) by 2050 (Kaplan 2016).

2.2. Circular Economy

Linear Economy (LE), or industrial economy, is the traditional and most common way of considering economic value of materials and products. This theory considers that to increase value, as much raw material as possible must be extracted, so that the highest number of products can be produced and sold. CE comes as a response to LE, to preserve value, not only monetary but also of products and materials, as much as possible. It can be quite difficult to define CE as it is a relatively new concept and can be termed an "umbrella concept" (Blomsma and Brennan 2017) being a somewhat ambiguous term.

It is worth noting that plastics' value is very difficult to recover due to its complicated manufacturing nature and applications. Under a CE perspective, recycling ocean plastic waste would be both a lucrative opportunity as well as a chance to mitigate a considerable environmental issue, effectively creating a significant stream of valorization of plastic waste. Recycling plastic waste should be more economic than processing virgin materials and while this is globally true, local issues might obstruct financial gains. For example, it can be too expensive to transport waste to a recycling plant, or policymakers might favor the production of new products.

In summary, to close loops for plastic, mechanical recycling is a viable solution and for this reason, it is further explored in the next section.

2.3. Mechanical Recycling

Mechanical recycling is the most widespread, technologically advanced, economic recycling strategy other than energy recovery. Additionally, mechanical recycling of plastics is the preferred strategy by the EU to implement a more circular economy of these materials (Lazarevic et al. 2010). Figure 2 shows the relative loop sizes for different recovery strategies.

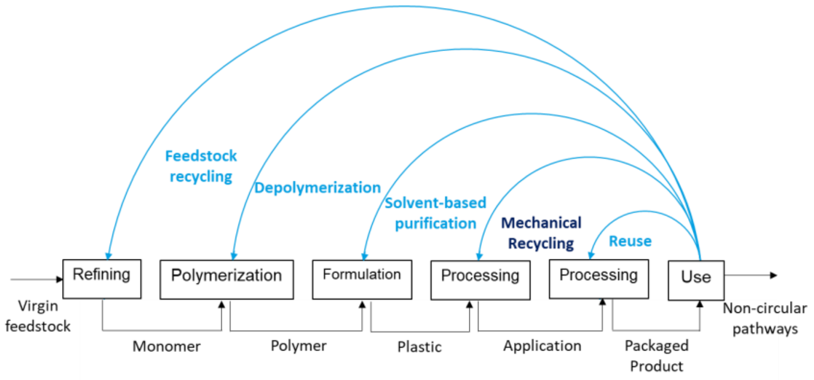


Figure 0 - Different recovery techniques and their “circularity”, adapted from Crippa et al., 2019

Notably, mechanical recycling is the next best strategy after reusing plastic products. This is because it is the recovery strategy that retains the highest value for plastics. Mechanical recycling is very much dependent on contamination and degradation of properties throughout the supply chain, as well as a careful optimization of processing parameters during manufacturing.

Overall results of mechanically recycled plastics found in literature have been satisfactory meaning mechanical properties were equivalent to the ones found in virgin plastics. Variability was found in the results, but all case studies analyzed found that recovered polymers had potential for being applied in the industry, even when mechanical properties of recycled plastics were lower than those of their virgin counterparts (Dahlbo et al., 2018).

There is relevant variability in recycled plastics’ mechanical properties and this unpredictability is one of the reasons why its use is not more widespread. There are two main reasons for this issue: not only are there significant differences in the quality of recovered plastics, but also several processing issues can arise throughout the supply chain.

3. Methodology proposed

To maximize the use of recovered plastics, it can be helpful to test mixtures of the recycled material with other materials, usually virgin, that can improve its mechanical properties. The added materials may or may not be other plastics. This is done because although a high-content mixture of recycled plastic might not be suitable for all applications, it can be to some. Overall results for testing of both recovered plastic and mixtures of recovered plastic found in literature have been satisfactory. This means mechanical properties for these mixtures were considered equivalent to the ones found in virgin plastics. Variability was found in the results, but all case studies analyzed found that recovered polymers had potential for widespread application in several industries, even when mechanical properties of recovered materials were significantly lower than those of their virgin counterparts (Dahlbo et al., 2018).

4. Experimentation

After a review of literature, the proposed methodology was to perform tensile testing on mixtures of recycled and virgin polypropylene (PP) and high-density polyethylene (HDPE). The test specimens were manufactured in a heat press, the Carver M-2089 model and the tensile tests were done in the INSTRON 5966 machine.

The material combinations considered specimens of PP and specimens of HDPE; the mixture of both materials was not considered. To improve test specimens' quality, there were two differences in the final test specimens namely by changing the temperature, curing time and applied pressure. These two combinations are referenced as M1 and M2, according to the chosen processing parameters.

Table 1 - Initial tests with different manufacturing methods M1 and M2

Reference	Material	Curing temperature [ºC]	Curing time [mins]	Pressure [T]	Cooling time [min]	Number of specimens
100% rPP_M1	rPP	190	10	5 to10	15	3
100% rPP_M2	rPP	190	10	8	10	3
75% rPP-25% vPP_M1	75% rPP – 25% vPP	190	10	5 to 10	15	3
75% rHDPE-25% vHDPE_M2	75% rHDPE – 25% vHDPE	160	10	5 to 10	15	3

The final experimental plan was defined as shown in Table 2, where different processing conditions and different percentage of recycled and virgin mixtures were considered. The material combinations considered specimens of PP and specimens of HDPE; the mixture of both materials was not considered.

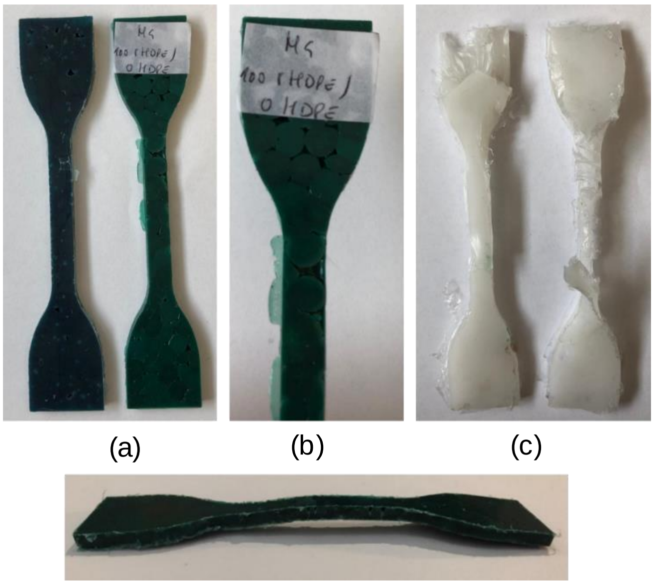
Table 2 - Experimental plan.

Reference	Material	Curing temperature [ºC]	Curing time [mins]	Pressure [T]	Cooling time [min]	Number of specimens
100% rPP_M1	rPP	190	10	5 to10	15	3
100% rPP_M2	rPP	190	10	8	10	3
100% vPP_M1	vPP	190	10	8	10	3
rPP - vPP_M1	100% rPP – 0% vPP	190	10	5 to 10	15	5 (of each)
	75% rPP – 25% vPP					
	50% rPP – 50% vPP					
	25% rPP – 75% vPP					
	0% rPP – 100% vPP					
rHDPE-vHDPE_M1	100% rHDPE – 0% vHDPE	160	10	8	10	5 (of each)
	75% rHDPE – 25% vHDPE					
	50% rHDPE – 50% vHDPE					
	25% rHDPE – 75% vHDPE					
	0% rHDPE – 100% vHDPE					

6. Results

6.1. Manufactured specimens

There were some limitations in the manufacturing of the test specimens. The defects caused by the limitations during the manufacture processing included superficial and inner gaps (Figure 2 (a) and (b)) pellets that did not melt properly (Figure 2 (b)), poor demolding (Figure 2 (c)) and warping of the test specimens (Figure 2 (d)) as well as localized burning of the pellets.

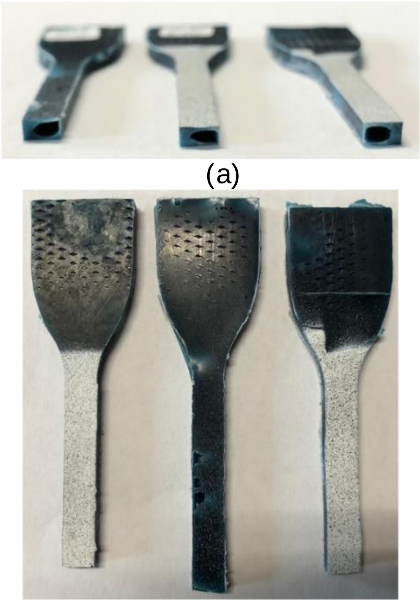


(a) (b) (c)

(d)

Figure 3 – Test specimens' defects: (a) superficial material gaps in one specimen of rPP and rHDPE (b) detail of pellets that did not melt (c) poor demolding and consequent deformation in a vPP specimen (d) warping of specimen after demolding

One of the most significant defects found in the specimens were the material gaps. Figure 3 (a) shows a detail of three rPP mixtures' test specimens that have fractured in a zone with a significant material gap.



(a)

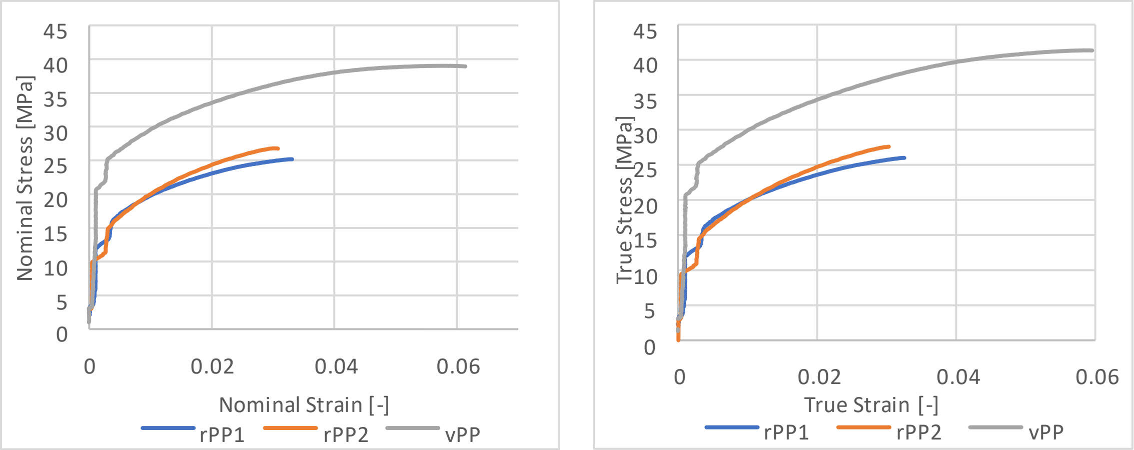
(b)

Figure 4 – Fracture of three 75% rPP – 25% vPP mixture test specimens: (a) fracture zone (b) closer detail of the specimens

These specimens had not only inner gaps but also superficial ones (Figure 3. (b)). This issue made the mechanical behavior of these specimens very fragile and they presented practically no ductile behavior.

6.2. Mixtures of recycled and virgin polyethylene

For the comparison of 100% virgin and 100% recycled polypropylene (PP) specimens, three test specimens of each group were tested. To investigate the specimens' quality, two different manufacturing conditions (M1 and M2) were considered. Figure 4. shows the nominal stress-strain curve and the true stress-strain curve for the three specimens.



(a) (b)

Figure 5 – True stress – true strain (a) and nominal stress – nominal strain (b) curves for 3 specimens of 100% recycled and 100% virgin PP

The comparison of the two best test specimens of the two recycled specimens (100%rPP_M1 and 100%rPP_M2), it can be concluded that the difference in the manufacturing parameters did not improve the quality of the test specimens. On the other hand, it is worth noting that for all specimens the beginning of the load-displacement curve revealed some irregularities than can be associated with the inner gaps inside the material.

Additionally, it can be concluded that the 100% virgin PP test specimens have a better mechanical behavior than the recycled specimens, as it was expected. Table 3 shows the mechanical properties of the three test specimens.

Table 3 – Mechanical properties for 3 specimens of 100% recycled and 100% virgin PP

Specimen reference	Nominal yield strength, $S_Y\,[MPa]$	True yield strength, $\sigma_Y\,[MPa]$	Modulus of Elasticity, $E\,[GPa]$	Tensile strength nominal, $S_{ts}\,[MPa]$	Tensile strength true, $\sigma_{ts}\,[MPa]$	Nominal strain at brake, $A\,[\%]$
100% rPP_M1_S1	15.82	15.50	4.3	25.17	26.00	3.3
100% rPP_M2_S1	14.89	15.91	3.9	26.79	27.60	3.1
100%vPP_M1_S1	24.97	24.29	7.4	39.02	41.33	6.1

It can be concluded that the yield strength values are within the reasonable interval for PP (10 - 500 MPa) and that the 100% recycled specimens have similar mechanical properties, aside from the Modulus of Elasticity. It is worth noting that this parameter was obtained from the tensile testing, which is not the recommended way to do it. Because there is such variability of mechanical behavior of polymers, the method to compute the Modulus of Elasticity depends on the stress – strain curves of the material analyzed.

Because the test specimens had such small linear regions (due to the inner gaps of material in the gauge length) this value is likely not representative of the true mechanical behavior of the material. The 100% virgin test specimen has an overall better mechanical behavior and was able to produce a much longer nominal strain at brake.

7. Conclusion

Although the manufacturing of the test specimens hindered the results that could be obtained from the methodology, it also highlighted the importance of using a high-standard manufacturing process to get accurate results. It was still possible to identify that even recovered materials of poor quality, which have been extensively degraded by exposure to elements in the ocean, present similar mechanical behavior of their virgin counterparts and can demonstrate reasonably good properties. Additionally, it was found that due to poor compatibilization of the recycled and virgin plastics, mixtures of both presented overall poorer mechanical properties than the 100% recycled or virgin test specimens.

In the future, appropriate manufacturing and virgin materials should be used to replicate different percentage mixtures and evaluate their mechanical properties and how well they compare to the virgin counterparts.

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