"Gheorghe Asachi" Technical University of Iasi, Romania

EVALUATION OF POST-CONSUMER MIXED POLYOLEFINES AND THEIR INJECTION MOULDED BLENDS WITH VIRGIN POLYETHYLENE

Laurens Delva*, Ludwig Cardon, Kim Ragaert

Centre for Polymer and Material Technologies (CPMT), Department of Materials, Textiles and Chemical Engineering, Faculty of Engineering and Architecture, Ghent University, Technologiepark 915, 9052, Zwijnaarde, Ghent, Belgium

Abstract

Recycling of solid plastic waste composed of post-consumer mixed polyolefines (polypropylene and polyethylene) was carried out by injection moulding of secondary material streams. The materials have been characterized by melt flow index (MFI), tensile, bending and impact measurements, density and differential scanning calorimetry (DSC). The sink-float technique was used to separate the polyethylene fraction, which was then blended into virgin polyethylene at different ratios and processed anew. The mechanical and physicochemical properties were likewise determined and these results were compared to theoretical values, predicted by the law-of-mixtures. It was found that the different postconsumer mixed polyolefines were of similar quality and had comparable properties. Furthermore, it was demonstrated that the tensile and bending properties of blends consisting of recycled separated polyethylene and virgin polyethylene follow the law-of-mixtures, while the impact strength does not and is in fact strongly reduced by the presence of different phases within the injection moulded part.

1. Introduction

Recent yearly plastics demand in Europe is up to 46.4 Mtonne, of which nearly 50% is made up by the polyolefines (PO) polypropylene PP (19%), high density polyethylene HDPE (12%) and low density polyethylene LDPE (17%) (PlasticsEurope et al., 2011). There is a steadily growing consumer awareness regarding recycling of materials, which is expressed by a yearly increase in the amount of recycled post-consumer plastics (PlasticsEurope et al., 2010, 2011). Of the yearly 24.7 Mtonne post-consumer solid plastic waste (SPW) this now generates, only 24% is recovered as secondary raw materials through recycling. The rest is either burnt for energy recovery (34 %), exported outside the EU or landfilled (PlasticsEurope et al., 2011).

Apart from energy recovery by burning, the means of recovering SPW include mechanical (secondary) recycling and chemical (tertiary) recycling (Al-Salem et al., 2009). In mechanical recycling, polymer materials are recovered through mechanical means such as grinding, washing, separating, drying, re-granulating and compounding. The more advanced techniques of chemical recycling reduce (by chemical degradation) the polymer scrap to smaller molecules, which are suitable for the production of new petrochemicals or polymers. Chemical recycling, however, remains very expensive and is generally not considered on an industrial level (Emans, 2012; Siddique et al., 2008). Energy recovery should only be considered a sensible way of waste treatment, when the alternative of material recovery is not economically viable. Yet, the greater part of

---

* Author to whom all correspondence should be addressed: e-mail: Laurens.Delva@ugent.be; Phone: +32 9 2424292; Fax: +32 9 2424292

polymer waste is still recovered in this fashion. What bottlenecks then, prevent the wider use of secondary polymer material streams?

From a socio-economical point, the major hurdle is that the public opinion on the sustainability of plastics is very poor (Comanita et al., 2016; Schanssema, 2011). Plastics are generally seen as non-recyclable and wasteful, even if industrial reports have demonstrated that the use of plastics can in many cases actually help save resources across the whole life-cycle. The Denkstatt study (Pilz et al., 2010) has been pivotal in balancing this awareness on the level of policy makers. It was the first study who analyzed the environmental impact of nearly 200 plastics products over their entire life-cycle. The results revealed that while the carbon footprint per capita of an average EU27+2 (Norway and Switzerland) amounts to about 14 tonnes CO_2, of which a mere 170 kg (or 1.3%) stems from the use of plastic products. Now it remains for the consumer and the market to accept products containing recycled polymers. This strategic goal has been defined as one of the key factors to success for (mechanical) recycling by various European associations related to polymer processing and recycling (PlasticsEurope et al., 2011).

Additionally, much of the secondary (polymer) materials are still transported out of the EU, instead of being used a raw materials in the EU industry, leading to shortage in their availability for those wanting to incorporate the secondary stream into their production (CEPI et al., 2012).

A major drawback in the mechanical recycling of different polymers is that the commonly used thermoplastic polymers remain immiscible in the melt state, leading to phase separation and inferior mechanical properties for the mixed recycled fractions, when compared to virgin material (Emans, 2012; Ragaert et al., 2017). Therefore, mechanical recycling of SPW is only feasible for either single polymer streams or mixtures of polymers that can be effectively separated into the individual polymers. Single polymer streams can only realized by a separate collection for each polymer type on the post-consumer level, which is not yet the case in any of the EU27 countries. Some known pilot projects include the collection of PVC building materials and the re-grinding of clean PP crates (Emans, 2012). Well-defined mixtures currently being collected included PET-PP (bottles and their caps) and PP-PE, the so-called PO fraction from collected packaging materials. PP and PE can be separated from this blend through a gravimetrical method (OVAM et al., 2009).

Even though such recycled fractions are commercially available, European plastics converters (mostly SMEs) remain apprehensive to incorporate these materials in their production ('as is' or mixed with virgin materials). A lack of information regarding the purity of the secondary materials stream, the processing related properties and the quantification of (loss of) mechanical properties generally keeps them distrustful of the recycled PO. Therefore, it is our belief that by generating better and more specific

technological insights into the possibilities and limitations of working with recycled PO, polymer converting SMEs may come to incorporate recycled PO in their production, which in turn may lead to a reduction in export of SPW outside of the EU and in the longer term, consumer acceptance for recycled polymer products.

Within this research, we consider the mechanical recycling of polyolefin (PO) materials, more specifically blends of polypropylene (PP) and polyethylene (PE). Other recycled polymers which have been investigated elsewhere include HDPE/poly-(vinyl alcohol) PVA blends (Brandalise et al., 2009), polyethylene tereftalate (PET) (Incarnato et al., 2000), reinforced PET/PP blends (Ershad-Langroudi et al., 2008; Inoya et al., 2012), acrylonitrile butadiene styrene (ABS) (Scaffaro et al., 2012) and poly-(lactic acid) PLA/PET blends (La Mantia et al., 2012).

PO blends are commonly mixed into virgin materials at a certain percentage: they can either be used 'as are' (Bertin and Robin, 2002; Borovanska et al., 2012), or one of the composing fractions (PE or PP) may be separated for further use (Brachet et al., 2008; Navarro et al., 2012; Stangenberg et al., 2004). Recycled PP can also be mixed with virgin PP (Martins and De Paoli, 2001, 2002). These blends are generally not pure and contain a small fraction of contaminants (Borovanska et al., 2012; Brachet et al., 2008; Vilaplana and Karlsson, 2008), which are other plastics, solvent residues or one of different possible additives.

Quite often, rheological and mechanical properties are found to follow a simple law-of-mixtures, in which the change in property value is proportional to the amount of recycled polymer which has been added to the virgin material (Incarnato et al., 1999; Navarro et al., 2012; Stromberg and Karlsson, 2009). The molecular weight is generally found to decrease due to the mechanical recycling processing and thermal degradation (chain scission) (Incarnato et al., 1999; Jin et al., 2012; Stromberg and Karlsson, 2009). On the other hand, it has been found that the crystallization and melt temperature of PO do not change significantly with mechanical recycling (Achilias et al., 2008; Jin et al., 2012).

Current methods for the improvement of PO blend properties include the use of a compatibilizer to homogenize the composing fractions within the PO blends (Borovanska et al., 2012; Ragaert et al., 2017; Vilaplana and Karlsson, 2008), the use of elastomers (Râpă et al., 2017), the addition of stabilizers (Brachet et al., 2008) or reinforcing agents (Jonna and Lyons, 2005).

Within this study, commercially available post-consumer mixed PO streams were characterized in detail regarding their composition and properties. After separating the PE fraction from one of these blends via a float-sink method, different amounts of this recycled PE was blended with virgin PE and test parts were injection moulded with the resulting compounds. These were tested for various mechanical and physicochemical properties, thus quantifying the

impact of the blending on product properties. These properties were compared to theoretical values, predicted by the law-of-mixtures.

2. Materials and methods

2.1. Mixed polyolefin stream

The postconsumer mixed polyolefin (MPO) waste streams were kindly donated in the form of regrind by two Belgian recycling companies Hallurec NV and Ekol NV. They are mainly composed of polyethylene (PE) and polypropylene (PP).

The identification of the various polymers in the samples was determined by differential scanning calorimetry (DSC) using a Netzsch DSC 204F1. The samples were heated at 10°C/min above the melting temperature, under a nitrogen atmosphere. An indication of the rheological behaviour was determined by melt flow index (MFI) at a temperature of 230°C and a weight of 2.16 kg with a Zwick Plastometer 4100 (ISO 1133). An average of ten measurements was made. The content of volatile components was determined by heating the different samples to 75°C during 8 hours. Different other properties were also measured: ash content (ISO 3451-1), density (DIN 53479), moisture uptake (DIN 53495), VICAT VST temperature (ISO 306 – CEAST 6520) and the coefficient of friction (ASTM D1894 – Hanatek Advanced Friction Tester).

2.2. Mixtures of virgin and recycled polyolefin materials

The float-sink technique was used to separate the PE fraction from the other polymer fractions in the mixed PO streams. This technique is based on the difference in density between the PE and the PP content (OVAM et al., 2009). The PE fraction generally has a density greater than 920 kg/m³, while the PP fraction has one lower than 920 kg/m³ (White and Choi, 2004). The separation was done by manually pouring the postconsumer materials in a alcohol-water fluid with a controlled density of 920 kg/m³. The chosen solvent was isopropanol because of the lower volatility, cost and toxicity compared with other solvents. The apparent density was constantly monitored with a density meter. The disadvantage of this float-sink technique is that the density can differ with fillers and additives (Tall, 2000). Only the PE fraction at the bottom of the barrel was used because of the uncertain nature of the floating particles.

This separated PE (sPE) fraction was used to prepare different mixtures of recycled PE with a commercially available virgin PE to compare the mechanical properties of the recycled material to these of different mixtures. The selected virgin PE was Purell 2410T from Basell with a MFI of 36 g/10min (190°C and 2.16 kg). The influence of the different mix ratios on the injection process and the mechanical properties (identical to the mechanical tests on the MPO stream) was monitored. Mixtures with ratios of virgin material versus recycled material of 100:0, 50:50, 30:70 and 0:100 were made. The mixtures were fed 'as-is' in the injection machine without prior compounding. This method was purposefully chosen to approximate real-time conditions in Flemish SME's, which are often not in the ability to invest in expensive compounding equipment.

2.3. Injection moulding

The samples were made on an injection moulding machine BOY 22S Dipronic with a universal screw (L/D of 18 and a diameter of 22 mm) equipped with a standard mould with a tensile bar (ISO 527), flexural bar (ISO 178) and impact test specimen (ISO 180). The temperature from the hopper to nozzle was set at respectively 180, 200, 220, 220 and 220°C. More details about the injection moulding process can be found elsewhere (Delva et al., 2013).

2.4. Mechanical properties

The tensile properties (ISO 527) were measured on an Instron 3601 dynamometer, at a crosshead speed of 50 mm/min with a load cell of 2 kN. An Instron 5560 dynamometer was used to measure the flexural properties (ISO 178). Izod impact properties (ISO 180) were determined using a Zwick 5110-100/00 apparatus. More details about the mechanical characterization can be found elsewhere (Delva et al., 2013).

Statistical analysis of the results was performed with Minitab 15 through either a one-way ANOVA test, with p=0.05 significance level or an independent sample t-test, with the same p=0.05 significance level.

3. Results

3.1. Mixed polyolefin stream properties

The different physical properties of the MPO streams are presented in Table 1. No large differences between the two delivered mixed PO streams can be detected, which indicates that the two MPO streams have a similar composition.

Table 2 shows the mechanical properties of both MPO streams. Once more, no large differences between the values for the two mixed PO streams can be observed.

3.2. Properties of the different blends of virgin and recycled PE

The float-sink technique was used to separate the PE fraction from the other polymer fractions in the mixed PO streams. Fig. 1 shows the DSC curves of the MPO and two endothermic peaks can be distinguished at peak temperatures around 133 °C and 169 °C respectively. These peaks can be attributed to the melting of the PE and PP fractions in the samples. The PE fraction consists mainly of HDPE which has a slightly higher melting point then LDPE and MDPE

(Manivannan and Seehra, 1997). After the separation step, the PE peak dominates the DSC curve and the secondary PP peak is nearly entirely gone, indicating that the separation is to a large extent complete, but still some small percentage of PP remains in the PE fraction. Fig. 2 shows the tensile (a) and flexural (b) modulus of samples with different virgin/sPE ratios. Comparison of the tensile modulus result groups by one-way ANOVA reveals a significant difference in values of tensile modulus (p=0.000) between the five groups. With the addition of larger fraction of recycled sPE, a seemingly linear increase in elastic modulus from that of the virgin PE can be noticed. The same trend is recorded in the corresponding flexural modulus of the different mix ratios. Comparison of these result groups by one-way ANOVA reveals a similar significant difference in values of flexural modulus (p=0.000) between the five groups.

Table 1. Physical properties of the mixed polyolefin streams. Average values are listed as mean ± standard deviation

	MPO Hallurec	*MPO Ekol*
MFI [g/10min]	10.3 ± 0.3	7.7 ±1.1
Volatile components [%]	0.002	0.006
Ash content [%]	1.25	2.52
Density [kg/m³]	821	894
Coefficient of friction [-]		
- Static	0.45 ± 0.10	0.50 ±0.02
- Dynamic	0.31 ± 0.03	0.41 ±0.01
Moisture uptake [%]	0.13	0.12
VICAT temperature [°C]	123.3	114.6

Table 2. Mechanical properties of mixed polyolefin streams

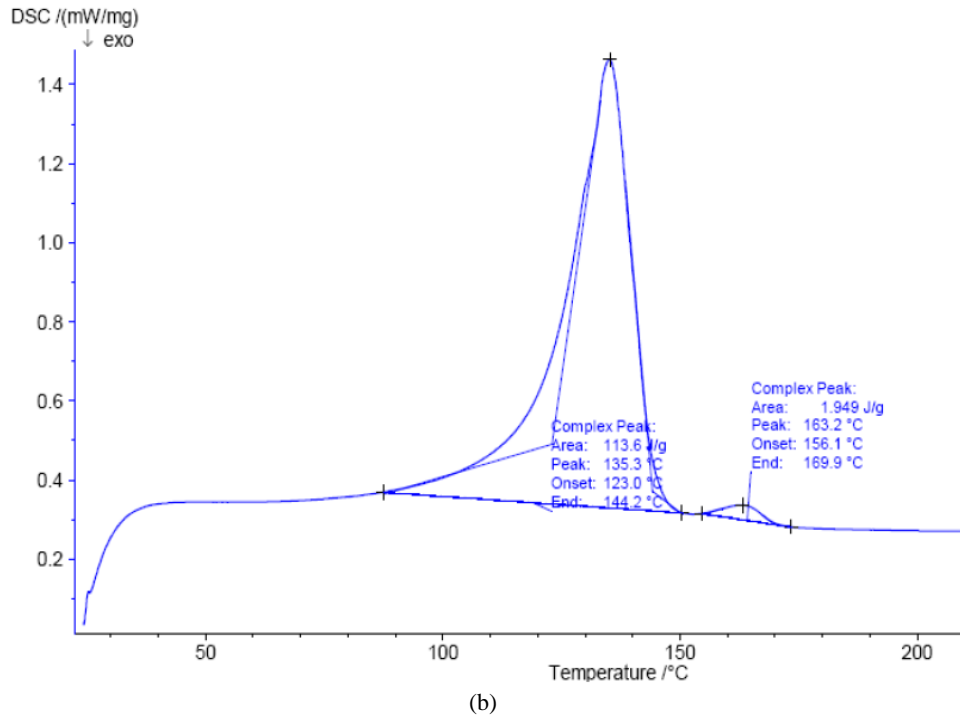|	*MPO Hallurec*	*Mean Variation[%]*	*MPO Ekol*	*Mean Variation[%]*
Tensile properties				
- Tensile strength [MPa]	17.5	3.5	15.4	5.9
- Tensile modulus [MPa]	291.7	9.6	300.8	9.7
- Strain at break [%]	21.4	12.6	15.6	15.3
Flexural properties				
- Flexural strength [MPa]	27.8	1.6	26.9	4.2
- Flexural modulus [MPa]	251.9	2.6	244.2	6.7
Izod impact strength [kJ/m²]	3.4	13.0	2.5	6.1

(a)

(b)
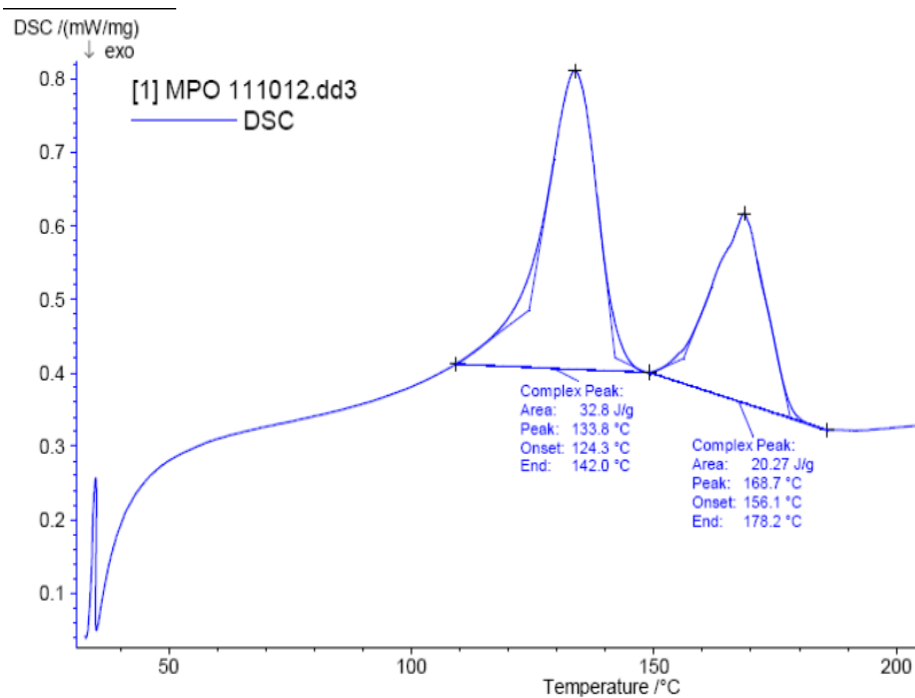
Fig. 1. DSC results before (a) and after (b) sink-float separation of the MPO
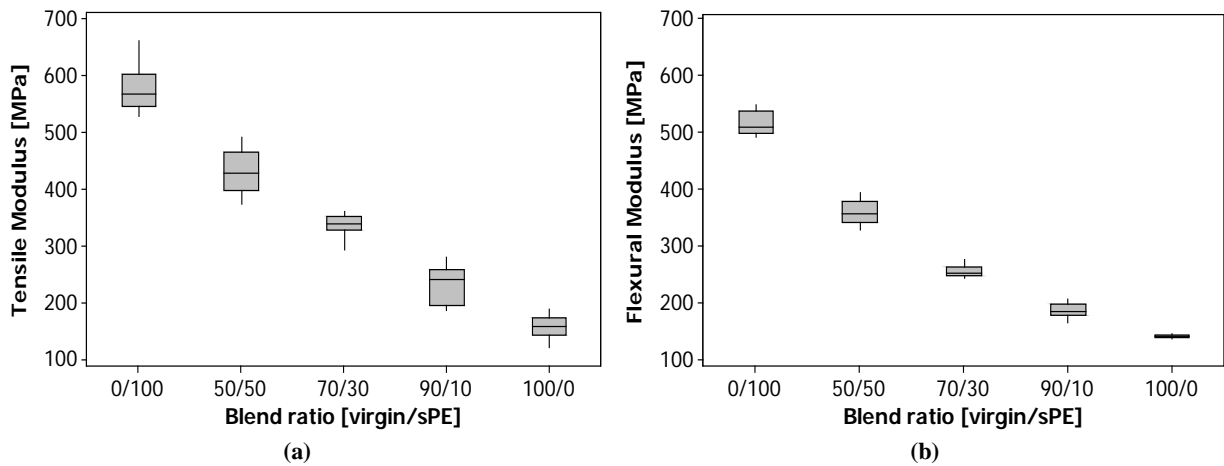

(a)

(b)

Fig. 2. Tensile (a) and flexural (b) modulus with different blend ratios virgin/sPE

The different MFI's and densities of the mixtures virgin/sPE are shown in Table 3. The sample with 100% sPE recycled fraction has a very low MFI of 0.12 g/10min, which increases with increasing incorporation of virgin material, which has a relatively high MFI of nearly 30 g/10min. The densities of the recyclates increase with higher amounts of sPE in the blends. Finally, Table 4 shows the impact strength of the different mixture ratios. The highest values are recorded for the 100% virgin and 100% sPE materials and the impact strength reduces with higher mixture ratios.

4. Discussions

The sPE fraction retrieved from the MPO was found to have a remarkably low MFI value, which would make it suitable mostly for extrusion-based processing. Quite likely, the acquired MPO consisted of reground extrusion-based product like foils or bottles. Due to this very viscous flow, the parts injected with 100% sPE were found to contain somewhat less material than those injected with the blends or virgin PE. The virgin PE used, on the other hand, was chosen specifically for injection moulding and had a quite high MFI, lending a better viscous flow to the blends and permitting a complete filling of the part under holding pressure.

Concerning the mechanical properties of the injection moulded parts, there is no significant difference between the flexural and tensile modulus for the 0/100 ($p = 0.001$), 50/50 ($p = 0.000$), 70/30 ($p = 0.000$) and 90/10 ($p = 0.001$) mixtures. A minor significant difference is noted for the virgin material ($p = 0.073$). This is attributed to the fact that the load is applied transversal to the main polymer chain

orientation. It is also noted that the sPE fraction has a significantly higher modulus than the virgin PE and that decrease of this value seems to follow the blending rate between the two polymer fractions.

Table 3. MFI and density values of the different blend ratios virgin/sPE

Blend ratio [virgin/sPE]	MFI [g/10min]	Density [kg/m³]
0/100	0.12 ± 0.02	942 ± 1
50/50	4.78 ± 0.47	933 ± 3
70/30	12.51 ± 0.94	927 ± 2
90/10	24.05 ± 3.52	925 ± 1
100/0	28.79 ± 4.30	922 ± 1

Table 4. Izod Impact Strength with different blend ratios virgin/sPE

Blend ratio [virgin/sPE]	Izod Impact [kJ/m²]
0/100	28.4 ± 2.5
50/50	4.4 ± 0.3
70/30	4.4 ± 0.5
90/10	24.5 ± 4.2
100/0	32.8 ± 2.3

The law of mixtures states that when two substances are mixed, the property of the mixture is a ratio of the properties of each substance, weighted by the proportion of each substance in the mixture. It is mainly used in fiber reinforced composite materials to predict properties at different fiber loadings (Gooch, 2010). This law is given in Eq. (1) with X the property and V the volume fraction of the different materials.

$$X = X_1 V_1 + X_2 V_2 \tag{1}$$

In order to verify whether the virgin/sPE blends follow the law-of-mixtures, the volume fractions of the materials are calculated with the measured densities of the recyclates and a comparison is made in Fig. 3 for the tensile modulus between the experimental results and the theoretical values provided by Eq. (1). It is found that the experimental values correlate very well to those dictated by the law-of-mixtures. The flexural modulus and density was found to follow the same trend.

Contrary, the results from the impact testing indicate that the unblended sPE and PE materials have the highest toughness values. A severe reduction of this toughness is noted for the 70/30 and 50/50 blends. This embrittlement is attributed to a phase separation of the composing polymers within the blends. The additional boundaries this induces within the part increase the resistance to plastic deformation and thus reduce the material's ability to absorb the energy from the impact. The effect is less pronounced for the lower blending ratio of 90/10, because the majority of the material matrix remains homogenous PE. This phenomenon is something to be taken into account when designing products for injection moulding with blends containing recycled PO.

As a closing thought, the authors would like to mention that a remaining aspect of recycling PO waste streams is the poor miscibility between the PE and the PP fraction (Sjöqvist and Boldizar, 2011).
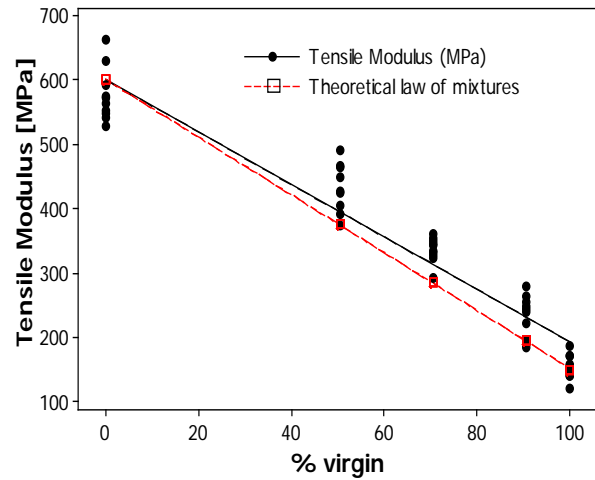

Fig. 3. Comparison between experimental values of the tensile modulus (•) and theoretical values ( ) derived from the law-of-mixtures

While this was circumvented in the current study by separating the PE from the MPO, it would mean a significant step for industry if this arduous extraction step could be removed and the recycled MPO could be successfully used 'as is'. Possible solutions include the addition of different compatibilizers such as creating a rubbery interphase while adding EPDM (Borovanska et al., 2012; Vilaplana and Karlsson, 2008), the possibilities of which remain the subject of further study.

5. Conclusions

Two commercially available recycled MPO streams have been mechanically characterized by tensile, flexural and impact measurements. Other important properties such as thermal and rheological properties were determined.

Overall, it was found that both recycled MPO streams were of comparable quality. From this MPO stream, the PE fraction was successfully separated and blended into virgin PE at different ratios. Furthermore, the mechanical and physical properties of the blends clearly followed the law-of-mixtures between the properties of the recycled sPE and virgin PE.

The impact strength however was strongly reduced in the presence of the second phase within the injection moulded part.

References

Achilias D.S., Antonakou E., Roupakias C., Megalokonomos P., Lappas A., (2008), Recycling techniques of polyolefins from plastic wastes, *Global Nest Journal*, **10**, 114-122.

Al-Salem S.M., Lettieri P., Baeyens J., (2009), Recycling and recovery routes of plastic solid waste (PSW): A review, *Waste Management*, **29**, 2625-2643.

Bertin S., Robin J.J., (2002), Study and characterization of virgin and recycled LDPE/PP blends, *European Polymer Journal*, **38**, 2255-2264.

Borovanska I., Dobreva T., Benavente R., Djoumaliisky, S., Kotzev G., (2012), Quality assessment of recycled and modified LDPE/PP blends, *Journal of Elastomers and Plastics*, **44**, 479-497.

Brachet P., Hoydal L.T., Hinrichsen E.L., Melum F., (2008), Modification of mechanical properties of recycled polypropylene from post-consumer containers, *Waste Management*, **28**, 2456-2464.

Brandalise R.N., Zeni M., Martins J.D.N., Forte M.M., (2009), Morphology, mechanical and dynamic mechanical properties of recycled high density polyethylene and poly(vinyl alcohol) blends, *Polymer Bulletin*, **62**, 33-43.

Cepi, Cirfs, Eurometaux, Eupr, Eurofer, Eupc, (2012), Recycling for a resource efficient EU economy, Position paper, On line at: http://www.cepi.org/system/files/public/documents/positionpapers/recycling/2012/2012_01_31JointPPrecyclingLongVersion-20120208-00005-01-E.pdf.

Comanita E.D., Hlihor R.M., Ghinea C., Gavrilescu M., (2016), Occurrence of plastic waste in the environment: ecological and health risks, *Environmental Engineering and Management Journal*, **15**, 675-685.

Delva L., Verberckmoes A., Cardon L., Ragaert K., (2013), *The Use of Rubber as a Compatibilizer for Injection Moulding of Recycled Post-consumer Mixed Polyolefines*, Proc. 2nd International Conference WASTES: Solutions, Treatments and Opportunities, 689-694.

Emans T., (2012), How to boost plastics recycling and increase resource efficiency?, Plastics Recyclers Europe.

Ershad-Langroudi A., Jafarzadeh-Dogouri F., Razavi-Nouri M., Oromiehie A., (2008), Mechanical and thermal properties of polypropylene/recycled polyethylene terephthalate/chopped rice husk composites, *Journal of Applied Polymer Science*, **110**, 1979-1985.

Gooch J.W., (2010), *Encyclopedic Dictionary of Polymers,* Springer, 520.

Incarnato L., Scarfato P., Acierno D., (1999), Rheological and mechanical properties of recycled polypropylene, *Polymer Engineering and Science*, **39**, 749-755.

Incarnato L., Scarfato P., Di Maio L., Acierno D., (2000), Structure and rheology of recycled PET modified by reactive extrusion, *Polymer*, **41**, 6825-6831.

Inoya H., Leong Y.W., Klinklai W., Takai Y., Hamada H., (2012), Compatibilization of recycled poly(ethylene terephthalate) and polypropylene blends: Effect of compatibilization on blend toughness, dispersion of minor phase, and thermal stability, *Journal of Applied Polymer Science*, **124**, 5260-5269.

Jin H.Y., Gonzalez-Gutierrez J., Oblak P., Zupancic B., Emri I., (2012), The effect of extensive mechanical recycling on the properties of low density polyethylene, *Polymer Degradation and Stability*, **97**, 2262-2272.

Jonna S., Lyons J., (2005), Processing and properties of cryogenically milled post-consumer mixed plastic waste, *Polymer Testing*, **24**, 428-434.

La Mantia F.P., Botta L., Morreale M., Scaffaro R., (2012), Effect of small amounts of poly(lactic acid) on the recycling of poly(ethylene terephthalate) bottles, *Polymer Degradation and Stability*, **97**, 21-24.

Manivannan A., Seehra M.S., (1997), Identification and quantification of polymers in waste plastics using differential scanning calorimetry, *Abstracts of Papers of the American Chemical Society*, **214**, 20-24.

Martins M.H., De Paoli M.-A., (2001), Polypropylene compounding with recycled material I. Statistical response surface analysis, *Polymer Degradation and Stability*, **71**, 293-298.

Martins M.H., De Paoli M.-A., (2002), Polypropylene compounding with post-consumer material: II. Reprocessing, *Polymer Degradation and Stability*, **78**, 491-495.

Navarro R., Lopez J., Parres F., Ferrandiz S., (2012), Process behavior of compatible polymer blends, *Journal of Applied Polymer Science*, **124**, 2485-2493.

Ovam, Soresma, Vkc, Federplast R.E., (2009), Inventarisation separation techniques hard polyolefines in polypropylene (PP) and polyethylene (PE).

Pilz H., Brandt B., Fehringer R., (2010), The impact of plastics on life cycle energy consumption and greenhouse gas emissions in Europe, Denkstatt report, On line at: http://www.plasticseurope.org/information-centre/publications-test.aspx.

PlasticsEurope, Eupc, Eupr, Epro, (2010), Plastics - the Facts 2010. An analysis of European plastics production, demand and recovery for 2009.

PlasticsEurope, Eupc, Eupr, Epro, (2011), Plastics - the Facts 2011. An analysis of European plastics production, demand and recovery for 2010.

Scaffaro R., Botta L., Di Benedetto G., (2012), Physical properties of virgin-recycled ABS blends: Effect of post-consumer content and of reprocessing cycles, *European Polymer Journal*, **48**, 637-648.

Schanssema A., (2011), Do plastics contribute to sustainability?, General Assemblee Fechiplast, Brussels.

Siddique R., Khatib J., Kaur I., (2008), Use of recycled plastic in concrete: A review, *Waste Management*, **28**, 1835-1852.

Sjöqvist M., Boldizar A., (2011), Molecular Modification and Compatibilization of Collected Polyethylene, *Journal of Polymers and the Environment*, **19**, 335-340.

Stangenberg F., Agren S., Karlsson S., (2004), Quality assessments of recycled plastics by spectroscopy and chromatography, *Chromatographia*, **59**, 101-106.

Stromberg E., Karlsson S., (2009), The Design of a Test Protocol to Model the Degradation of Polyolefins During Recycling and Service Life, *Journal of Applied Polymer Science*, **112**, 1835-1844.

Tall S., (2000), *Recycling of Mixed Plastic Waste: Is Separation Worthwhile?*, PhD thesis, Tekniska högskolan i Stockholm, Stockholm, Sweden.

Ragaert K., Delva L., Van Geem K., (2017a) Mechanical and chemical recycling of solid plastic waste, *Waste Management*, **69**, 24-58.

Ragaert K., Hubo S., Delva L., Veelaert L., Du Bois E., (2017b), Upcycling of contaminated post-industrial polypropylene waste: A design from recycling case study, *Polymer Engineering & Science*, DOI: 10.1002/pen.24764.

Râpă M., Matei E., Ghioca P.N., Grosu E., Iancu L., Spurcaciu B., Trifoi A.R., Gherman T., Pica A., Predescu A.M., Cincu C., András A.A., (2017), Improvement of some post-consumer polypropylene (rPP) by melt modification with styrene-diene block copolymers, *Environmental Engineering and Management Journal*, **16**, 2615-2624.

Vilaplana F., Karlsson S., (2008), Quality concepts for the improved use of recycled polymeric materials: A review, *Macromolecular Materials and Engineering*, **293**, 274-297.

White J.L., Choi D., (2004), *Polyolefins: Processing, Structure Development & Properties*, Hanser Gardner Publications, Cincinnati, 271.