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Article

Effect of Mis-Sorting on the Mechanical Properties of Recycled Polypropylene

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Abstract: The effect of contamination of polypropylene (PP) with selected polymers is studied to simulate the effect of mis-sorting in recycling streams. Polystyrene (PS), polyethylene terephthalate (PET), polycarbonate (PC), acrylonitrile-butadiene-styrene (ABS) and polylactic acid (PLA) were compounded with PP at different concentrations varying between 3 and 10%. Infrared spectroscopy proved the absence of chemical bonds between the constituents. The samples for mechanical testing were injection moulded and further tested for their tensile and impact properties. Critical behaviour was induced by the introduction of a weld line as a result of the application of multiple gating points during injection moulding. Results generally show the applicability of PP mixtures within the investigated range of inclusions, without much sacrifice in mechanical performance. However, in the case of ABS and PLA, more care should be taken when designing complex parts with weld lines, due to reduced toughness.

Keywords: recycling; polypropylene; mis-sorting; strength; stiffness; toughness

1. Introduction

Polymers, especially thermoplastics, play a vital role in modern times. They are extremely versatile in their use, such as packaging (39%), building and construction (23%), transportation (8%), electrical appliances and electronics (6%) and houseware (4%) [1,2]. Household plastics are made up of 15.4% polypropylene (PP), 13.4% low-density polyethylene (PE-LD), 9.1% polyvinyl chloride (PVC), 8.7% high-density polyethylene (PE-HD), 5.4% polystyrene (PS) and 5% polyethylene terephthalate (PET), in addition to other thermoplastics and thermosets [2]. When it comes to packaging, plastics should ideally not only provide the necessary protection for the product but also be easily recyclable, imposing a minimum impact on the environment [3]. Although metals and glass are possible alternatives to plastics, their higher density has a devastating impact on the carbon footprint during transportation [4] and during recycling, due to their relatively high melting temperatures.

In recent years, the use of biopolymers has increased. Bioplastics are defined as biodegradable and / or derived from renewable resources and microbial metabolisms [5]. In 2022, global production of biopolymers reached 1.8 million metric tons [6], which represented 1% of the total European plastic production [2]. Bioplastics are more expensive and often have inferior mechanical properties compared to their fossil-based counterparts. However, they are especially favourable for packaging [3] due to their positive environmental impact [7]. Until now, there has been no separate recycling stream for biopolymers such as polylactic acid (PLA) [8].

Although we have come so far in recycling plastics, it is estimated that in Europe, only 18.5% of the European production is mechanically recycled [2], while the rest is incinerated or landfilled. In Germany, in 2021, 31.6% of total plastic waste was mechanically recycled while 58.3% was thermally recycled [9]. However, this does not even come close to the European circular economy target, pursuing the recycling of 50% of plastic waste by 2025 and 70% by 2030 [10,11].

Generally, plastics recycling follows one of three main approaches: mechanical recycling (subdivided into primary and secondary recycling), chemical recycling, and thermal recycling (also termed as incineration). Mechanical recycling involves collecting, sorting, shredding, washing, drying, re-extrusion, and pelletising the plastic. The primary approach is mainly related to the recycling of uncontaminated waste of known history, such as post-industrial wastes. In this case, re-granulated and reprocessed plastics [5] render properties comparable to those of virgin material. Secondary recycling usually involves plastic streams of mixed types and colours of unknown history. Here, extensive sorting of the waste stream is needed to separate plastics according to their type [12]. Due to sorting errors, recycled plastic is usually of lower quality compared to the original one. Furthermore, the thermal and mechanical stresses applied to plastics during mechanical recycling inevitably lead to material degradation [13,14], and therefore inferior qualities than the virgin counterparts.

Chemical recycling is often the best option for highly diverse, contaminated, or deteriorated streams [15]. During pyrolysis, the hydrocarbon chains are broken and the pure monomers or oils are recovered. These can be reused for the synthesis of new polymers, such as in the case of PVC [16], while having a lower emission and carbon footprint than incineration [17] in addition to preventing water and soil pollution in the case of landfilling [13]. Chemical recycling is expected to gain more importance in the future [4]. Finally, incineration is relatively far down in the waste hierarchy and is therefore highly controversial. The process involves burning off plastic waste and the recovery of energy [18].

Successful recycling of plastic waste requires an efficient sorting step ahead [19]. Macro-sorting is done on whole or nearly whole objects, based on colour and material type, using optical and near-infrared sensors. The waste is then chopped into smaller flakes and further separated by size, density, or electrostatic charging. For polymers with a large density difference, Dodbiba et al. [20] recommended the use of air tabbing, i.e., shaking the plastic flakes on a table with an inclined plane while jetting air. Light plastics are easily affected by air streams and thus move upwards, while heavier ones move downwards due to gravity. If the density difference allows for sink-float separation, then this process can be used, as it renders high recovery rates [21]. In case of small density differences, a tribo-electrostatic separation should be used.

Despite technological advances, the accuracy of plastic wastes is often limited to around 95% [12]. Separation of black or multilayer objects is still not possible; novel materials such as biopolymers are not yet accounted for. Moreover, the influence of foreign polymers on the properties of recycled material is not yet clear. Having 3% PLA in PET results in PLA agglomeration, whereas 5% PLA causes PET to stick to the walls of the mould during injection moulding [8]. In addition, the presence of 0.17% PLA causes transparent PET to become opaque [22,23]. On the other hand, Wojnowska-Baryła et al. [8] claimed that 10% of PLA does not have any significant effect on the mechanical properties of PS. Also, in [24], it was concluded that acrylonitrile-butadiene-styrene (ABS) can be easily dispersed in polycarbonate (PC) without a compatibilizer. Ruj et al. [25] concluded that up to 15% PVC in other polymers are not critical for low-grade products, while Serranti et al. [21] suggested that the purity of recycled material should be higher than 97% to be used in high-quality products. When reinforced polymers (e.g., with glass fibres) are processed with the same type of polymer, an increase in mechanical properties can be observed [40]. Low-grade recycling materials are often used in flooring tiles [26], Gypsum boards to improve water absorption and swelling [27] or landscaping [20], concrete and asphalt [5], as well as in urban furniture. To improve the performance of recycled polymers, they are often mixed with virgin material [28].

In this study, the effect of contamination of PP with some selected polymers as a result of mis-sorting on the mechanical behaviour is studied. PS and PET were selected based on their common use in packaging material and their frequent presence in the waste stream. ABS and PC were chosen as representatives for engineering polymers that are often incorrectly disposed in the packaging waste stream. PLA, one of the most commonly used biopolymers, is expected to find increased application within the next couple of years and is not yet accounted for neither during sorting nor as a contaminant in other polymer streams.

2. Materials and Methods

2. Materials and Methods

The influence of PS, PET, ABS, PC and PLA as a foreign polymer (FP) within PP (further referred to as the parent material PM) was investigated to assess the effect of mis-sorting during waste treatment on the quality and behaviour of recycled PP. For this purpose, different concentrations of FP ranging from 3% to 10% were compounded with PP, pelletised and further injection moulded. The samples were tested for mechanical behaviour.

2.1. Materials

Post-industrial PP, PS, PET, ABS, and PC were provided by Friedel Kunststoff Recycling GmbH in Böhmenkirch, Germany. PLA used in this study was obtained from yoghurt cup cut-outs.

Material mixtures. Different material mixtures were prepared by adding selected polymers (PS, PET, ABS, PC, PLA) to the parent material (PP) at different gravimetric concentrations of 3%,5%,7%, and 10%.

2.2. Sample Preparation

Samples of each mixture were prepared by compounding and injection moulding. Furthermore, the parent material was prepared at different temperatures corresponding to the processing temperature of the associated mix for reference purposes (see Table 1). Further samples were prepared from the pure SPs.

Table 1. material extrusion parameters.

		Polymer blends					Pure polymers				
		ABS	PS	PET	PLA	PC	ABS	PS	PET	PLA	PC
Temperature [°C]	Zone 1	160	160	170	130	195	160	160	200	130	210
	Zone 2	210	210	220	180	245	210	210	250	180	260
	Zone 3	220	220	230	190	255	220	220	260	190	270
	Zone 4	225	225	235	195	260	225	225	265	195	275
	Zone 5	230	230	240	200	265	230	230	270	200	280
	Zone 6	230	230	240	200	265	230	230	270	200	280
	Zone 7	240	240	250	210	275	240	240	280	210	290
	Zone 8	240	240	250	210	275	240	240	280	210	290
	Zone 9	245	245	255	215	280	245	245	285	215	295
Die zone		240	240	250	210	275	240	240	280	210	290
Screw speed						147 rpm					
Throughput						10 kg/h					

Material drying. Prior to extrusion, each polymer was dried in a Bierther DR 204 MT hot air dryer, with a dew point of -50 °C. ABS and PS were dried for 2 h at 80 °C, while PET and PC were dried for 5 h at 130 °C and 120 °C, respectively. PLA was dried overnight for at least 12 h at 50 °C.

Compounding. Material compounding was carried out on a Leistritz LSM 3034 twin screw co-rotating extrusion machine, equipped with nine heating zones in addition to a separate heating zone for the die. The screws have a diameter of 34 mm with a length-to-diameter ratio of 30. Gravimetric dosing of the parent material and the supplement material was achieved using an MDS-Balance twin-feeder from Movacolor. Each feeder is equipped with a load cell that monitors the change in hopper mass over time and controls the screw speed of the feeder to ensure constant material feed and homogeneous mixture. The mixture was extruded into filaments of 2-3 mm in diameter. Filaments were cooled in a 1.5 m water bath, dried and pelletised. The pull speed of the pelletiser was kept constant for each mixture, but had to be adjusted for each supplement to ensure adequate cooling, as fast speeds tend to shorten the polymer residence time in the cooling bath; insufficient cooling causes sticking problems within the pelletiser. The screw speed was kept constant at 147 rpm, and the throughput was set at 10 kg/h.

The temperature profile for compounding was selected as the minimum possible temperature that allows full melting of the foreign polymer, as detailed in Table 1. For all blends, the lie zone was set to be 5 °C cooler than the last extrusion heating zone. Pure supplement materials, except for PC, was processed at the same profile as that of its associated mixtures. PC was processed at an increased temperature of 295 °C, since processing its mixtures at lower temperatures caused elevated torques on the machine.

Injection moulding. Before further processing, all mixtures were dried at 80 °C for 2 h. The test specimens were produced using a Demag 420/430 injection moulding machine, equipped with a single screw with three heating zones, in addition to a nozzle heater. Table 2 lists the injection moulding parameters for each case under consideration. The screw speed was set for all cases at 200 rpm.

Table 2. Injection moulding parameters.

		Polymer Blends						Pure Polymers				
Temperature [°C]		ABS	PS	PET	PLA	PC	PP	ABS	PS	PET	PLA	PC
	Zone 1	195	195	195	195	195	195	195	195	250	170	270
	Zone 2	205	205	205	205	205	205	205	205	265	180	285
	Zone 3	210	210	210	210	210	210	210	210	270	185	290
	Nozzle	220	220	220	220	220	220	220	220	290	195	300
	Mould	40	40	40	40	40	40	40	40	85	30	85
	Drying	80	80	80	80	80	80	80	80	130	50	120
Drying time [h]		2	2	2	2	2	2	2	2	2	16	5
Screw speed [mm/s]		200										
Injection pressure [bar]		▪ tensile specimens without weld line: 500										
		▪ tensile specimens with weld line: 480										
		▪ specimens for Charpy-impact testing: 325										
Holding pressure [bar]		▪ tensile specimens without weld line: 300										
		▪ tensile specimens with weld line: 300										
		▪ specimens for impact testing: 210										
Holding time [s]		▪ tensile specimens without weld line: 12										
		▪ tensile specimens with weld line: 12										
		▪ specimens for impact testing: 10										
Cooling time [s]		15										

Tensile specimens, according to DIN EN ISO 527-2, standard type 1A (10 mm width, 4 mm thickness) were injection moulded using a single film-type gate, with a longitudinal fill along the axis of the sample. Furthermore, a tensile sample (10 mm width, 3 mm thickness) with a weld line, in addition to tensile impact samples with and without weld line were produced. The weld line in the specimen’s cross-sectional area was obtained using a two-gate system at both ends of the cavity. The weld line forms a weak line in the middle of the sample and intensifies the contamination effect within the material. In addition, notched Charpy impact test specimens were injection moulded.

The mould was tempered at 40 °C for all cases, except for pure PLA, PC and PET, where the mould temperature was set according to the values given in Table 2. For each start of the machine or mould change, the mould was left to temper for at least 15 min; samples resulting from the first five injection moulding cycles were discarded to ensure equivalent conditions for all samples. For each material change, at least 300 cm³ of material was purged before injection moulding, to avoid cross-contamination.

Material testing

The influence of various foreign polymers on PP was quantified through the mechanical and rheological properties of the material. The tensile modulus (E), yield strength (σ_y), elongation at break (ϵ_b), the impact strength (notched Charpy and tensile impact), as well as the melt volume-flow rate (MVR) were tested.

Tensile Test. Tensile testing of samples with and without weld line was carried out using a Shimadzu Autograph AG-X plus universal testing machine, equipped with a 10 kN load cell and an optical extensometer (TRViewX). Tensile tests were performed according to DIN EN ISO 527-2 using tensile specimens with dimensions according to type 1A. A 20 N preload was applied to the specimen at the beginning of the test, followed by continuous loading at a crosshead speed of 1 mm/min up to 0.27% strain, to accurately determine the modulus of elasticity. After that, the test speed was increased to 50 mm/min up to failure. For all materials under consideration, at least 12 specimens were tested.

Impact Test. The impact strength of the materials under investigation in the tensile and bending modes according to DIN EN ISO 8256 and DIN EN ISO 179-1, respectively, was determined for specimens with and without the weld line.

Tensile impact testing was conducted on a Zwick-Roell mechanical impact tester equipped with a 7.5 J hammer for all materials, except for the pure polymer samples without a weld line as well as the PC specimens with weld line; these required 50 J and 15 J hammers, respectively. In all cases, a traverse of a mass of 60.976 g was used. The energy at break E_c was calculated according to the modified equations (1)-(3) as per the standard, where E_s is the measured absorbed impact energy, E_q is the remaining energy in the pendulum after impact according to Eq. (2), m_{cr} is the mass of the traverse in kg, and m_p is the pendulum mass in kg. The Charpy impact test of the single-notched specimens was performed with a 1 J hammer. The results of at least 12 specimens were considered.

$$E_c = E_s - E_q \quad (1)$$

$$E_q = \frac{E_{max} \times \mu \times (3 + \mu)}{2 \times (1 + \mu)} \quad (2)$$

$$\mu = \frac{m_{cr}}{m_p} \quad (3)$$

Fourier-Transformation Infrared Spectroscopy. The IR spectra for all mixtures and pure materials under consideration were measured using the Shimadzu IRTracer-100 in the MIR range, using an ATR equipped with a diamond PUCK in the reflectance mode. The measurements were performed using a resolution of 4 cm⁻¹, conducting 128 scans per spectrum to guarantee a high-resolution spectrum.

Melt volume-flow rate. Injection moulded specimens were shredded to obtain small flakes of the different material blends under consideration. A Thermo HAAKE Meltfixer 2000 tester was used to measure the melt volume-flow rate (MVR) according to DIN EN ISO 1133-1 using the recommended test temperature (230°C) and weight (2.16kg) for PP. The melt flow rate generally represents the speed of extrusion of a polymer under defined temperature, through a defined die and under defined constant pressure. The tester chamber was thoroughly cleaned at the beginning of each measurement. Shredded material of 6±0.05 g weight was introduced within 60 s into the chamber. After an initial compaction, achieved by a piston movement of 10 mm the material was heated for 5 min. Then the load was applied and the free fall piston travel per time was measured and further converted into extruded volume per time. Ten Measurements were taken at 30 s interval. For each blend concentration, a total of three specimen would be tested.

3. Results

3.1. Effect of Foreign Polymer Inclusion on the Tensile Behaviour of PP

Figure 1 shows the effect of adding ABS, PC, PET, PLA, and PS on the tensile properties of the parent PP material. Generally, it can be seen that apart from PET, the material stiffness remains largely unaffected by the addition of any foreign polymer. For example, for the 10% PP/PC mix, the modulus of elasticity increased by 9.7% compared to pure PP, while the addition of 10% PET to the PP stream resulted in an increase of 41.2% in the tensile modulus. Similarly, the supplements did not cause any significant change in the tensile strength of PP, even at a concentration of 10%. However, the introduction of foreign polymers into the PP stream had an adverse impact on the elongation at break, especially at higher concentrations of 10%. A maximum reduction of 46.8% was observed in case of a blend with 10% PET. It is also worth noting that the inclusion of up to 7% PS was found to increase the elongation at break by 25.3%, as well as the associated scattering.

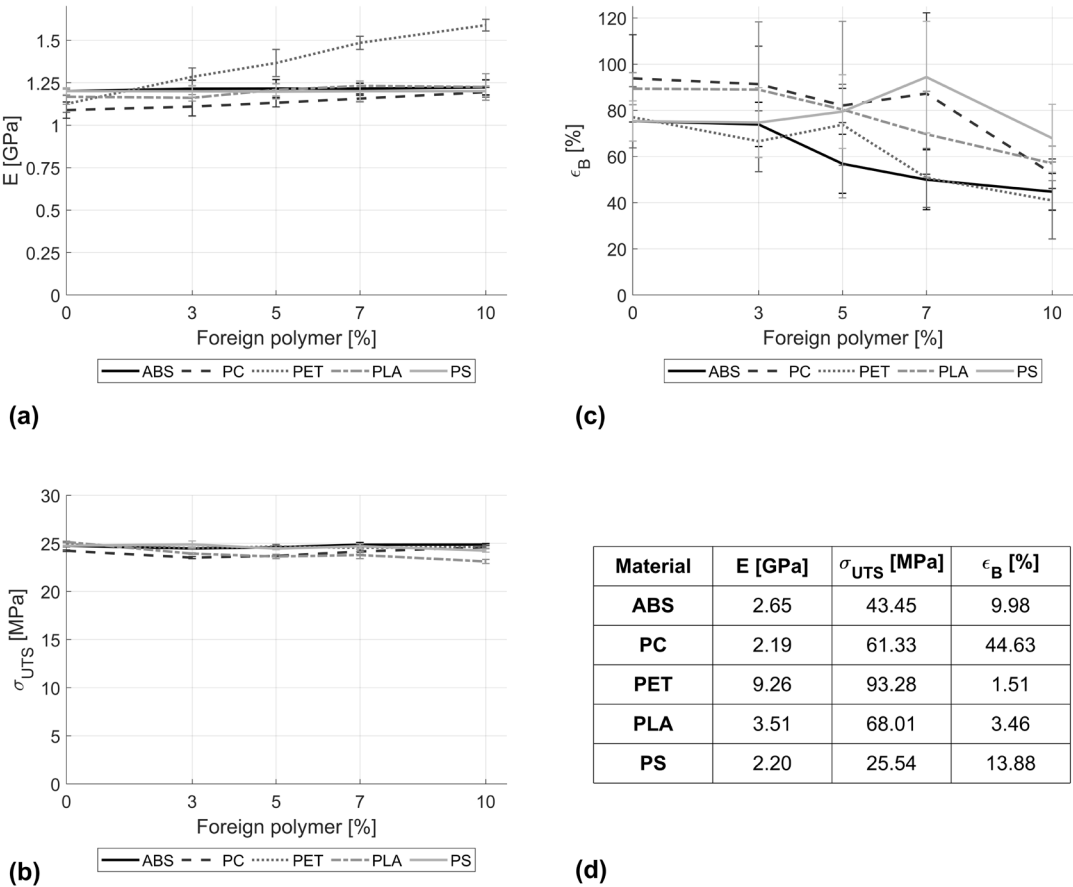


Figure 1. Effect of adding ABS, PC, PET, PLA, and PS on the (a) stiffness, (b) ultimate tensile strength, (c) elongation at break of PP stream in the absence of a weld line. (d) reference values of pure supplement polymers.

Figure 2 shows the effect of the polymer inclusions on the tensile modulus, strength, and elongation at break of PP when a weld line is present in the specimen. It can be seen that supplements of up to 10% barely influence the stiffness of PP. This can be related to the fact that the tensile modulus is measured within the elastic region, where the weld line does not yet have an influence. However, in case of the PET as an inclusion within PP, an increase of 34.5% in the tensile modulus of PP was observed.

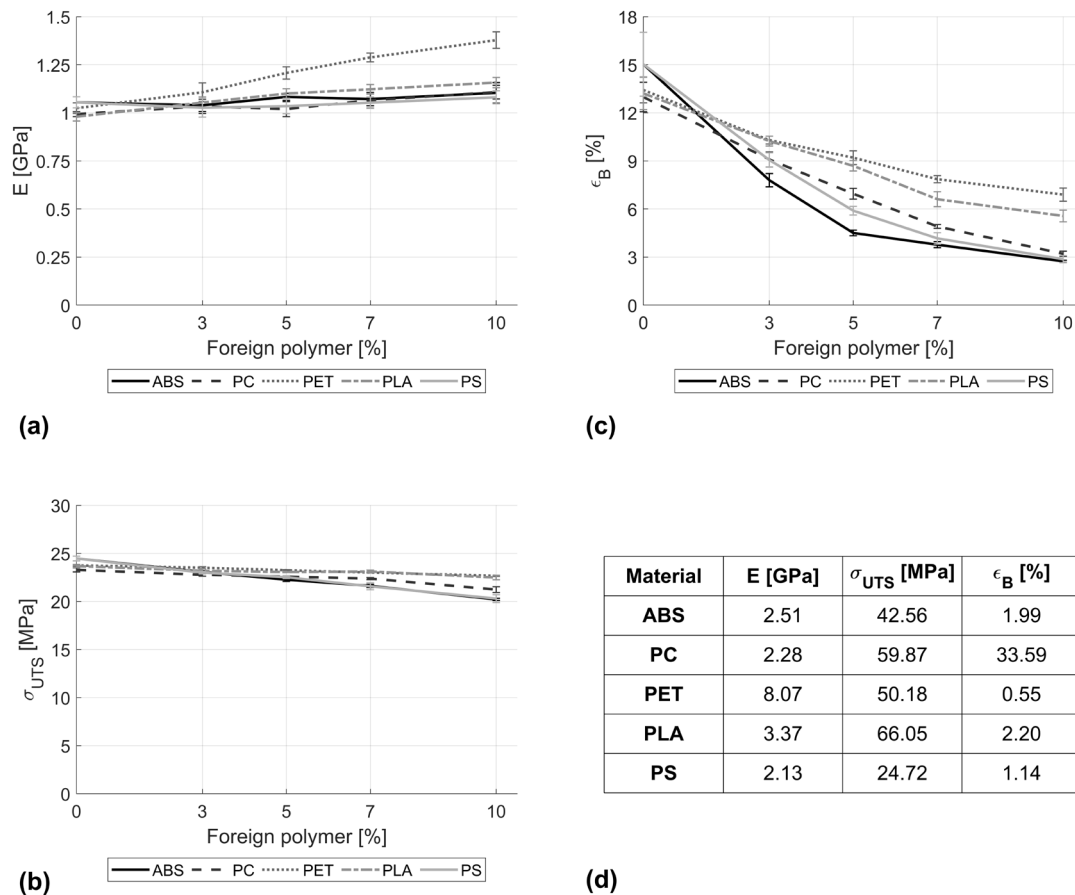


Figure 2. Effect of adding ABS, PC, PET, PLA, and PS on the (a) stiffness, (b) ultimate tensile strength, (c) break elongation of PP stream in the presence of a weld line. (d) reference values of pure supplement polymers.

In contrast, the tensile strength was found to suffer from the presence of foreign polymers within the PP. The inclusion of 10% ABS or PS resulted in a 17.5% reduction in strength. In the case of PP mixtures with PET or PLA, only minor changes ($< 5\%$) in tensile strength could be observed. The elongation at break was largely affected by foreign inclusions, even at minor concentrations of 3%. The elongation at break was found to decrease with increasing amounts of foreign polymer within the parent material. At 10% ABS a loss of more than 80% in the elongation at break with respect to the pure PP could be detected.

On the basis of the aforementioned results, it becomes evident that the presence of a weld line emphasizes the effect of foreign polymers within PP. In this work, weld lines were intentionally formed during injection moulding, creating two separate melt streams that meet at the centre of the mould cavity. Due to the fact that these streams take different paths, temperature differences are more likely to occur between the two, leading to stress concentrations [29–31], discontinuity in macromolecular entanglement [31], and discontinuous macromolecular orientation parallel to the weld line [32]. In all cases, the samples under investigation failed due to this artificially induced defect, leading to a loss of mechanical properties. In specimens without the weld line, material failure would occur at the weakest point of statistically distributed molecular defects. In the presence of foreign polymer, these often act as inclusions and are related to higher stress concentrations, and thus form sites for failure initiation. This effect can be seen for concentrations higher than 5%.

3.2. Effect of Foreign Polymer Inclusion on the Impact Behaviour of PP

Figure 3a and Figure 3b show the impact test results carried out on samples without a weld line in tensile and bending modes. Regardless of the test type, the inclusion of foreign polymers resulted in a clear reduction in the impact strength of PP. This deterioration increases with increasing concentration of the foreign polymer. However, the trend is not the same for all supplement polymers under consideration. As depicted in Figure 3b, the Charpy impact strength of PP mixed with up to 7% PS remains unaffected, in contrast to the impact strength of pure PP. It is first at 10% PS within the mix that the general trend towards a reduced impact strength can be observed. In the case of PLA, a slight insignificant increase in impact strength could even be observed at a concentration of 3% with respect to pure PP.

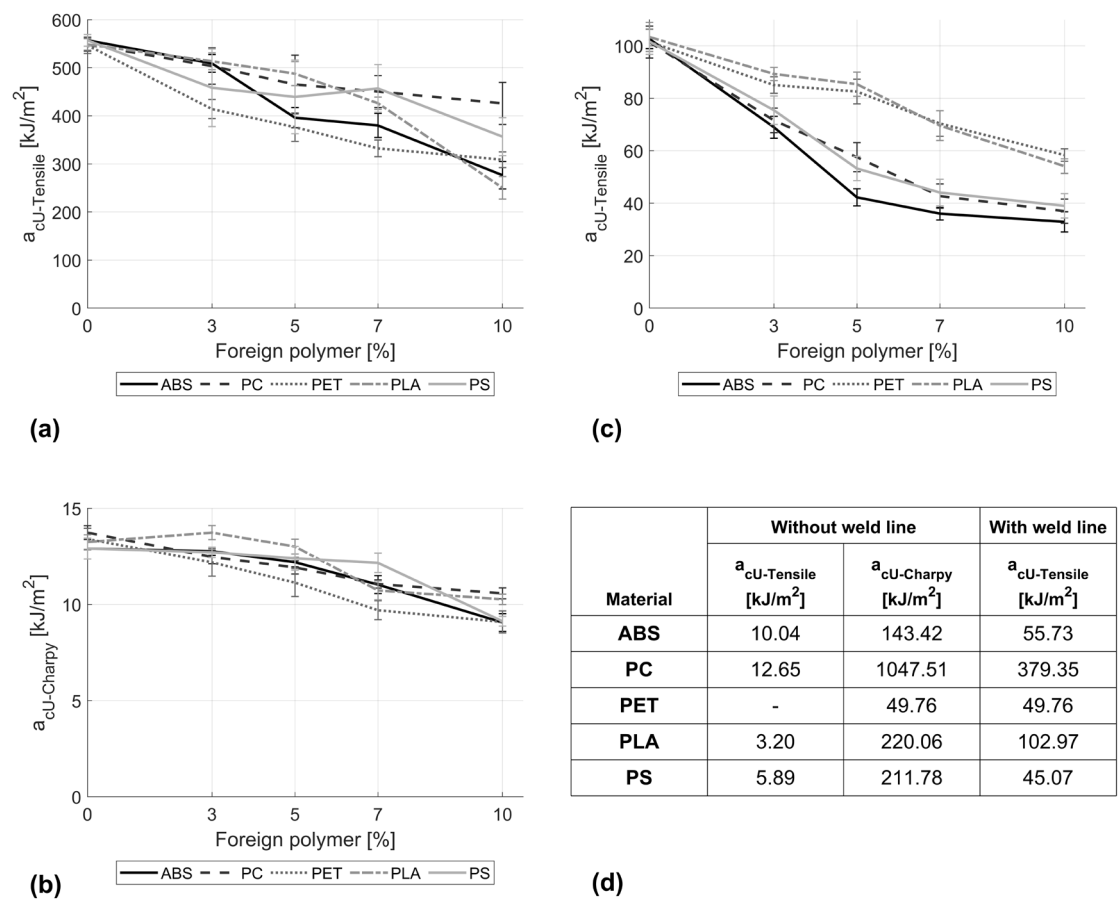


Figure 3. Effect of adding ABS, PC, PET, PLA, and PS on the (a) bending (Charpy), (b) tensile impact strength of PP in the absence of a weld line, and (d) reference values of pure SP materials.

A similar trend was observed in the case of the tensile impact test (Figure 3a), although the results were an order of magnitude higher than those obtained in the bending mode. This can mainly be related to the sample configuration and the type of load. In case of the Charpy impact test, the bending load causes tensile stresses at the notch area, resulting in crack initiation and further propagation at low energy absorption levels across the cross section of the sample. However, impact tension induces tensile stresses throughout the cross section of the sample, requiring higher energy up to failure. It should be noted that it was not possible to test the tensile impact of pure PET specimens, as these tended to slip out of grips; an increase in clamping force inevitably led to material crushing.

Figure 3c shows the effect of foreign polymers on the tensile impact strength of PP in the presence of a weld line. Similar to the aforementioned observation in the case of samples without a weld line (Figure 3b), the tensile impact strength of PP was significantly reduced even at low concentrations of 3% of the SP. An increase in the percentage of SPs within PP leads to a continuous

reduction in the tensile impact strength. At concentrations of 10% ABS, PS, or PC, PP was found to retain only around 40% of its impact strength. In contrast, PET and PLA inclusions appeared to have lower impacts, on average retaining 55% of the initial impact tensile strength.

3.3. Effect of Foreign Polymer on the Melt Volume-Flow Rate of PP

Figure 4a depicts the average measurements carried out for the case of pure PP. Results indicate insignificant changes in MVR over time at small standard deviation. In contrast, a PP blend including 10% PLA (usually processed at temperatures lower than 230 °C) rapidly degrades, leading to an increase in MVR from 11.3 cm³/10min to 14.3 cm³/10min within 10 min, as per Figure 4b. To ensure the comparability of measurements, the average MVR was calculated for all blends under consideration using the first three measurements.

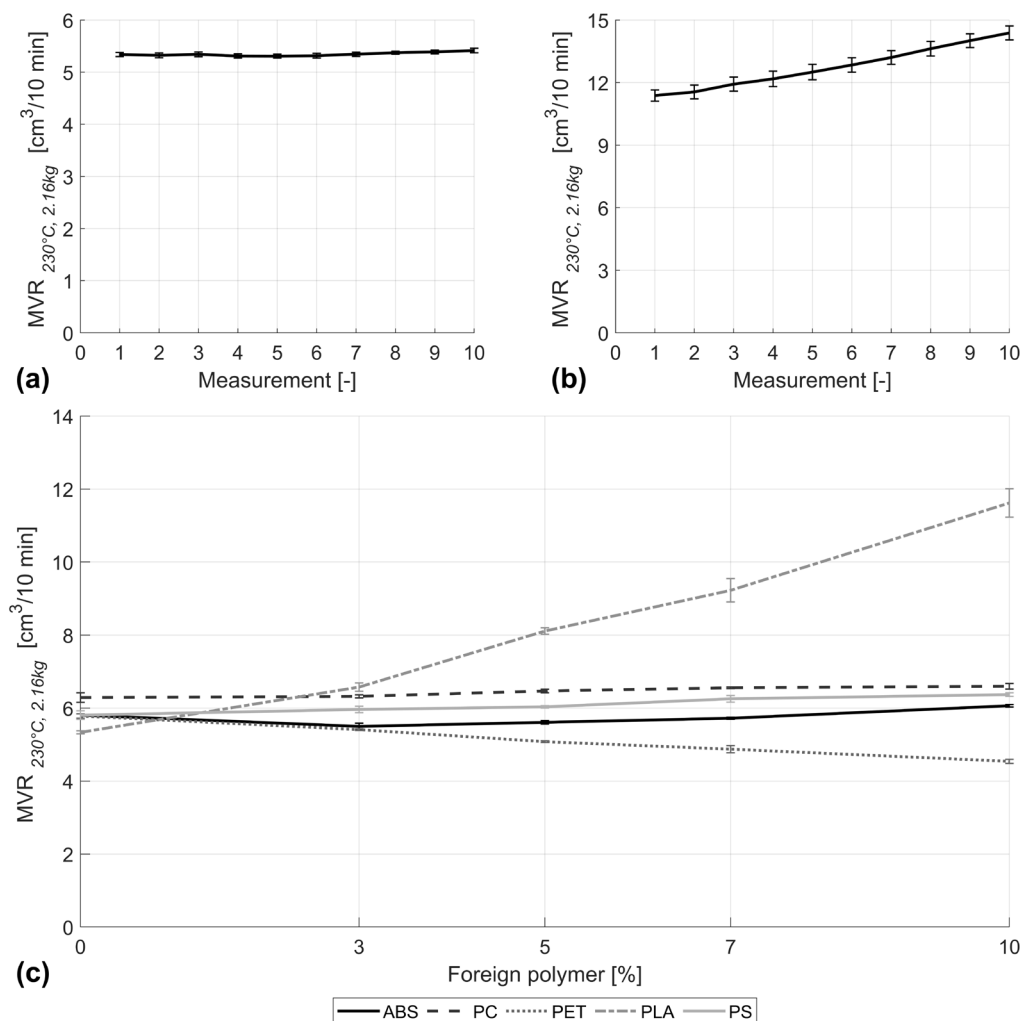


Figure 4. Melt volume-flow rate for (a) pure PP processed at same conditions as for the PP/PLA blend, (b) PP with 10% PLA, and (c) PP and its blends.

Based on that, Figure 4c shows the change in MVR of PP for all blends under consideration. Among all the contaminating materials, PLA seems to have the major influence on the MVR, causing a significant increase of 118% at a loading percent of 10. In contrast, PC, PS, and ABS showed minor increase in the MVR at 10%, averaging 3.5%, 8.6%, and 4.5%, respectively. However, it should be noted that for 3% ABS in PP, the MVR of PP seemed to decrease initially before increasing once more with further increase in the ABS content. PET follows a completely different trend, where the 22% reduction in MVR at 10% PET content relates to an increased viscosity.

3.4. Effect of Foreign Polymer Inclusion on the IR-Spectrum of PP

Error! Reference source not found.a shows the results of the FTIR scan of the PP and its mixtures with ABS. The distinctive peaks of PP, evidence the symmetric and asymmetric stretching of the CH₃ group at 2868 cm⁻¹ and 2950 cm⁻¹, respectively, as well as those of the CH₂ group at 2838 cm⁻¹, and 2916 cm⁻¹, respectively. The CH₃ vibration in umbrella mode at 1375 cm⁻¹ and that of the symmetric in-plane vibration of the C-H(CH₃) group at 1455 cm⁻¹ were also easily identified in the pure PP spectrum and are in line with literature findings [33,34].

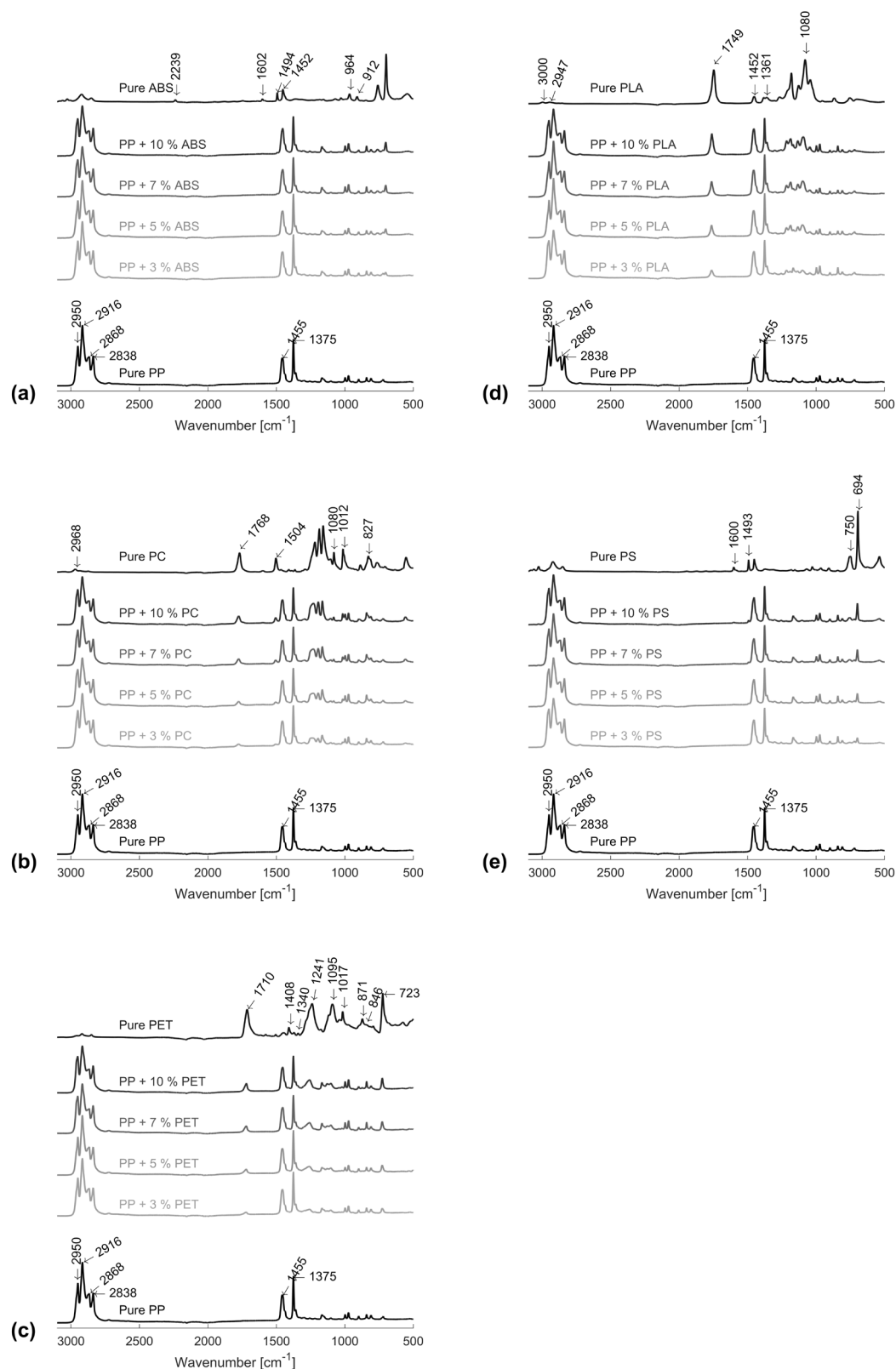


Figure 5. FTIR spectrum of PP, ABS, and their blends at different ABS concentrations.

The IR spectrum of pure ABS under consideration shows the characteristic absorbance peaks of the acrylonitrile $\text{C}\equiv\text{N}$ bond at 2239 cm^{-1} and the styrene's aromatic ring vibration at 1602 cm^{-1} and 1494 cm^{-1} , the scissoring of the CH_2 group at 1452 cm^{-1} , and the C-H deformation of the hydrogen atoms found in the alkenic carbon in the butadiene phase at 964 cm^{-1} and 912 cm^{-1} , all being in

accordance with literature [35,36]. The mixture of PP and ABS evidences the existence of the distinctive peaks of both polymers.

The spectra of PC and its blends with PP are illustrated in **Error! Reference source not found.b**. The characteristic PC vibration peaks of PC, including the asymmetric stretching of the C-H group at 2968 cm⁻¹, the C=O stretching at 1768 cm⁻¹, the C-C stretching at 1504 cm⁻¹, the C-C-C bending at 1080 cm⁻¹, the O-C-O simultaneous stretching at 1012 cm⁻¹, and the C-H deformation at 827 cm⁻¹ could be clearly identified [33,36].

The effect of mixing different concentrations of PET in PP on the IR-spectrum of PP is summarised in **Error! Reference source not found.c**. Numerous distinct PET peaks, in accordance with literature [33], could be identified, including the aromatic skeletal stretching band at 1408 cm⁻¹, the CH₂ wagging at 1340 cm⁻¹, the C=O stretching at 1710 cm⁻¹, the broad peaks at 1095 cm⁻¹ and 1241 cm⁻¹ due to ester stretching, the benzene ring vibration at 871 cm⁻¹, 723 cm⁻¹, and 1017 cm⁻¹, and the CH₂ rocking at 846 cm⁻¹. Here, it is the peak at 1710 cm⁻¹ that showed a varying intensity with the PET concentration in PP.

In case of mixing PLA into PP, **Error! Reference source not found.d** shows the existence of the characteristic stretching of C-O bonds at 1080 cm⁻¹, C=O stretching at 1749 cm⁻¹, the symmetric and asymmetric stretching of CH₃ at 2947 cm⁻¹ and 3000 cm⁻¹, as well as their symmetric and asymmetric bending at 1361 cm⁻¹ and 1452 cm⁻¹. Here, the intensity of the C=O stretching at 1749 cm⁻¹ varies with the concentration of PLA in PP [37].

Finally, **Error! Reference source not found.e** illustrates the IR spectra of PP and its mixtures with PS. According to [33], the distinctive benzene ring vibration peaks lie at 1600 cm⁻¹ and 1493 cm⁻¹. The out-of-plane mono-substitution deformation peaks at 694 cm⁻¹ and 750 cm⁻¹ of PS changes its intensity with the varying content of PS within PP. Table 3 summarises the distinctive identification wavenumbers and their associated bonds for each of the tested polymers.

Table 3. Summary of the distinctive FTIR wavenumbers associated with polymer identification [33–37].

Wavenumber [cm ⁻¹]	Assignment	ABS	PC	PET	PLA	PP	PS
694	Out-of-plane mono-substitution						•
750	Out-of-plane mono-substitution						•
723	Benzene ring vibration			•			
827	C-H deformation		•				
846	CH ₂ rocking			•			
871	Benzene ring vibration			•			
912	C-H deformation in the butadiene phase	•					
964	C-H deformation in the butadiene phase	•					
1012	O-C-O simultaneous stretching		•				
1017	Benzene ring vibration			•			
1080	C-C-C bending		•				
1080	C-O bond stretching				•		
1095	Ester group stretching			•			
1241	Ester group stretching			•			
1340	CH ₂ wagging			•			
1361	Symmetric bending of CH ₃ group				•		
1375	Umbrella vibration of CH ₃ group					•	
1408	Aromatic skeletal stretching			•			
1452	Scissoring of CH ₂ group	•					
1452	Asymmetric bending of CH ₃ group				•		
1455	Symmetric in-plane vibration of C-H(CH ₃)					•	
1493	Benzene ring vibration						•

1494	Aromatic styrene ring vibration	•					
1504	C-C ring stretching		•				
1600	Benzene ring vibration						•
1602	Aromatic styrene ring vibration	•					
1710	C=O stretching			•			
1749	C=O stretching				•		
1768	C=O stretching		•				
2239	Acrylonitrile C≡N bond	•					
2838	Symmetric stretching of CH ₂ group					•	
2868	Symmetric stretching of CH ₃ group					•	
2916	Asymmetric stretching of CH ₂ group					•	
2947	Symmetric stretching of CH ₃ group				•		
2950	Asymmetric stretching of CH ₃ group					•	
2968	Asymmetric C-H group stretching		•				
3000	Asymmetric stretching of CH ₃ group				•		

4. Discussion

ABS as a foreign polymer in the PP recycling stream. In case of a good bond between PP and ABS within the blend, elastomeric polybutadiene in ABS [38] is expected to contribute towards improved toughness of the semi-crystalline PP. However, such an interface is only achievable through the addition of compatibilisers [39–41]. The current study confirms these findings, as the incorporation of ABS into PP without such coupling agents did not improve the tensile stiffness or strength of the parent polymer. However, results also show that the mix up to 10% generally did not negatively impact the strength and stiffness of PP. For concentrations of up to 3%, no significant effect on the ductility of PP could be observed. This is also supported by the MVR results, which suggest that for lower ABS concentrations, no molecular changes occurred in PP and thus no significant change in the MVR of PP.

Based on these results, up to 3% ABS can be allowed within a PP stream without negatively affecting its mechanical properties. Due to the acceptable tensile properties observed in samples with a weld line, it can be assumed that such a recycling material can be used in complex products that may require multiple gates during injection moulding. For simpler parts (without weld line), lower-quality streams with 5-10% ABS can be used without any sacrifice in strength, stiffness, or processability of PP.

PC as a foreign polymer in the PP recycling stream. PC is an amorphous polymer, which is immiscible with PP [42–46]. Due to the high melting temperature of PC (280-315°C) with respect to that of PP (215-260°C), the mixture was processed at the higher temperature levels to ensure full melt of the PC. However, at 280 °C, PP showed a 2.14% reduction in tensile strength, compared to PP processed at 245 °C (as in case of the experimental setup for the ABS blend). A similar observation was reported by Van Bruggen et al. [47] where the impact strength of pure PP decreased by 3.7%, when the processing temperature of pure PP was increased from 250 °C to 300 °C.

Despite the deterioration in strength of PP under the given processing conditions and the immiscibility of PC and PP, the mix did not show a significant loss in strength and stiffness. This can be interpreted in terms of the good dispersion of the PC phase during the compounding phase. As a result, the well-dispersed PC phase associated with higher mechanical properties acts as reinforcement within the PP, thus retaining its overall mechanical performance.

According to these findings, for parts produced without a weld line, contamination of PP with PC of up to 10% will not have a significant effect on the mechanical properties of PP, providing the mix is compounded at temperatures high enough to melt the contaminating polymer. Once compounded, the mixture can be injection moulded at the conventional processing temperatures of PP without any significant change in the MVR of PP. The PC would then act as a dispersed

strengthening phase. However, for applications with weld line, a decrease in toughness and elongation at break should be expected.

PET as a foreign polymer in the PP recycling stream. PET is immiscible in PP [48,49], due to the lack of chemical and polar compatibility. PP/PET blends tend to establish a two-phase morphology, where relatively large spherical droplets of PET are present within PP [50–52]. This theory is supported by the MVR findings, indicating an increased viscosity of the PP/PET blend, since the flow of PP is hindered by the crystalline PET phases. Compatibilisers are necessary to create a bond between the two phases. The here presented results show that PP/PET blends behaved according to the rule of mixtures, where the stiffness of the mix linearly increased with increasing PET content, while the ductility linearly decreased. Here, PET acts as the stiffening component to the more ductile PP. Similar results were reported in [53–57], where fabrics and textiles produced out of a polyolefin/PET blend showed superior properties. Li et al. [58] claimed that the inclusion of high melting temperature polymers into PP acts as a microfibrillar reinforcement. In addition, Inoya et al. [59] proposed that a homogeneous PP/PET blend can be achieved by deformation of the dispersed phase through adequate mixing to prevent its agglomeration.

The present study proves that a 5% mis-sorting of PET in PP is not expected to cause significant deterioration in the mechanical properties of PP. In fact, apart from the increased brittleness of PP (related to improved stiffness), the incorporation of 5% PET does not seem to affect the tensile strength or the strain to failure. Even at higher concentrations of PET, recycled material can further be considered for complex parts involving a weld line, as it behaves as a reinforced PP blend with enhanced stiffness. However, care should be taken during processing, since higher injection pressures are to be expected due to increased melt viscosity.

PLA as a foreign polymer in the PP recycling stream. Similar to the other polymers under consideration in this study, PLA is also incompatible with PP. Consequently, PP/PLA blends tend to form a multiphase system with poor mechanical performance [60–62]. PP-g-maleic anhydride is often used as a compatibilising agent to mitigate the blend's polarity for a better interface. The results presented here show that the introduction of PLA into PP insignificantly enhances the stiffness, without any impact on strength or ductility. Increasing the amount of PLA beyond 5% led to the embrittlement of PP. However, the toughness of the PP weld lines in the presence of PLA seemed to suffer, even at low concentrations of 3%.

Based on the above, it is recommended to use PP streams with PLA mis-sorting in applications that do not require high toughness or complex gating systems that lead to the formation of weld lines. Such a mix is, however, still usable in general applications where stiffness is the key factor. It should be noted that in this study, the PP stream with PLA mis-sorts was processed at 215°C, which is normally considered too low for PP (225–245°C). Processing at higher temperatures around 240°C cause PLA degradation (as evidenced by the significantly increased MVR), which could lead to lower ductility and toughness of the mix. It is to be noted that the reduced viscosity must also be considered at the processing stage.

PS as a foreign polymer in the PP recycling stream. PS is immiscible in PP [63]. Therefore, it is generally suggested to use compatibilisers for PP/PS blends. However, in [64,65], high shear mixing techniques were used to efficiently blend PP and PS without the addition of compatibilisers. Here, a twin-screw counter-rotating extruder was used to bring high shear into the material. Although this is generally not the case in this study, the incorporation of PS into PP did not negatively influence the stiffness and tensile strength or its processability. For up to 5% PS, there was even no significant change in ductility or toughness with respect to the parent polymer. A further increase in PS content to 7% seemed to improve ductility, although not statistically significant, due to the increased scattering of the results. This effect is nullified at a higher PS content of 10%, bringing back the ductility to its original value, while having a negative impact on the toughness.

Experiments carried out on samples with a weld line evidence that the incorporation of PS hinders good bonding at the weld line, thus linearly decreasing the overall toughness, ductility, and tensile strength with increasing PS content. On the one hand, the benzene ring within the PS chain is expected to hinder the mobility of the PP molecules, thus strengthening the material. However, the

immiscibility of PP and PS encourages the agglomeration of PS, thus decreasing overall mechanical performance. These two mechanisms work against each other, which is reflected in the increased standard deviation of the elongation at break for samples without a weld line up to 7% PS. A further increase in the PS content is expected to encourage the formation of agglomerates, leading to the deterioration of the ductility. Hence, it can be concluded that the mis-sorting of PS up to 7% will not cause a significant change in the mechanical properties of PP. At 10% PS, only the toughness of PP would suffer. If this mix is, however, used in the manufacturing of complex geometries that require multiple gates in the mould, a significant decline in the ductility and toughness of PP should be expected. However, this should not render this polymer stream unusable for mechanical recycling.

5. Conclusions

The contamination of polypropylene (PP) with selected polymers is studied to simulate the effect of mis-sorting in recycling streams. ABS, PC, PET, PLA, and PS are all immiscible in PP. Conscious mixing usually involves the addition of coupling agents, to improve bonding between PP and the supplement material. This study proves, that to some extent the presence of foreign polymers in PP can be accepted. Accordingly, it is generally recommended to compound the blend at temperatures high enough to ensure the melt of the supplement polymer, using a twin-screw extruder before injection moulding the final product. Many of these contaminants then tend to form a secondary reinforcing phase within the PP.

Figure 6 provides a graphical summary of the results of this study. The plot depicts the properties, of PP when mixed with up to 10% of the foreign polymer. It can be concluded that the inclusion of ABS, PET, and PS increases the material stiffness with no adverse influence on the material's strength, whereas PC and PLA inclusion decreases the PP's strength with no enhancement in the material's stiffness.

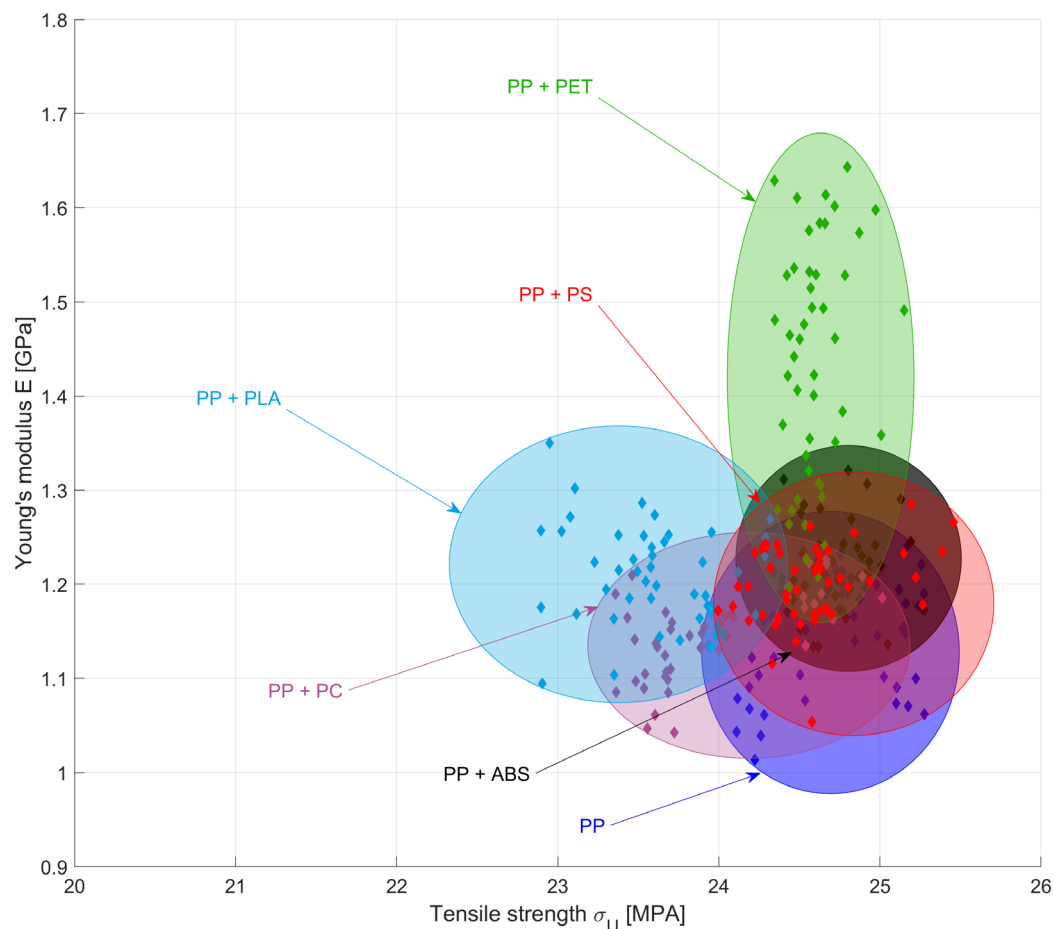


Figure 6. Effect of supplement polymer inclusion on the strength and stiffness of PP.

Moreover, it can be stated that ABS, PC, and PS inclusions, although not affecting its processability, generally render PP unsuitable for complex parts that involve a weld line due to reduced toughness and ductility. However, such mis-sorts are acceptable for simple components without a weld line. Inclusion of PET or PLA within PP at 10% would generally result in reduced toughness and ductility. Moreover, PLA significantly degrades at dwell times greater than 3 minutes leading to an increased MVR of 118% after 10 min. This might render the PP stream unsuitable for extrusion applications. In contrast, PET decreases the MVR of PP by more than 22%. Finally, it should be noted that, for all supplement polymers under investigation, the tensile strength and stiffness of PP did not suffer even in the presence of 10% supplement immiscible polymer.

The introduction of a weld line emphasized the effect of the defects within the PP blend. Following these results is generally the more conservative way for product design. In accordance, knock-down or safety factors can be reduced.

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