

The effect of polyethylene on the properties of talc-filled recycled polypropylene

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ABSTRACT

The reinforcement of recycled polypropylene (rPP) with mineral fillers, to obtain modulus values of 3000–4000 MPa has proven challenging for recyclers, whereas this is common practice for virgin PP. The main difference between recycled and virgin PP is the contaminating presence of other polymers. In this study, the composition of rPP sourced from electrical and electronic waste was analytically estimated. The rPP was found to be a PP/HDPE blend with ca. 90/10 m% ratio. Furthermore, the effect of HDPE on the thermal and physical properties of talc-filled PP was investigated by means of re-engineered blends and talc-filled compounds. It was found that HDPE has a profound effect on the degree to which rPP can be reinforced by talc. However, the quantified effects of the HDPE alone were not of sufficient magnitude to account for the full difference in properties between talc-filled rPP and virgin PP.

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Introduction

Waste from electrical and electronic equipment (WEEE) is one of the fastest-growing waste streams in Europe [1,2]. (filled) Polypropylene (PP) is one of the major polymer fractions found in WEEE. [3,4]. Currently, there is a strong European momentum to increase the use of high-quality recycled plastics [5]. The most accessible way for companies to use post-consumer recycled (PCR) plastics remains a drop-in strategy, which requires the PCR to match the properties of the equivalent virgin plastic as closely as possible [6]. Components such as internal frames are typically considered very suitable for PCR, as they are non-visual components. Nowadays, talc-filled PP is commonly chosen for such parts as the material can reach high (up to 4500 MPa) stiffness values in a cost-effective way. The effect of talc on the mechanical properties of virgin PP has been extensively studied [7–11]. Until now, industrial attempts to reach a high stiffness talc-filled PP based on recycled PP (rPP) have failed. The reinforcing effect of the talc is not as high for rPP as it is for virgin. It has been surmised that this is due to contamination with either high-density polyethylene (HDPE), copolymer-PP (cPP), or both. These contaminating polymers are a legacy of the sorting process.

The EEE-industry uses two types of PP: homopolymer-PP (hPP), which is most frequently used, and cPP, which is used for high-impact parts. During recycling, no distinction is made between both types by either of

the dominant separation techniques, near-infrared spectroscopy (NIR) or density separation. As a result, both types of PP end up in the same material stream. Furthermore, the EEE-industry also utilises small amounts of HDPE [12–14]. As a minority stream, the polyethylene (PE) stream is not economically viable to be separately recovered and is usually not sorted out from the PP. Some studies on polyolefin blends have indicated that the addition of 10–20 m% of HDPE to hPP will increase the elastic-modulus (E-modulus) [15,16], while others report exactly the opposite, being a decrease in E-modulus by adding as little as 5 m% HDPE to PP [17,18]. The large variation in molecular architectures and weight distributions makes it difficult to be able to apply a ‘one fits all’ rule for the properties of PP/PE [19].

Whether an HDPE contamination adversely affects the ability of rPP to be reinforced by talc has not been researched up to date. Therefore, this study explores the effect of HDPE on the properties of talc-filled PP. The focus is twofold: (i) estimating the effective HDPE content in a commercial rPP; and (ii) evaluating the effect of HDPE on the thermal and mechanical properties of a talc-filled (r)PP compound.

Materials and methods

Materials

The polymers used in this study are listed in Table 1, accompanied by some key properties from their

Table 1. Overview of the used polymers.

Polymer	Grade and supplier	MFR (g/10 min)	E-Modulus (MPa)	Density (g/cm ³)
hPP	HF700SA Borealis	21	1350 (F)	0.905
HDPE	25055E Dow	25	870 (F)	0.953
rPP	2131HR9004 MGG	8	1100 (T)	0.940

Notes: MFR values are according to ISO1183, measured with 2.16 kg weight, at 230°C for PP and at 190°C for PE. Reported modulus values are either flexural (F) or tensile (T).

datasheets. The selected virgin polymers are representative for the considered applications. The recycled grade is a PCR black polypropylene from WEEE, intended for general use.

A high-aspect ratio talc with a density of 2.78 g/cm³ and a particle size of 4.2 µm (Jetfine T1-CA; Imerys minerals) was used as reinforcing filler.

Sample preparation

All blends were compounded in a Coperion ZSK 18 co-rotating twin-screw compounder ($L/D = 40$). They are listed in Table 2 with nomenclature in the form of xPP/HDPEy/Talcz, wherein x denominates the PP type (hPP or rPP), y describes the m% of HDPE on the total polymer amount (PP+HDPE) and z the amount of talc in the total compound. If either y or z is zero, this block is taken out of the name. E.g. hPP/HDPE10/Talc20 is a blend of 80 m% polymer (of which 72 m% PP and 8 m% HDPE) and 20 m% talc.

The hPP/HDPE blends (samples 1–5) were mixed manually before feeding volumetrically. For the compounds containing talc (samples 6–11) the matrix was gravimetrically fed and talc volumetrically added via a side feeder. During compounding, screw speed was set by the mixing torque ($\approx 30\%$ of max.) at 220°C (120–1200 rev min⁻¹).

All samples were injection moulded (ENGEL e-victory 28 T), obtaining test specimens according to ISO 527 and ISO 179 standards. Mould temperature (40°C), barrel temperature (220°C) and injection speed (90 mm/s) were kept constant.

For all talc-filled compounds, the filling rate was verified by pyrolysing an injection moulded sample (≈ 5 g) in a furnace (550°C; 30 min).

Table 2. Overview of the samples studied.

nr.	Sample name	PP (m%)	HDPE (m%)	Talc (m%)
1	hPP/HDPE2	98	2	/
2	hPP/HDPE5	95	5	/
3	hPP/HDPE10	90	10	/
4	hPP/HDPE20	80	20	/
5	hPP/HDPE30	70	30	/
6	hPP/HDPE10/Talc20	72	8	20
7	hPP/HDPE10/Talc40	54	6	40
8	hPP/Talc20	80	/	20
9	hPP/Talc40	80	/	40
10	rPP/Talc20	80	/	20
11	rPP/Talc40	80	/	40

Mechanical tests

Tensile tests were performed according to EN ISO 527-1, after conditioning (>48 h; 23°C; 50% RH), on an Instron 5565, using a 5 kN static load cell. A clip-on extensometer (gauge length 50 mm) was used to measure the strain during the elastic deformation (1 mm/min). The extensometer was removed after a strain of 0.3%. Afterward, the test was continued (50 mm/min) until specimen failure.

Impact strength was measured according to ISO179 (pendulum energy 2.75 J; Tinus Olsen model Impact 503).

Physicochemical analysis

DSC was performed with a Netzsch Polyma DSC 214 and analysed with Netzsch Proteus 70 Thermal Analysis software, according to EN-ISO1358. A correction was run before each measured set. Samples of 10–15 mg were prepared in an aluminium crucible with pierced lid. A cycle, heating from 25°C to 250°C, cooling from 250°C to 25°C, followed by a second heating from 25°C to 250°C, in a nitrogen atmosphere (40 ml/min), was conducted. All heating/cooling rates were 5°C/min. Only values from the second heating are reported as an average of three measurements \pm standard deviation. The reference enthalpy values for 100% crystallinity are 207 J/g for PP [20] and 293 J/g for PE [21]. Crystallinity of all samples was calculated in respect to their composition using Equation (1), where ΔH_m is the melt enthalpy of the polymer fraction, ΔH_m^∞ is the reference enthalpy for 100% crystallinity and x is the weight fraction in the blend.

$$X_c(\%) = \frac{\Delta H_m}{\Delta H_m^\infty} \cdot 100\% \quad (1)$$

FTIR was performed on samples 1–5 and rPP, each with a thickness <1 mm, according to ASTM E168, E1252. The instrument used is a Bruker Tensor 27, with OPUS (vs 6.5) software and a ZnSe-crystal in ATR mode (range 4000–600 cm⁻¹). Reported results are an average of at least eight measurements \pm standard deviation.

Morphological analysis

Scanning electron microscopy (SEM) analysis was conducted on the talc-filled samples obtained from impact bars. Samples were fractured after immersion in liquid nitrogen for approximately 1 min, dried overnight, and coated with 10 nm of gold by an automatic sputter coater Plasmatool-SC prior to analysis. The SEM instrument used is a Phenom Pro G5 Desktop SEM with 10 kV accelerating voltage.

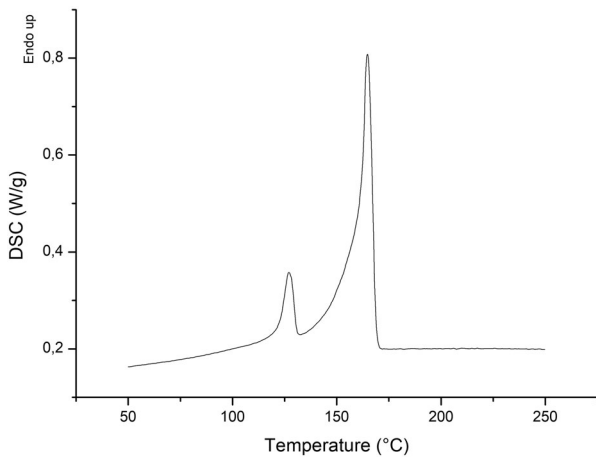


Figure 1. DSC measurement of commercial rPP sourced from WEEE.

Results and discussion

Effective composition of rPP

The composition of the used rPP is unknown. DSC measurements of rPP show (Figure 1) two distinct melting peaks. The first peak (127.5°C), is assigned to HDPE and the second peak (164.9°C) is assigned to PP [22]. However, from the PP peak, it is not possible to identify the type(s) of PP (homopolymer or copolymer), as the melting behaviours of cPP and hPP are too similar [23]. Further focus was put on quantifying the amount of HDPE present in the recycled PP grade. There is no direct analytical method for the determination of composing fractions in a polymer blend if the curves of the separate mono-materials are not available [24,25]. Therefore, a derivative estimation method is set up via DSC and FTIR, extrapolating results from the virgin blends.

Figure 2 shows the $\Delta H_{PP}/\Delta H_{HDPE}$ enthalpy ratio from DSC against known HDPE content in the hPP/HDPE blends. The concentration dependence is fit linearly with equation $\log y = 2.0797 - 1.4916 \log x$, with a

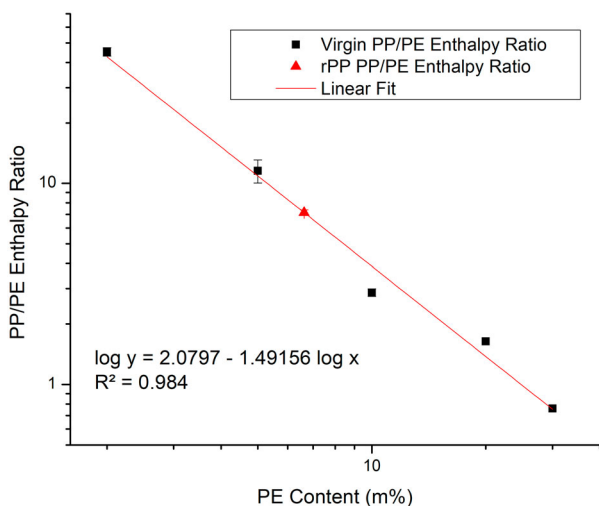


Figure 2. Melt enthalpy ratio of PP/HDPE blends.

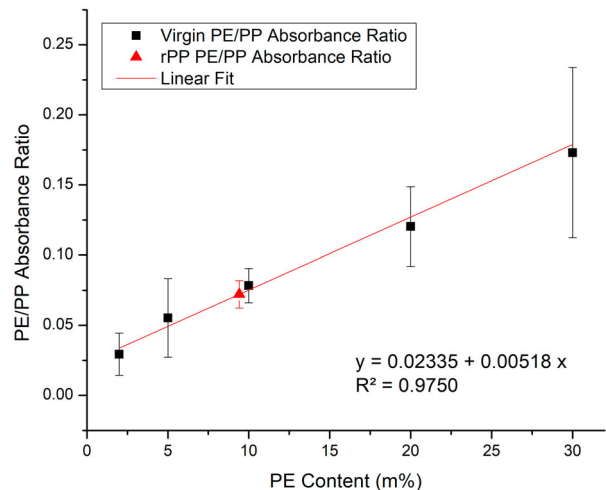


Figure 3. FTIR absorbance ratio 729/2914 cm^{-1} of hPP/HDPE blends.

determination coefficient (R^2) of 0.984. By plotting the experimentally determined ratio ($\Delta H_{PP}/\Delta H_{HDPE} = 7.16$) of rPP on the linear fit equation, it was possible to estimate a value for the amount of HDPE (ca. 6.6 m%).

Similar FTIR measurements were consequently performed. First, analyses were performed on hPP and HDPE to determine representative spectrum peaks of these polymers (2914 cm^{-1} (CH stretching in CH_2) and 729 cm^{-1} (CH_2 rocking in paraffin structure) respectively); the 2914 cm^{-1} peak is observed for both PP and HDPE, while the peak at 729 cm^{-1} is observed only for the HDPE-containing samples [26,27]. A baseline was set with samples 1–5. On Figure 3, the results of the ratio of the representative absorbance peaks (729 $\text{cm}^{-1}/2914 \text{ cm}^{-1}$) as a function of the HDPE content are shown. A linear fit with equation $y = 0.02335 + 0.00518x$ and $R^2 = 0.9750$ is obtained. When the values of the rPP are plotted on the equation, an amount of ca. 9.4 m% of HDPE is estimated.

The estimated value for HDPE content found with the FTIR-derivative method is higher than for DSC; initially, this appears to be a discrepancy. However, it is important to note that with FTIR it is not possible to distinguish the PE-typical absorbance peak of pure HDPE from the one related to the PE comonomer in cPP [27]. Therefore, it is acceptable for the estimation to be higher from FTIR. Nonetheless, recycled materials are known to vary in composition and moreover, both techniques used measure very small sample sizes. Therefore, a worst-case scenario of 10 m% HDPE is selected for further trials to evaluate the influence of HDPE in neat and talc-reinforced hPP.

Effect of HDPE contamination on PP

In Figure 4 the tensile modulus of hPP/HDPE blends are plotted as a function of the amount of HDPE up to 10 m

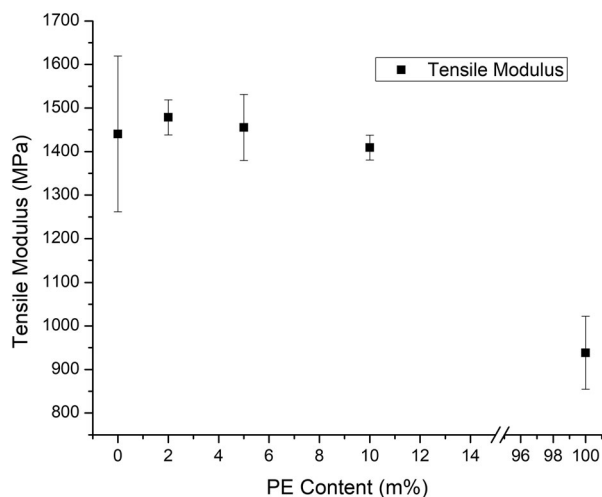


Figure 4. Tensile modulus PP/HDPE blends.

%. No significant change in the E-modulus could be determined. However, this may be due to the large variation on the results for hPP. In a qualitative appreciation, it could be argued that the mean modulus values seem to decline with increasing HDPE, which would be in agreement with existing studies [17,28]. Nevertheless, this drop in properties remains minor. It has been stated that such initial stability of the mechanical properties could be due to a good dispersion and distribution of the second phase, which keeps the effect on the properties of the matrix negligible [20].

The crystallinity degree (χ_c) was determined for both separate fractions in the hPP/HDPE blends and are represented in Figure 5. All values were properly recalculated according to Equation (1).

For the hPP matrix, χ_c drops steadily with rising HDPE content, implying an inhibition of PP's crystallization. Indeed, a decrease in crystallization onset temperature (T_c) was observed with increasing HDPE content (117.1°C; 117.9°C; 115.1°C; 111.8°C; 110.0°C for hPP, hPP/HDPE2, hPP/HDPE5, hPP/HDPE10,

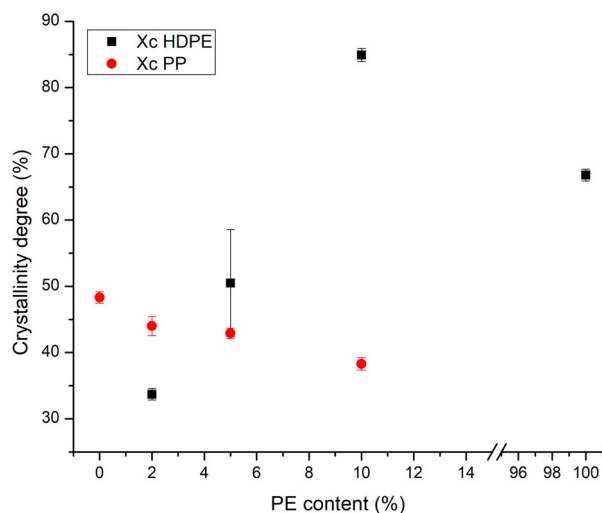


Figure 5. Crystallinity degree values (%Xc) of hPP/HDPE blends.

and HDPE, respectively). The drop in χ_c can be explained by the physical hindrance caused by a higher mobility of the linear HDPE chains; which can inhibit the crystallization of PP before phase separation occurs by physically nestling in between the PP chains. Further, into the crystallisation process, phase separation will occur, reducing this effect [29]. It must be noted that the initial crystallinity of the neat hPP (nearly 50%) is quite high for a PP grade and is attributed to the proprietary molecular architecture of the polymer. It stands to reason that the smallest contamination will disturb this highly effective crystallization.

The evolution of HDPE's crystallinity with increasing HDPE content is remarkable: the χ_c value initially starts lower than that of pure HDPE, but then significantly exceeds this value for hPP/HDPE10. In low amounts (2 m%), HDPE is likely to form very small droplets throughout the matrix; it has been previously reported that indeed fewer coalescence phenomena will occur [20].

These small droplets present a relatively (to their volume) large surface to the PP matrix, leaving them little ability to form their own nuclei in their limited bulk [30]. As such, the formation of crystals in these small phases is severely inhibited. With increasing HDPE content, the HDPE dispersed phase increases in size [29], reducing the interphase/volume ratio and increasing the nuclei in the bulk. As such, HDPE crystallinity is able to grow towards the value of pure HDPE, as is observed for 5 m%. Remarkably, in the hPP/HDPE10 blend, the χ_c of the HDPE fraction exceeds that of pure HDPE. This could be due to heterogeneous nucleation of the now sufficiently sizeable HDPE phase on the edges of the pre-crystallized PP. Indeed, it has been found that in PP/HDPE blends epitaxial growth of HDPE on the already formed PP crystals could occur [23,30].

Talc-filled PP/HDPE compounds (virgin and recycled)

As it was determined that – at the worst case – the rPP contains 10 m% of HDPE, the effect of the contaminating HDPE on PP's ability to be reinforced by talc is investigated with compounds containing 10 m% of HDPE, at each time relative to the PP content. The reinforcing effect of talc in hPP is achieved not only by the rigid filler effect of the talc but also because talc will synergistically promote the crystallinity of the matrix, resulting in higher stiffness of the matrix itself [9], [11]. We will isolate the magnitude of the latter effect by quantifying the matrix crystallinity separately from measuring the effective stiffness of the new compounds.

Effective filler rate and morphology

Table 3 shows the measured talc filling content of all talc-filled compounds, determined via ash content of

Table 3. Measured talc filling content for the studied samples.

Sample	Measured talc filling content (m%)
hPP/Talc20	18
hPP/Talc40	37
hPP/HDPE10/Talc20	16
hPP/HDPE10/Talc40	37
rPP/Talc20	16
rPP/Talc40	37

the filled materials. Results of filled and unfilled samples were compared to isolate the intentionally added filler. As such, reported values are only of the filler, and the measured residues of the matrix material were already included in the determination of these values.

The effective filling content is consistently somewhat lower than the intended filling rate.

The morphology of the talc-filled samples was examined by SEM, evaluating the distribution and dispersion of the talc particles. Both of these influence the homogeneity of the composite and its increase in mechanical properties. Agglomerations of talc can cause premature failure, as there is no stress transfer between the filler particles and the polymeric resin [31–34]. Figure 6 shows the SEM images of two samples (hPP/HDPE10/Talc40 and hPP/Talc20) at identical magnification. The results indicate efficient mixing with good distribution and dispersion of the talc particles throughout the matrix. All samples show the similar distribution and dispersion patterns.

Crystallinity

The χ_c of the different polymers in the talc-filled blends are shown in Figure 6.

The results show that talc has a significant influence on the χ_c of hPP, increasing it, due to its highly effective nucleation effect on PP [9,10,35,36]. Talc typically induces an increase inhomogeneity of the crystalline phase, a decrease in the spherulite size and the possibility to increase overall crystallinity. The presence of sufficient talc (at the ‘20 m%’ level) is seen to

significantly increase the χ_c of all materials except for HDPE in hPP/HDPE10. There, adversely, χ_c is reduced instead. For the pure hPP, a spectacular increase up to 70% crystallinity is observed, which is extraordinary for PP [19,20,37] and surely a significant contributor to this material’s suitability for talc reinforcement.

It can be observed for all material that a further increase of the intended talc content to ‘40 m%’ does not significantly affect the χ_c any further; the effects of (anti-)nucleation have been fully realised.

HDPE does not show the same ability as PP to crystallise on talc [38], which was confirmed for the neat HDPE in a control experiment (results not shown). The extra surfaces introduced by talc in fact now inhibit the increase of χ_c in the HDPE fraction, thus counteracting the nucleating effect of the PP matrix that was observed for the unfilled hPP/HDPE10. As a result, there is no overall crystallinity gain from the HDPE fraction. Here, adversely, a decrease in χ_c is noted. This is not so for the PE in the rPP. There, a severe increase similar to that in hPP can be observed. In other work, it was shown that the χ_c of HDPE for an analogous PP/HDPE blend is typically suppressed, similar to what is observed in unfilled rPP [19]. It is hypothesised that the increase in χ_c of HDPE in rPP with the addition of talc is possibly due to the increase in the size of the HDPE dispersed phase. This is a known phenomenon when the viscosity of the (PP) matrix increases – which it does, due to the addition of talc [39] – which inhibits HDPE breakup during extrusion [40,41].

It is interesting to note that the HDPE fraction in both the hPP/HDPE10 and rPP sample shows similar crystallinities at ‘40 m%’ talc-filled compounds, indicating that an equilibrium is reached.

Additionally, it is observed that the presence of HDPE also inhibits the ability of the PP fraction of hPP/HDPE10 to realise its full crystallinity increase from the talc addition. χ_c values do increase for PP in

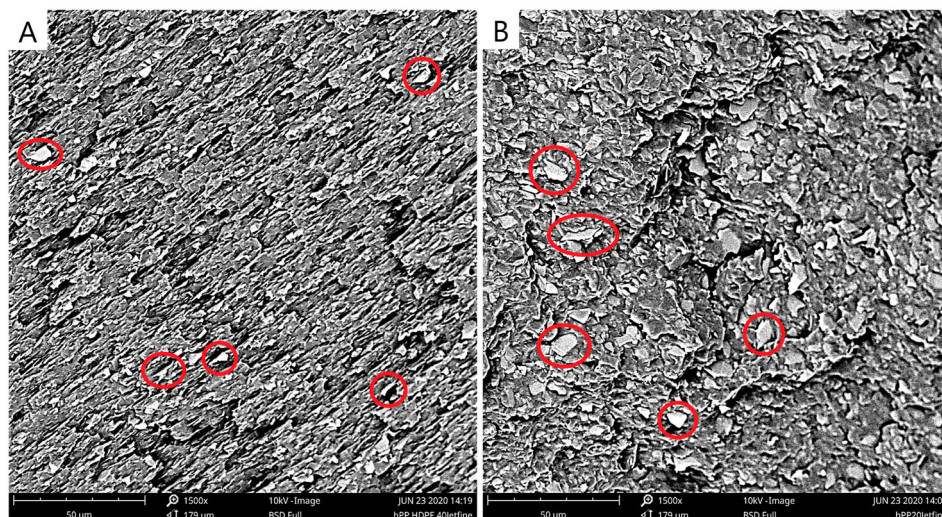


Figure 6. SEM analysis of hPP/HDPE10/Talc40 (A) and hPP/Talc20 (B). Examples of talc particles are highlighted for visual support.

hPP/HDPE10 but much less so, levelling out around 55%. This indicates that the presence of HDPE indeed has a profound effect on the maximum χ_c of talc-filled hPP. The effect is even more pronounced for rPP, where the χ_c for the PP fraction is limited to less than 50%. A possible explanation could be the presence of copolymer-PP in rPP, as cPP has a lower maximum χ_c than hPP [37]. Furthermore, it is realistic to assume that the PP in rPP itself consists out of a wide variety of PP types, rather than the neat high-crystalline hPP, with molecular architectures and χ_c much more spread out across the typical spectrum of PP.

Mechanical properties

Figure 7 shows the effect of talc content on the E-modulus of the samples studied. All compounds show an increase in E-modulus with the addition of talc.

This reinforcing effect is partially due to increase in crystallinity of the matrix, as previously discussed. Furthermore, talc induces constraints in the deformability of the PP polymer matrix, as the matrix can transfer part of the stress to the mineral filler, which has a substantially higher elasticity modulus [42]. The increase in E-modulus values is proportional to m% talc for all compounds, which is also confirmed in previous studies [43–45]. A so-called improvement factor α is introduced to compare the potential for effective reinforcement of the different matrices. The higher α , the higher the effect of talc on the stiffening of the matrix. This factor is calculated by means of Equation (2)

$$E_c = (\alpha * n) + E_m, \quad (2)$$

With E_c = E-modulus talc-filled compound, in MPa, E_m = E-modulus of the matrix material, in MPa, α = Improvement factor, in MPa/m%, n = Talc content, in m%.

From the linear fits shown in Figure 8, the increase in E-modulus for hPP, hPP/HDPE10 and rPP by

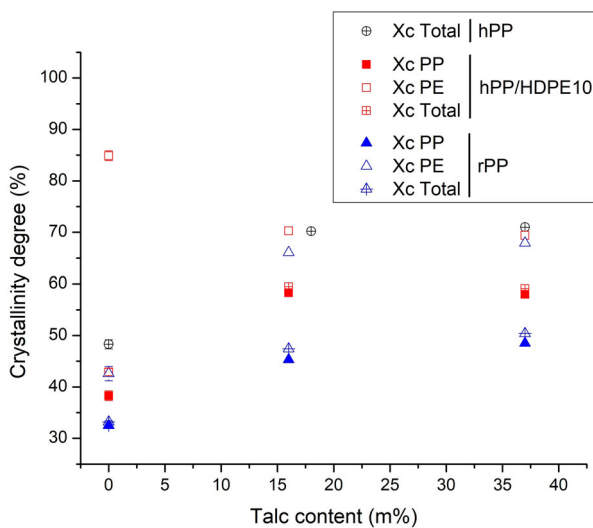


Figure 7. Crystallinity degree of the different samples studied as a function of talc content.

means of talc is found to be $\alpha = 92, 83$ and 58 MPa/m%, respectively ($R^2 > 0.978$). The results indicate that HDPE (10 m%) in a PP matrix has a noteworthy adverse influence on E-modulus of talc-filled samples. The drop in E-modulus can in part be assigned to χ_c , which shows an overall decrease in the hPP/HDPE10 blend compared to pure hPP, as previously discussed. Another factor to include is the immiscibility of HDPE in PP. The stress transfer between PP and HDPE is not optimal, inherently causing a decrease in E-modulus [46]. χ_c of the rPP matrix is found to be significantly smaller than the other samples, which results in a noteworthy influence on the overall E-modulus of the material. The fact that rPP inherently consists of a blend of PP and HDPE partially explains the lower values for E-modulus compared to hPP. The various grades of PP and HDPE present in a recycled grade, each one with different crystallisation behaviours, could explain a further drop in crystallinity. Other residues of non-compatible materials (contaminants) are also likely to be present. These contaminants act as stress concentrators that can further decrease the stiffness of the compounds. This notwithstanding, HDPE and non-polymeric contaminants alone are not expected to induce all of the severe drops in E-modulus compared to hPP. It is likely to assume that copolymer-PP is present in the rPP grade and has a more profound effect than initially assumed. This could, however, not be confirmed by FTIR or DSC measurements and was not the focus of this paper. Nevertheless, the presence of cPP could further explain the overall lower χ_c and E-modulus of rPP. As part of the current discussion, we will briefly explore this theory via an appreciation of impact strength.

It is observed from Table 4 that rPP shows significantly higher impact strength values than both hPP and hPP/HDPE10, indicating the possible presence of cPP in its composition. It is noteworthy that the addition of talc up to '20 m%' does not substantially

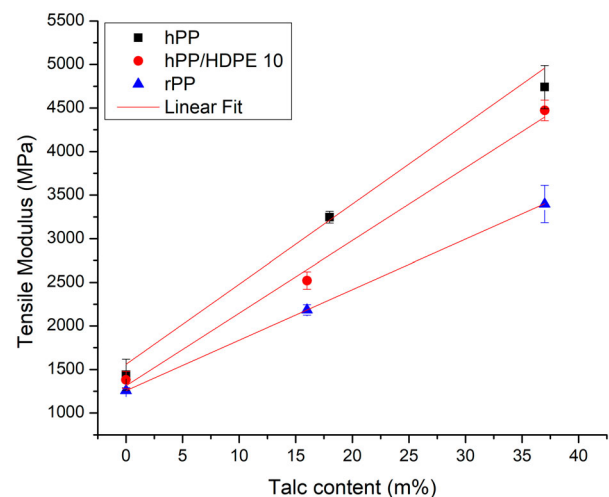


Figure 8. Tensile modulus of the samples – effect of talc content.

Table 4. Impact strength results for the samples studied.

Property	Talc content (m%)	Matrix		
		hPP	hPP/HDPE10	rPP
Impact strength (kJ/m ²)	0	1.80 ± 0.32	3.01 ± 0.11	5.05 ± 0.15
	16–18	3.20 ± 0.07	3.12 ± 0.04	5.45 ± 0.41
	37	2.16 ± 0.03	2.18 ± 0.04	3.72 ± 0.14

affect the impact strength of both rPP and hPP/HDPE10, and even increases it for hPP. A previous study likewise found that an increase in impact strength for lower filling rates (<15 vol.-%) is possible with small particle size fillers [38]. This could indicate a sufficiently strong interfacial region between filler and matrix, initiating crazing, leading to increased energy dissipation and improved impact resistance for hPP [47]. This effect also counteracts the immobilisation of the matrix which tends to reduce the impact resistance and keeps impact values nearly unaffected for the rPP and hPP/HDPE10 compounds. However, with an additional increase in talc content to the higher '40 m%' level, the impact strength decreases. As more talc is introduced in the matrix, its mobility decreases further, so less energy can be absorbed before failure [43].

The significantly higher impact resistance of rPP gives a strong indication that certain amounts of cPP are present in the composition [48]. The contribution of cPP to the ability of hPP to be reinforced by talc was not explored in the present work and little is known about its effect. Additional research is needed to gain further insights on the influence of cPP on the thermal and physical properties of talc-filled recycled polypropylene.

Conclusion and outlook

In this research, the effect of HDPE on the ability of recycled PP to be effectively reinforced by talc was assessed. At first, the actual composition of the rPP was estimated and found to be a blend of maximum of 10 m% HDPE in PP. Baseline testing with a virgin hPP/HDPE blend showed that the presence of up to 10 m% of HDPE in the blend did not substantially alter E-modulus compared to the neat hPP. However, a significant influence on hPP's capacity for crystallization was observed. Furthermore, the effect of HDPE in talc-filled PP was evaluated for both the virgin hPP/HDPE10 blend and a commercial rPP. The addition of talc in hPP, hPP/HDPE10 and rPP increases E-modulus for all materials. However, a drastic difference in E-moduli increase is observed between hPP/HDPE10 and the neat hPP and then again for the rPP. The former is empirical evidence that HDPE does in fact inhibits PP's ability to be fully reinforced by talc. The latter indicates that the HDPE contamination is most likely not the only cause for the unsatisfying reinforcement results of the commercial rPP grade. A suspected

fraction of cPP affects E-modulus even further and merits further research. Likewise, it could be considered whether it has sufficient merit to attempt the separation of either (or both) the HDPE or cPP fractions in the sorting process of WEEE plastics. Without such a refinement step, it is unrealistic to expect that rPP from WEEE will be able to perform as virgin hPP in terms of obtaining very high modulus values via talc filling.

Considerations for further studies, aiming to determine the composition of rPP and the presence of impurities include the use of other methods such as SEM-EDX, mapping using Raman or infrared spectroscopy, and atomic force microscopy (AFM).

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References

- [1] Babu BR, Parande AK, Basha CA. Electrical and electronic waste: a global environmental problem. *Waste Manag Res.* 2007;25(4):307–318.
- [2] Widmer R, Oswald-Krapf H, Sinha-Khetriwal D, et al. Global perspectives on e-waste. *Environ Impact Assess Rev.* Jul. 2005;25(5):436–458.
- [3] Achilias DS, Antonakou EV. Chemical and thermochemical recycling of polymers from waste electrical and electronic equipment. *Recycl Mater Based Environ Friendly Tech.* 2015. doi:10.5772/59960.
- [4] Ragaert K, Delva L, Van Geem K. Mechanical and chemical recycling of solid plastic waste. *Waste Manag.* 2017;69:24–58.
- [5] "Circular Plastics Alliance." Available from: https://ec.europa.eu/growth/industry/policy/circular-plastics-alliance_en.
- [6] Vyncke G, Onnekink J, Feenstra T, et al. Design from recycling for post-consumer WEEE plastics. *Int Conf Polym Mould Innov.* 2018: 6.
- [7] Zhou Y, Rangari V, Mahfuz H, et al. Experimental study on thermal and mechanical behavior of polypropylene, talc/polypropylene and polypropylene/clay nanocomposites. *Mater Sci Eng A.* 2005;402(1–2):109–117.

- [8] Velasco JJ, De Saja JA, Martinez AB. Crystallization behavior of polypropylene filled with surface-modified talc. *J Appl Polym Sci.* **1996**;61(1):125–132.
- [9] Ferrage E, Martin F, Boudet A, et al. Talc as nucleating agent of polypropylene: morphology induced by lamellar particles addition and interface mineral-matrix modelization. *J Mater Sci.* **2002**;37(8):1561–1573.
- [10] Naiki M, Fukui Y, Matsumura T, et al. Effect of talc on the crystallization of isotactic polypropylene. *J Appl Polym Sci.* **2001**;79(9):1693–1703.
- [11] Maiti SN, Sharma KK. Studies on polypropylene composites filled with talc particles. *J Mater Sci.* **1992**;27(17):4605–4613.
- [12] Plastics Europe. *Plastics – the facts 2019*. Brussels, Belgium: Plastics Europe; **2019**.
- [13] Maris E, Botané P, Wavrer P, et al. Characterizing plastics originating from WEEE: a case study in France. *Miner Eng.* **2015**;76:28–37.
- [14] Bharath Kumar BR, Doddamani M, Zeltmann SE, et al. Processing of cenosphere/HDPE syntactic foams using an industrial scale polymer injection molding machine. *Mater Des.* **2016**;92:414–423.
- [15] Gupta AK, Gupta VB, Peters RH, et al. The effect of addition of high-density polyethylene on the crystallization and mechanical properties of polypropylene and glass-fiber-reinforced polypropylene. *J Appl Polym Sci.* **1982**;27(12):4669–4686.
- [16] Baker JM. Tensile properties and morphology of blends of polyethylene and polypropylene. *Texas Nat Resour Conserv Comm.* **1996**;25(September):1–26.
- [17] Lin J-H, Pan Y-J, Liu C-F, et al. Preparation and compatibility evaluation of polypropylene/high density polyethylene polyblends. *Materials (Basel).* **2015**;8(12):8850–8859.
- [18] Hubo S, Ragaert K. Mirror welding of recycled polyolefins. *Polym Process Soc.* **2016**;0(1):2016.
- [19] Van Belle A, Demets R, Mys N, et al. Microstructural contributions of different polyolefins to the deformation mechanisms of their binary blends. *Submitt Polym.* **2020**;12(5):1171.
- [20] Jose S, Aprem AS, Francis B, et al. Phase morphology, crystallisation behaviour and mechanical properties of isotactic polypropylene/high density polyethylene blends. *Eur Polym J.* **2004**;40(9):2105–2115.
- [21] NETZSCH. Determination of the degree of crystallinity of polymers (Pe and Pp), p. 881505, 2006.
- [22] Kaiser G, Schmölzer S, Claire S, et al. *Handbook DSC*. Selb, Germany: Netsch Werbe Undservice GhhH; **2015**.
- [23] Li J, Shanks RA, Olley RH, et al. Miscibility and isothermal crystallisation of polypropylene in polyethylene melts. *Polymer (Guildf).* **2001**;42:7685–7694.
- [24] Kisiel M, Mossety-Leszczak B, Frańczak A, et al. Quantitative analysis of the polymeric blends. *Prog Rubber Plast Recycl Technol.* **2019**;35(2):75–89.
- [25] Camacho W, Karlsson S. From recycled mixed plastic waste. *Polym Eng Sci.* **2001**;41(9):1626–1635.
- [26] Krehula LK, Katančić Z, Siročić AP, et al. Weathering of high-density polyethylene-wood plastic composites. *J Wood Chem Technol.* **2014**;34(1):39–54.
- [27] Wang C, Wang Y, Dang Y, et al. Synthesis of a novel titanium complex catalyst and its catalytic performance for olefin polymerization. *Russ J Appl Chem.* **2015**;88(10):1723–1727.
- [28] Bartlett DW, Barlow JW, Paul DR. Mechanical properties of blends containing HDPE and PP. *J Appl Polym Sci.* **1982**;27:2351–2360.
- [29] Blom HP, Teh JW, Bremner T, et al. Isothermal and non-isothermal crystallization of PP: effect of annealing and of the addition of HDPE. *Polymer (Guildf).* **1998**;39(17):4011–4022.
- [30] Na B, Zhang Q, Wang K, et al. Origin of various lamellar orientations in high-density polyethylene/isotactic polypropylene blends achieved via dynamic packing injection molding: bulk crystallization vs. epitaxy. *Polymer (Guildf).* **2005**;46(3):819–825.
- [31] Karásek L, Sumita M. Characterization of dispersion state of filler and polymer-filler interactions in rubber-carbon black composites. *J Mater Sci.* **1996**;31(2):281–289.
- [32] Ai Wah C, Yub Choong L, Seng Neon G. Effects of titanate coupling agent on rheological behaviour, dispersion characteristics and mechanical properties of talc filled polypropylene. *Eur Polym J.* **2000**;36(4):789–801.
- [33] Osman MA, Atallah A, Suter UW. Influence of excessive filler coating on the tensile properties of LDPE-calcium carbonate composites. *Polymer (Guildf).* **2004**;45(4):1177–1183.
- [34] Balogun YA, Buchanan RC. Enhanced percolative properties from partial solubility dispersion of filler phase in conducting polymer composites (CPCs). *Compos Sci Technol.* **2010**;70(6):892–900.
- [35] Karian HG. *Polypropylene and polypropylene composites*. Whitmore lake: Marcel Dekker, Inc.; **2003**.
- [36] Teh JW. Structure and properties of polyethylene-polypropylene blend. *J Appl Polym Sci.* **1983**;28(2):605–618.
- [37] Caveda S, Pérez E, Blázquez-Blázquez E, et al. Influence of structure on the properties of polypropylene copolymers and terpolymers. *Polym Test.* **2017**;62:23–32.
- [38] Karger-Kocsis J. *Polypropylene structure, blends and composites volume 3 composites*. Dordrecht: Chapman & Hall; **1995**.
- [39] Öksüz M, Eroglu M, Yildinm H. Effect of talc on the properties of polypropylene/ethylene/propylene/diene terpolymer blends. *J Appl Polym Sci.* **2006**;101(5):3033–3039.
- [40] Taylor GI. The viscosity of a fluid containing small drops of another fluid. *Proc R Soc London Ser A Contain Pap Math Phys Character.* **1932**;138(834):41–48.
- [41] Utracki LA, Shi ZH. Development of polymer blend morphology during compounding in a twin-screw extruder. part I: droplet dispersion and coalescence – a review. *Polym Eng Sci.* **1992**;32(24):1824–1833.
- [42] Callister W, Rethwisch D. *Materials science and engineering*. Hoboken: John Wiley & Sons; **2011**; p. 885.
- [43] Premalal HGB, Ismail H, Baharin A. Comparison of the mechanical properties of rice husk powder filled polypropylene composites with talc filled polypropylene composites. *Polym Test.* **2002**;21(7):833–839.
- [44] Guerrica-Echevarría G, Eguiazábal JI, Nazábal J. Influence of molding conditions and talc content on the properties of polypropylene composites. *Eur Polym J.* **1998**;34(8):1213–1219.
- [45] Jahani Y. Comparison of the effect of mica and talc and chemical coupling on the rheology, morphology, and mechanical properties of polypropylene composites. *Polym Adv Technol.* **2011**;22(6):942–950.
- [46] Graziano A, Jaffer S, Sain M. Review on modification strategies of polyethylene/polypropylene immiscible thermoplastic polymer blends for enhancing their mechanical behavior. *J Elastomers Plastics.* **2018**;51(4):291–336.
- [47] Michler GH, Tovmasjan IM. *Plaste und Kautschuk*. Berlin: Springer; **1988**.
- [48] Ashby M. *CES EduPack 2019*. Granta design. Cambridge: Granta Design; **2019**.