

Determining the PE fraction in recycled PP

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ABSTRACT

The presence of a polyethylene (PE) fraction in recycled polypropylene (PP) will influence the processing as well as mechanical and thermal properties of recycled polypropylene. The objective of this work has been to compare methods used to determine the fraction of PE in recycled PP, establishing calibration curves for each method. Plastics waste will be a mix of different grades – homopolymers and copolymers. It has therefore been tested how specific material grades affect the results. Characterization methods used were differential scanning calorimetry (DSC), FT-IR spectroscopy, NMR, and gel content measurement after peroxide extrusion. We have applied the derived calibration curves for two different post-consumer, recycled PP (rPP) in addition to a known 50/50 blend of PE and PP. DSC, NMR, FT-IR and gel content give quite consistent estimates of the PE content.

1. Introduction

Polyethylene (PE) and polypropylene (PP) are popular polymers for use in applications such as packaging, and therefore end of life material collection, separation and recycling is critical. However, in the current recycling of PP, the general handling of the material and existing sorting technologies does not yield pure PP. The same material sources typically contain PE products and therefore a PE fraction is expected to be present in recycled PP.

Quality assurance of recycled household plastic is necessary since the presence of small amounts of PP in PE or vice versa affects the performance of the material and determines whether the material can be used for high value applications [1]. For many applications, optimum properties of blends also depend on the correct mix of PE and PP. A significant negative synergy between PE and PP was found regarding yield strength, impact strength, tensile energy to break and tensile modulus [2]. Knowing the composition of these blends is therefore critical to assure the quality of recycled polyolefins waste [3], and a range of methods have been investigated by different authors to measure the composition.

One candidate method of quantitative analysis of blends is measuring the melting enthalpies of compounds using differential scanning calorimetry (DSC). In interpreting results, one should be aware of previous observations where it was found that the presence of two polymers in the blend has influence on the crystallization of its components [4]. This could be due to the influence of one component on the

nucleation of the other in a way that the fraction of crystalline PE varies with the presence of PP.

Several applications have been found for low-tacticity polypropylene, notably as hot-melt adhesives, and bitumen modifiers [5]. New catalysts have reduced the amount of low-tacticity PP appearing during isotactic PP (iPP) production. Low crystallinity PP can, however, also be obtained by modifying iPP. Also, recycled PP (rPP) can be used rather than virgin PP, but the presence of PE may influence the results in a negative way.

Methods using chromatographic techniques [6] (high-T gradient HPLC) and temperature rising elution and crystallization analysis fractionation (TREF) [7] have been presented, although these demand non-standard equipment and high competence. Each of the methods TREF and crystallization analysis fractionation (CRYSTAF) were shown to work best according to the exact type of PE or PP. For a general case, as for rPP, combinations of TREF and CRYSTAF should be used but these instruments are not standard laboratory equipment.

In a study of the rheological behaviour of PE-PP blends [8], using an instrumented die, it was found that the pressure drop varied with the PE fraction. The overall results will, however, depend on the specific properties of each component which makes this not relevant for a general batch of recycled PP.

The law of mixing (LOM) has been used to predict different properties of recycled PE-PP blends with known composition of grades with identified properties [9]. It was found that properties like density and MFI in general followed the LOM analyzing PE and PP grades of known

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Table 1
Material grades included in the study.

Polymer	Polymer type	MFI [g/10 min]	Density [kg/m ³]
PP-1	Homopolymer	2.8–3.5 ^a	905–917
PP-2	Random copolymer	1.5 ^a	905
PP-3	Block copolymer	0.3 ^a	900
PE-1	LDPE	7.5 ^b	920
PE-2	MDPE	6.0 ^b	934
PE-3	HDPE	0.25 ^b	959
rPP-1	Recycled	8.3 ^a	912
rPP-2	Recycled	20.4 ^a	970

^a 230 °C, 2.16 kg.

^b 190 °C, 2.16 kg.

Table 2
PP and PE content [%] in produced blends.

Blend #	PP	PE
1	100	0
2	95	5
3	90	10
4	85	15
5	70	30
6	50	50
7	25	75
8	0	100

properties. Tensile strength and yield strength also had a quite good correlation with the LOM while the E-modulus had lower correlation. For impact properties no correlation to the LOM was found, and therefore impact testing is not considered to be a valid method for analysis of a rPP of unknown composition.

DSC and FT-IR analyses on blends of PE and PP for determining the PE content in rPP have been reported earlier [10] using high density PE, low density PE and iPP to establish calibration curves. This was done by analyzing hot pressed films of virgin PE/PP blends with content of specific polymer grades. Calibration curves from both DSC and FT-IR measurements were used to estimate the PE content in rPP collected from different sorted post-consumer waste streams. As PP copolymers, which are frequently used in packaging and can be expected to represent an important fraction of rPP, were not included in these studies, this will reduce the general value of these results.

The ASTM standard D7399-18 describe a FT-IR method to determine the PP fraction in low density PE. In the standard it is described that derived calibration curves will be dependent on the specific material grades used. How this will work with blends of general grades is not clear.

The relevance of measurement of gel content for determining the PE content in rPP relates to the fact that peroxides will cross-link PE while PP chains are subject to chain scission. In compounds extruded with peroxide one will therefore expect to find a gel content relating to the PE fraction in the material.

When studying PE-PP blends with the focus on recycled materials, different commercial types of both PE and PP should be considered. Different PE types may have different branching and crystallinity while PP materials may be present as homopolymers or copolymers with varying ethylene content. Materials for the analyses presented in this

Table 3
Series of blends produced for the study (see Table 1 for details of the grades).

Series	PP grade	PE grade
s1	PP-1	PE-3
s2	PP-1	PE-1
s3	PP-2	PE-2
s4	PP-2	PE-mix
s5	PP-3	PE-3

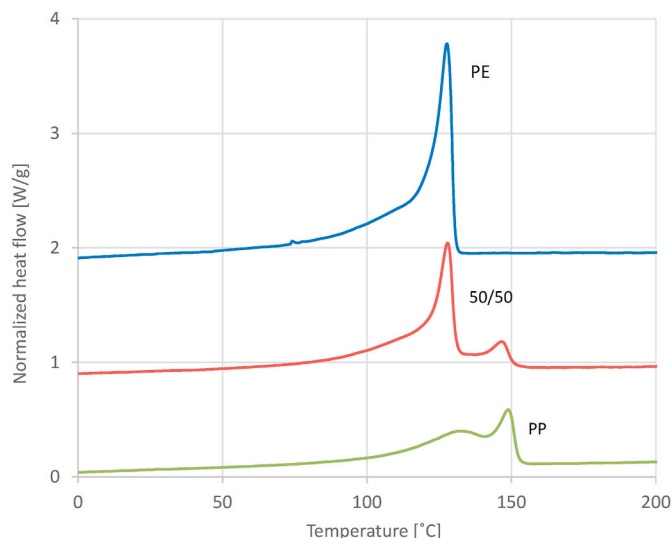


Fig. 1. Normalized heat flow from melting thermograms of series 4 samples with 0, 50 and 100% PP – shifted curves.

paper were selected taking this into account.

In this paper, four techniques (DSC, FT-IR, NMR, and gel content) are applied to laboratory made blends of PE and PP, using different types of both polymers. Results are evaluated and especially the alternative methods for making calibration curves from FT-IR analysis are compared. The established calibration curves for each method are finally applied to two different rPP's and a known PE-PP blend.

2. Experimental

Blends made from selected PE and PP grades were compounded and analyzed with four characterization techniques: DSC, FT-IR, NMR and gel content after peroxide extrusion.

2.1. Materials

In polypropylene recycling a mix of different material grades is encountered including homopolymers and copolymers. This is also the case for the PE fraction in the recycled material.

To test alternative methods, different grades of both PE and PP were used to produce a series of blends with known content as input to the characterization, as shown in Table 1.

By inspecting the pellets, one sees that rPP-2 consists of a mix of at least three different materials. The blended material has a density of 970 kg/cm³, which is very high for a PP blend. As will be seen from the FTIR analysis, the material has an unidentified component which may give rise to the high density.

2.2. Material compounding

The materials were processed on a DSM Midi 2000 15 cm³ batch extruder.

The processing temperature for the PE-PP blends was 230 °C and the cycle time for processing of pellets was 3 min with nitrogen flushing with extruder running at 70 rpm. For samples extruded with 2 wt % peroxide, the extruder start temperature was 200 °C during filling and then increased to 230 °C, and the processing continued for 2 min with nitrogen flushing.

2.2.1. Blends produced

Different series of blends were produced based on different combinations of polymers with relative PP and PE content as in Table 2. Five series of blends were produced, see Table 3. In one of the series, a blend

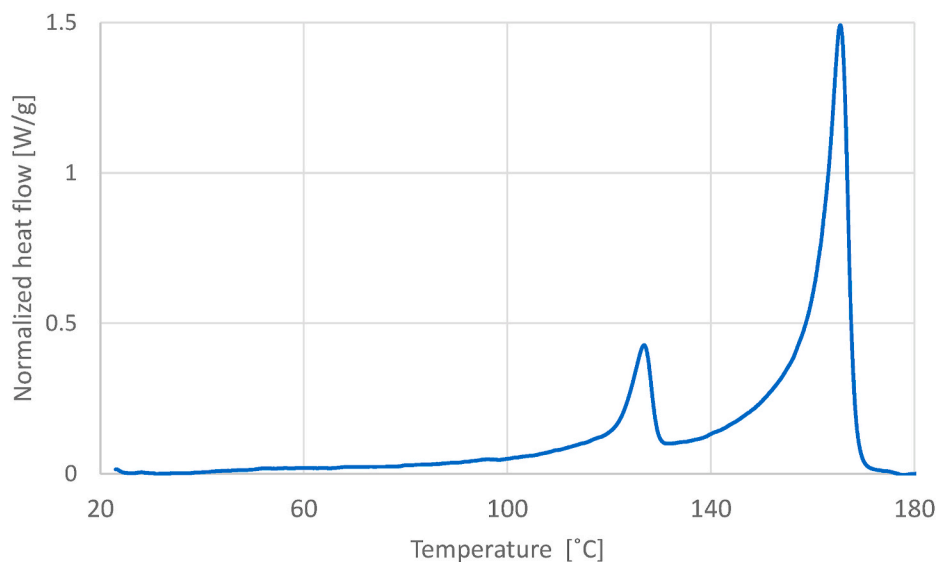


Fig. 2. Melting thermogram of series 5 sample with 10% PE.

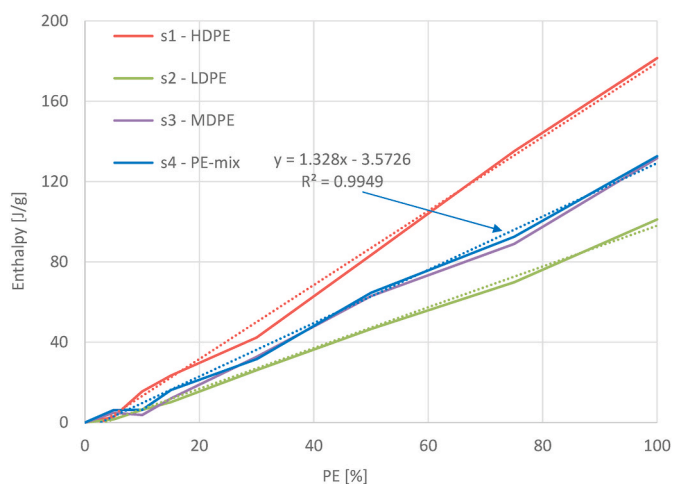


Fig. 3. Melting enthalpy as function of PE content for series with different PE materials and PE-mix (series 4) and the linear fit to the latter.

of equal parts of the three PE grades was made – called PE-mix – which then was blended with PP.

A special blend was also produced with equal parts of the six polymers (PE-1, PE-2, PE-3, PP-1, PP-2, PP-3), thus containing 50% PE.

2.3. Characterization

2.3.1. DSC

The samples were analyzed with a PerkinElmer DSC 8500. The heating rate was 10 K/min from 30 °C to 200 °C with isothermal steps at the start and stop to ensure instrument stability. Sample weights were about 5 mg.

For the data analysis, due to overlap of the melting peaks for PE and PP, an upper limit for the PE peak, T_{PE} was defined. Depending on the material grades, the estimated T_{PE} was in the range 127–135 °C for the different PE grades. Then, based on the thermogram for pure PP, the contribution of the PP shoulder below T_{PE} was estimated and scaled according to the known PP fraction. For PP copolymers, the low temperature shoulder extended down to around 80 °C. The melting enthalpy of PE was then calculated from the PE peak corrected for the PP contribution below T_{PE} . For rPP with overlap between PE and PP peaks,

and where the properties of the pure PP are unknown, a linear estimate for the low-temperature PP contribution below T_{PE} was used, fitting the lower temperature limit to each rPP grade. This step will imply some uncertainty of the estimates.

2.3.2. FT-IR

Measurements were performed with a Cary 670 FTIR spectrometer from Agilent Technologies using Attenuated Total Reflection mode (ATR). A diamond ATR crystal was used for the measurements (analysis depth 2.0 μm at 1000 cm⁻¹). The measurements were performed with 4 cm⁻¹ resolution using 16 scans in the range 4000 to 400 cm⁻¹. For making a calibration curve from blends with different PP and PE content 3 to 5 measurements were performed on each blend.

2.4. NMR spectroscopy

The NMR spectroscopy experiments were performed at 11.7T (500 MHz proton resonance frequency) by using a Bruker Avance III spectrometer, equipped with 4-mm and 3.2 mm solid-state probe. All the ¹³C NMR measurements were conducted at 298 K at a MAS spinning rate of 10 kHz with a cross-polarization magic angle spinning (CP/MAS) pulse sequence. The number of acquisitions was 2048. All the spectra were processed using TopSpin 3.2 software.

2.5. Gel content from peroxide extrusion

The compounds were first extruded with 2 wt % peroxide (Luperox 101XL45 purchased from Sigma-Aldrich). Compounds were then treated according to the standard ASTM D2765 [11] consisting of cryo-grinding using liquid N₂ in a Retsch Ultra Centrifugal mill ZM 200 with a 0.75 mm sieve, followed by extraction in boiling xylene. After extraction, the residual compound is dried and weighed, and the gel content is related to the amount of undissolved compound. The resulting gel content is then related to the PE content of known blends.

3. Results and discussion

3.1. DSC

Due to the overlap of melting peaks, the procedure described above was used to separately estimate the melting enthalpy for PE and PP.

For series 4 – the PE mix blended with the random copolymer (see Table 3) – the curves for 0, 50 and 100% PP are shown in Fig. 1. The low

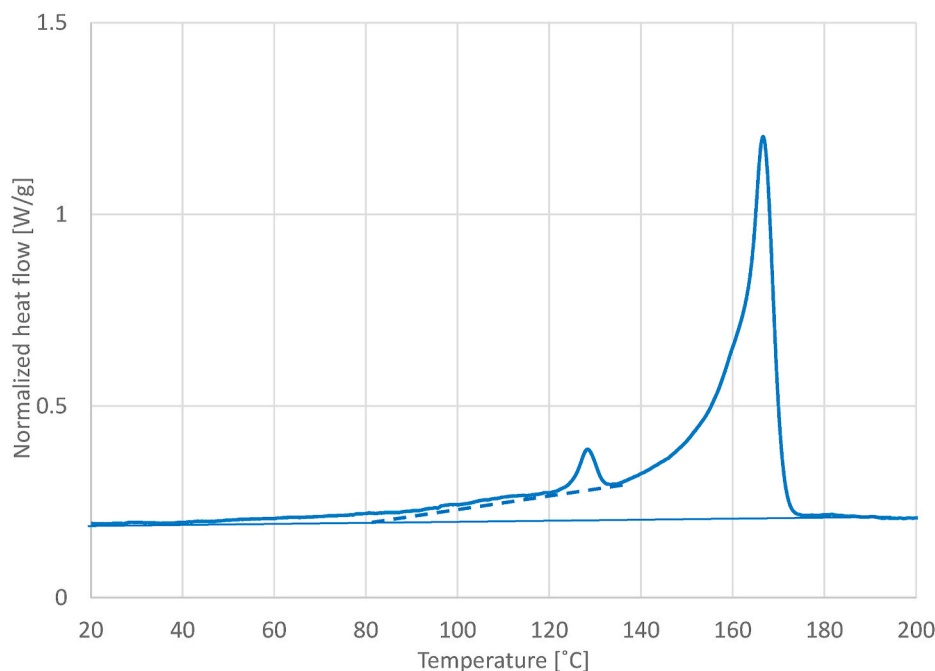


Fig. 4. Thermogram rPP-1.

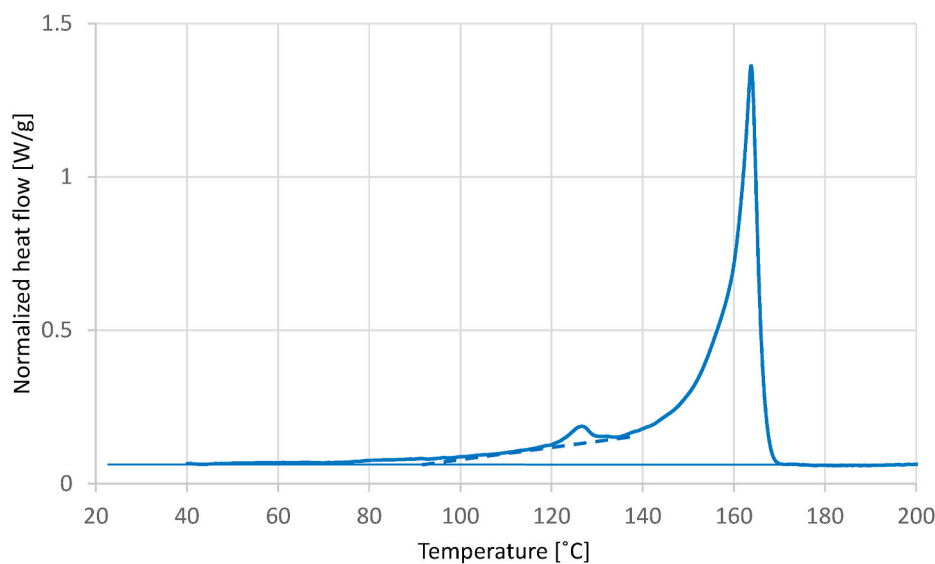


Fig. 5. Thermogram rPP-2.

temperature shoulder of the melting peak of 100% PP extends down in the range of 80 °C. We will have this in mind, as a general batch of recycled PP can be expected to contain copolymer.

For series 5, with the PP block copolymer, Fig. 2 shows the thermogram with 10% PE. The overlap of peaks is also significant in this case.

For series 1 and 2, with the homopolymer PP-1, PE and PP peaks were well separated. For both random copolymers and block copolymers shoulders of the PP melting peaks are clearly overlapping with the PE peak. This is likely due to the ethylene components of the PP copolymers. Estimation of the overlap in the test series listed above, using the method described above, is therefore important for the correct estimate of the PE peak.

Proceeding according to the method described, the normalized enthalpy of the PE peaks was calculated for all series. The results derived

are plotted in Fig. 3 displaying consistent, linear trends between PE melting enthalpy and PE fraction for all PE grades.

Fig. 3 shows how the result varies with the type of PE material, and that the MDPE overlaps with the PE mix. The results for series 5 – HDPE mixed with PP block copolymer – overlapped with series 1.

To extrapolate a master curve to be applied to a general rPP, the results for the PE mix blended with the PP random copolymer in series 4 are used, assuming this is most representative for a mix of recycled PP. The linear fit to series 4 is displayed on Fig. 3.

When analyzing rPP grades, the PE peak is estimated by a linear extension of the PP peak below T_{PE} , as described above. The inverted trendline for series 4 displayed in Fig. 3 was then used as a calibration curve to estimate the PE content from the PE melting enthalpy ΔH in J/g,

$$PE_4 = 0.753 \cdot \Delta H + 2.69 \tag{1}$$

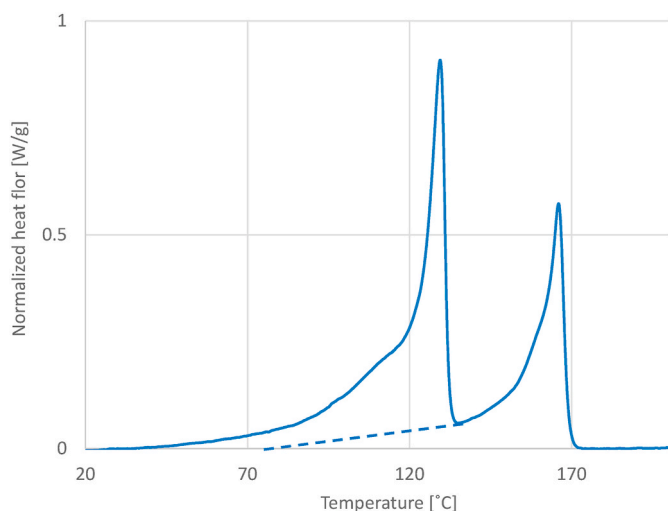


Fig. 6. Thermogram for the special blend – 50/50 PE-PP. Schematic estimate of PP shoulder.

Table 4
Melting enthalpies and estimated PE content for test samples.

Sample	ΔH [J/g]	% PE
rPP-1	2.62	4.7
rPP-2	2.49	4.6
Special blend – 50/50 PE-PP	69.4	54.9

As the goal is to apply the derived calibration curves to rPP, the same analysis is applied to rPP-1 and rPP-2. In this analysis, where the specific knowledge of the pure PP fraction is unknown, a geometric approach is chosen extrapolating the part of the PP shoulder above the PE peak down to around 80 °C.

Fig. 4 and Fig. 5 display the thermograms of the two rPP's with the extrapolated low-temperature PP shoulders.

From these thermograms, the PE peak is slightly more pronounced for rPP-1 than for rPP-2 but the low-temperature shoulders of the PP peaks, overlapping the PE peaks, also differ.

Fig. 6 shows the thermogram of the special 50/50 PE-PP blend which illustrates the overlap of the peaks due to the ethylene component in the PP copolymers. The figure includes an estimate of the low temperature PP shoulder.

From the figures above, the melting enthalpy of the PE peaks are presented in Table 4 with the PE content estimated from eq. (1).

3.2. FT-IR

FT-IR analysis was performed on five series of PP/PE blends with PP content from 0 to 100% as in Table 2. Fig. 7 shows a spectrum with 50/50 PP/PE (from Series 3). Three different methods to prepare calibration curves for determination of PP content have been tried out based on the measurements on PP/PE blends with known PP content. Camacho and Karlsson [1] describe a calibration curve based on the ratio of the heights of

$1168\text{ cm}^{-1}/(1168\text{ cm}^{-1}+716\text{ cm}^{-1})$ peaks.

Agilent [3] describes a calibration curve from the ratio of $1376\text{ cm}^{-1}/1462\text{ cm}^{-1}$ peaks (which is similar to the method described in ASTM D7399-18), and PerkinElmer [12] uses the ratio of the $716\text{ cm}^{-1}/1376\text{ cm}^{-1}$ peaks.

For the method using the $1376\text{ cm}^{-1}/1461\text{ cm}^{-1}$ ratio there are problems with the linear relationship between the PE/PP content and the peak ratio at low PE content. This was observed for all the series with PE/PP blends tested. The position of the so called 1461 cm^{-1} peak is not constant, for pure PP it is placed around 1455 cm^{-1} moving up to 1470 cm^{-1} for pure PE which may cause some inaccuracy for the method.

For the method using the $716\text{ cm}^{-1}/1376\text{ cm}^{-1}$ ratio it is a problem making a calibration curve over the whole PP/PE composition range. For PE contents from approximately 50% and downwards a relatively linear relationship between the ratio and PE content is found, but for e. g pure PE the ratio is very high, making it impossible to make a proper calibration curve for a PE concentration of 0%–100%.

The method using the ratio $1168\text{ cm}^{-1}/(1168\text{ cm}^{-1}+716\text{ cm}^{-1})$ was

Table 5
Average ratio $1168\text{ cm}^{-1}/(1168\text{ cm}^{-1}+716\text{ cm}^{-1})$ with standard deviation as a function of PE content in series 4.

% PE	Average ratio $1168\text{ cm}^{-1}/(1168\text{ cm}^{-1}+716\text{ cm}^{-1})$	Standard deviation
0	1.00	0.00
5	0.83	0.05
10	0.70	0.06
15	0.56	0.01
30	0.43	0.06
50	0.22	0.08
75	0.14	0.01
100	0.00	0.00

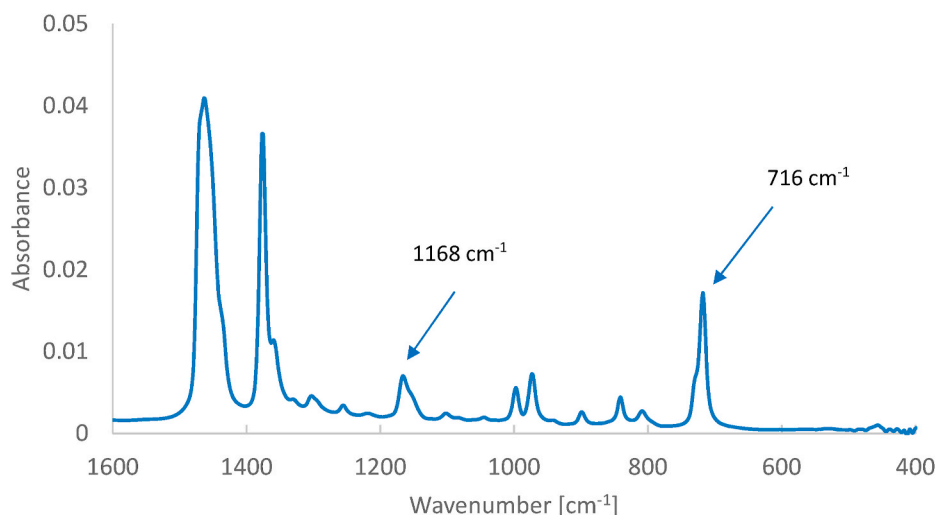


Fig. 7. FT-IR spectrum of 50/50 PP/PE blend (from Series 3). The two peaks used for making a calibration curve are marked.

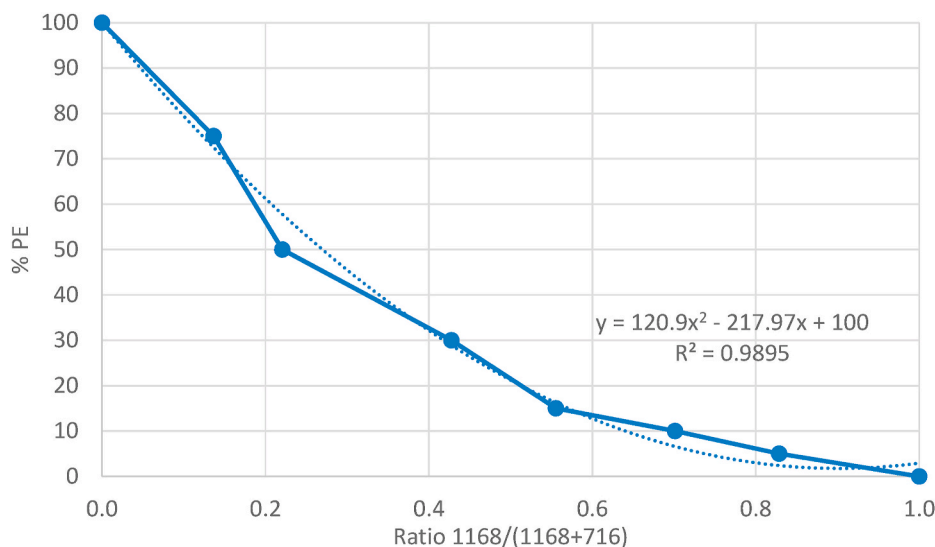


Fig. 8. Calibration curve for 1168/(1168 + 716) peaks based on measurements on series 4 blends.

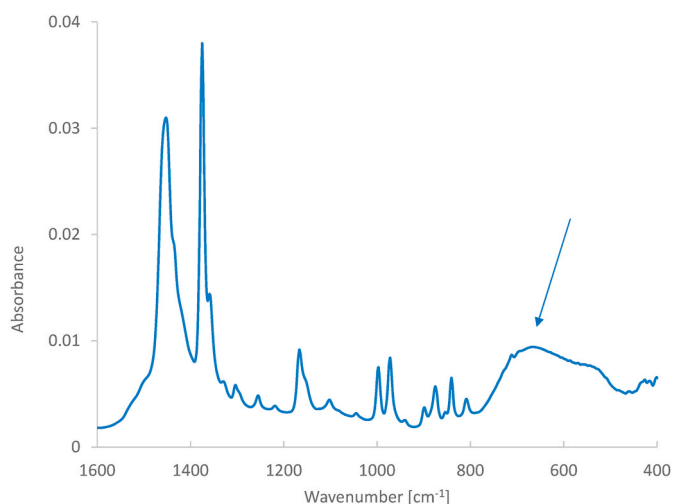


Fig. 9. FT-IR spectrum of rPP-2 showing a broad unidentified peak (marked with arrow) overlapping the 716 cm⁻¹ peak.

found to work best over the whole concentration range studied, this was found for all the series of PE/PP blends tested (the peaks are shown in Fig. 7). The calibration curves found could easily be curve fitted with a correlation coefficient close to 1.

The ratio 1168 cm⁻¹/(1168 cm⁻¹+716 cm⁻¹) as a function of PE content in series 4 blends are shown in Table 5. The calibration curve based on measurements on series 4 blends is shown in Fig. 8. The results from testing the calibration curve are shown in Table 8.

$$PE = 120.9I^2 - 217.97I + 100 \quad (2)$$

It was not possible to apply the calibration curve to rPP-2 because this PP has an unidentified broad peak overlapping the 716 cm⁻¹ peak (see Fig. 9).

The PE content as a function of the 1168 cm⁻¹/(1168 cm⁻¹+716 cm⁻¹) ratio for the other series with PP/PE blends are shown in Fig. 10–13. The curve fitting of the PE content as a function of the 1168 cm⁻¹/(1168 cm⁻¹+716 cm⁻¹) ratio for all the different series are quite good with a correlation coefficient close to one.

3.3. NMR

NMR was applied to series 1 and 4 in this study. PE and PP show distinct peaks in the NMR spectra of series 4 samples, see Fig. 14. Series 4 contains the mix of the three PE's in combination with the random copolymer. The ethylene component of the random copolymer is not visible in the spectrum of 100% PP.

Derived calibration curves for series 1 and 4 are given in Fig. 15 and Fig. 16.

It is assumed that the calibration curve for series 4 is most relevant to use with a general rPP,

$$PE = 1.0426I - 4.1599 \quad (3)$$

3.4. Gel content for samples extruded with peroxide

Figs. 17–19 show the gel content as a function of PE content for samples from series 1, series 3 and series 4, respectively. The gel content was measured on samples after compounding with 2% peroxide.

In series 1, PP-1 which is the homopolymer, a gel content of 0 was measured for 100% PP because it does not form cross-links after extrusion with peroxide. PE-3 is a HDPE which cross-links when extruded with peroxide (gel content approximately 50%). In blends of PP-1 and PE-3, the samples PP/PE 90/10 and 50/50 gave a gel content of approximately 5 and 20%, respectively.

For series 3, PP-2 which is a PP random copolymer, a gel content of around 5% was found after extrusion with peroxide due to cross-linking of the PE part of the copolymer. PE-2 is a MDPE, and without added peroxide this polymer has a gel content near zero because cross-linking is not expected to take place, extruded with peroxide a gel content from 56 to 59% was measured. A 50/50 blend of PP-2/PE-2 had a gel content of approximately 20%.

In series 4 PP-2 is mixed with a PE mix which consists of 1/3 of PE-1, PE-2 and PE-3, gel contents from 5% (pure PP) to 70% (pure PE mix) were measured.

Based on the gel content measurements, calibration curves were made for the three different PP/PE combinations. The calibration curves show that the gel content increases linearly with increasing PE content, as expected.

The calibration curves for the three series, where subscripts refer to the respective series, are:

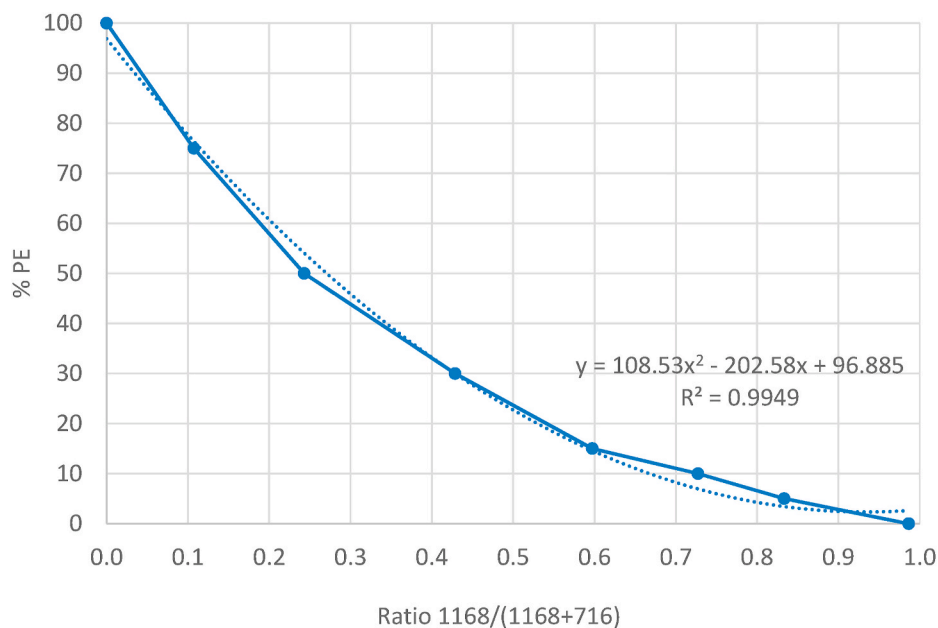


Fig. 10. PE content as a function of the ratio of 1168/(1168 + 716) peaks for series 1 blends.

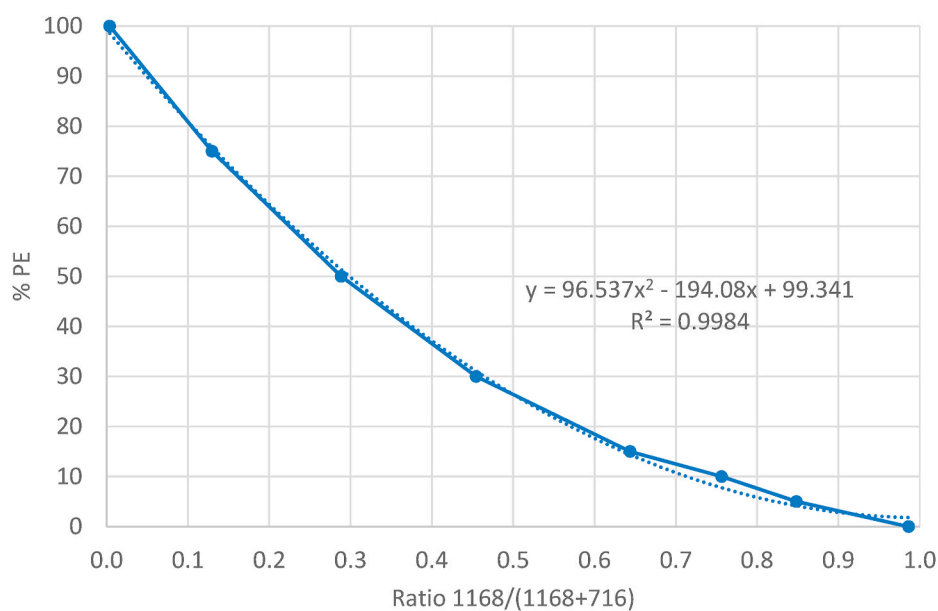


Fig. 11. PE content as a function of the ratio of 1168/(1168 + 716) peaks for series 2 blends.

$$PE_1 = 2.0995I + 2.1554 \tag{4}$$

$$PE_3 = 1.8975I - 2.7197 \tag{5}$$

$$PE_4 = 1.485 I - 3.221 \tag{6}$$

Table 6 shows the estimated PE content for the rPP materials and the special blend 1. Both rPP's have a gel content after extrusion with peroxide, indicating that the rPP's contains some PE. The rPP-1 has a relatively large deviation in gel content between the two measurements, which may also be explained by inhomogeneous distribution of PE in the PP material. There is a significant variation between the % PE estimated from the three different calibration curves. For the special blend 1 with a known PE content of 50% the estimation from the different calibration curves varies from 44 to 69%.

For the special blend 1, an average gel content of 31.6% was determined. Table 7 shows the 1/6 gel content of each of the materials that is included in the special blend 1 (based on the extraction of pure

individual material extruded with 2% peroxide). The sum of these individual gel contents is 30.7%, which corresponds well to the gel content of 31.6% measured on the special blend 1.

4. Overview of model tests on rPP and the special blend

To test the derived calibration curves, we selected two available rPP grades and included the special 50/50 PE-PP blend used in our study:

- o 50/50 PE-PP mix – special blend
- o rPP-1
- o rPP-2

The calibration curves based on series 4 were applied to these three materials. Results obtained for the four methods are given in Table 8.

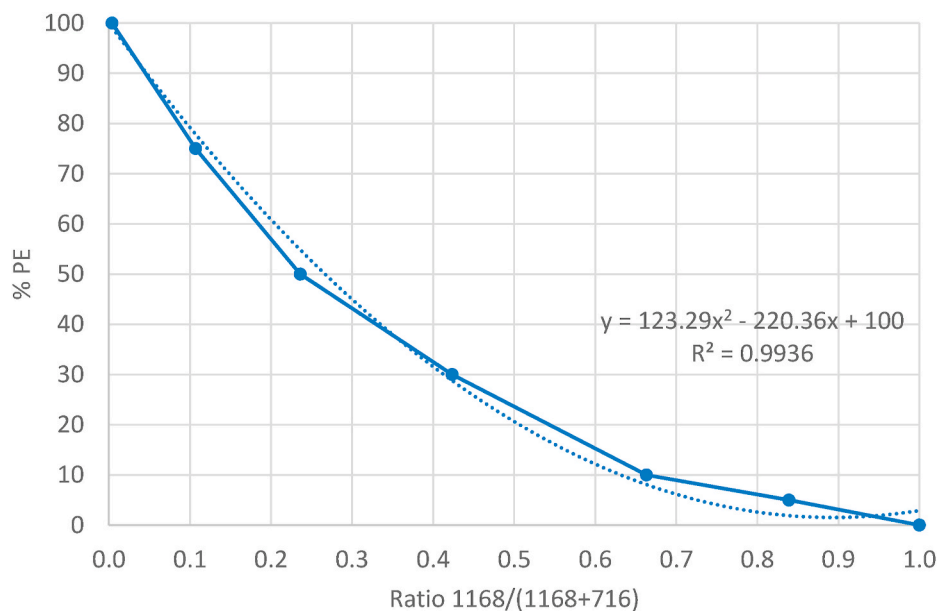


Fig. 12. PE content as a function of the ratio of 1168/(1168 + 716) peaks for series 3 blends.

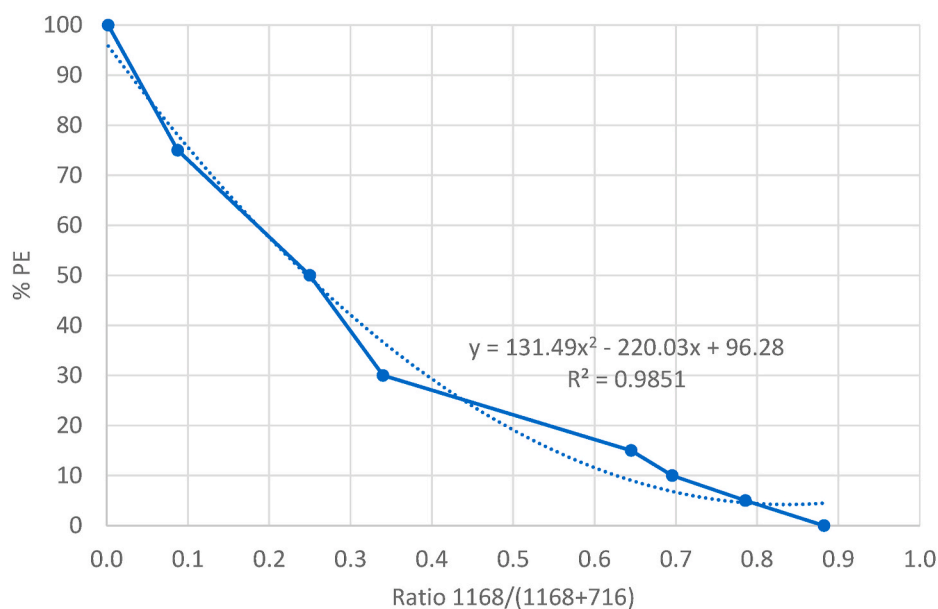


Fig. 13. PE content as a function of the ratio of 1168/(1168 + 716) peaks for series 5 blends.

As a check, rPP-1 extruded with 2% peroxide was also analyzed by FT-IR. Applying the established calibration curve, the result was 3% PE in accordance with other results.

5. Conclusion

Four different methods to be used to estimate the fraction of PE in recycled PP have been tested. Recycled PP is likely to contain different types of PP – homopolymer, random copolymer and block copolymer. In the same way, the PE fraction to be present is likely to be a mix of different types – LDPE, MDPE and HDPE. Therefore, all these types have been included in the study reported in this paper and the results show significant differences between the different types of PE and PP.

As basis for the model testing, results obtained from the series of samples based on a mix of the three different polyethylene grades blended with the PP random copolymer were used.

Comparison of the four methods shows agreement between results from DSC, FT-IR, NMR, and gel content. As PP copolymers contain an ethylene fraction, in DSC they show a low temperature shoulder overlapping with the PE peak. This overlap must be evaluated, and a method to account for the overlap was proposed to establish the calibration curves based on the properties of the known PP grade. Also, a method to estimate the overlap for rPP was suggested where detailed knowledge of the specific PP part is not available.

The respective calibration curves for the gel content were consistent, but the method may be less accurate for small PE content as is the case for rPP-1 and rPP-2. This is explained by the ethylene content of PP copolymers which may give additional cross-links in the PP fraction.

Of the methods tested, DSC and FT-IR are the most convenient for determining the PE fraction in rPP. The choice of FT-IR method was based on a comparison of three different methods to make calibration curves. DSC and FT-IR instruments are available in many laboratories,

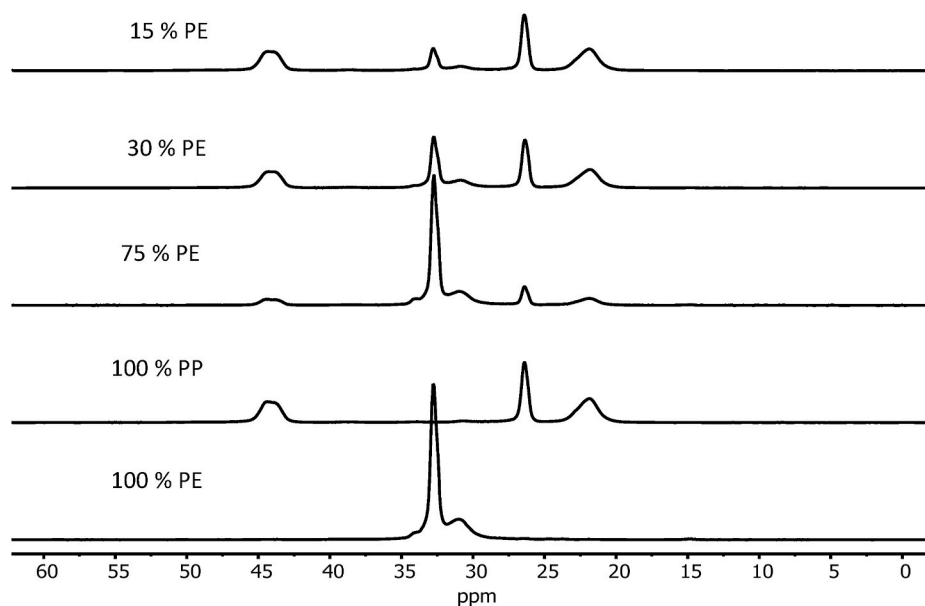


Fig. 14. Series 4 NMR spectra with PE fraction varied from 0 to 100%.

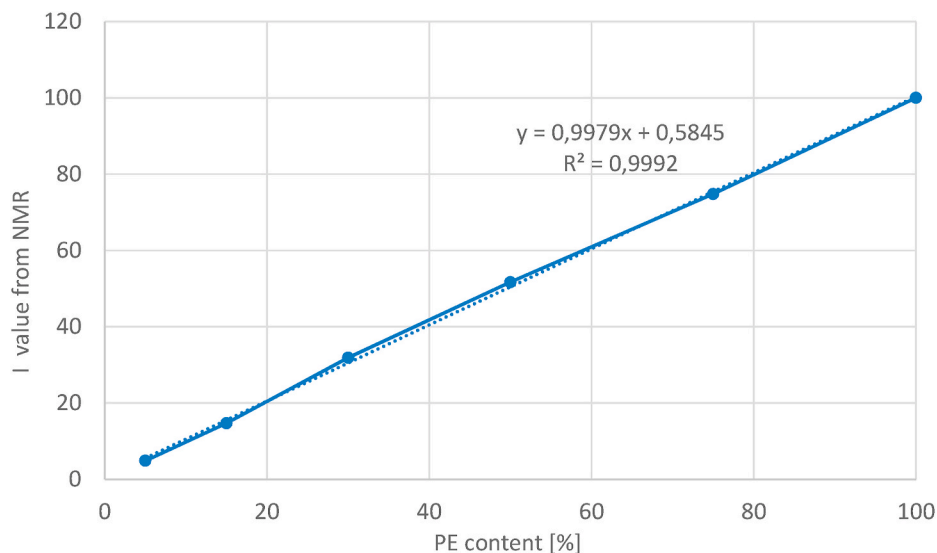


Fig. 15. NMR calibration curve for Series 1 – PP homopolymer and HDPE.

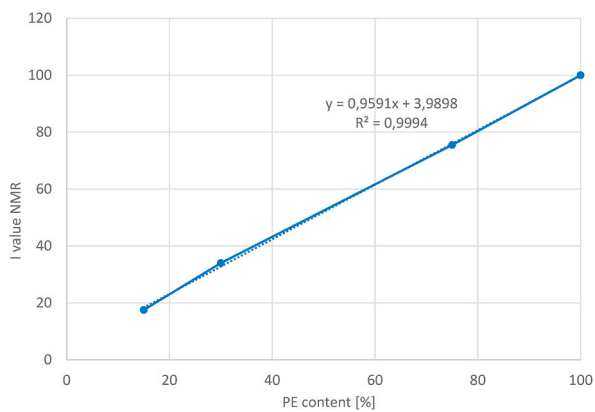


Fig. 16. NMR calibration curve for Series 4 – PP random copolymer and PE mix.

and the measurements are quick and easy to perform, especially after preparation of a calibration curve. Solid state NMR is not a common analysis technique as DSC and FT-IR, and the measurements are more time consuming. The extraction method is also quite time consuming due to the need to first extrude the rPP with peroxide, grinding of the extruded samples with following extraction and drying of samples.

Author statement

Larsen, Åge G.: Conceptualization, Methodology, Data curation, Writing- Original draft preparation.

Olafsen, Kjell: Conceptualization, Methodology, Data curation, Writing- Original draft preparation.

Ben Alcock: Methodology, Data curation, Writing- Reviewing and Editing.

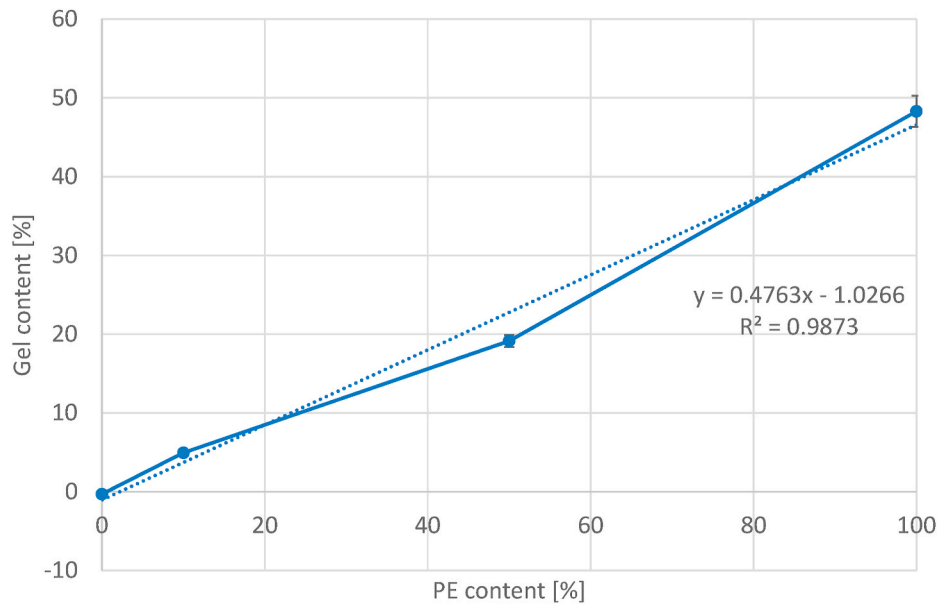


Fig. 17. Calibration curve based on PP-1 and PE-3 – Series 1.

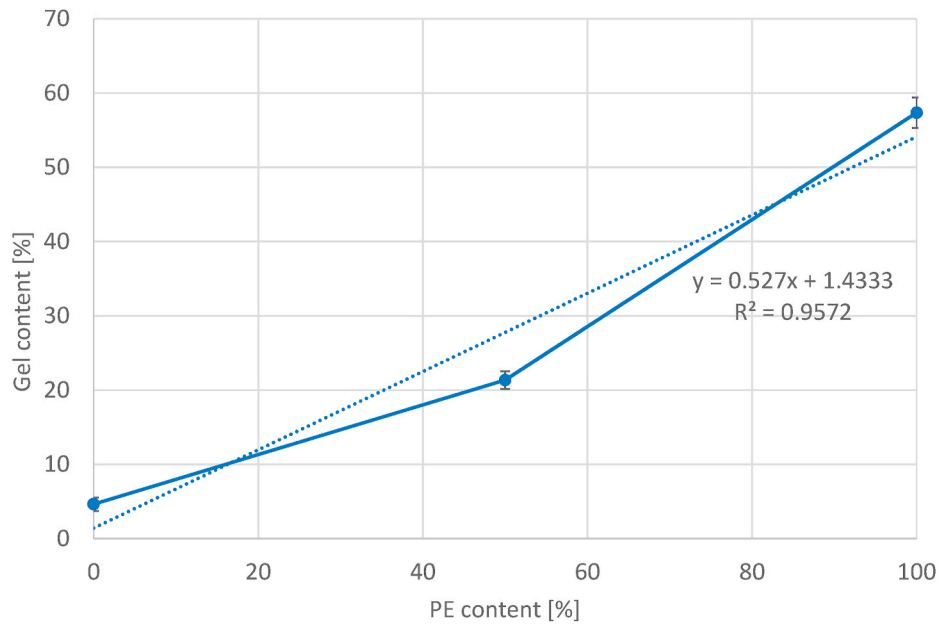


Fig. 18. Calibration curve based on PP-2 and PE-2 – Series 3.

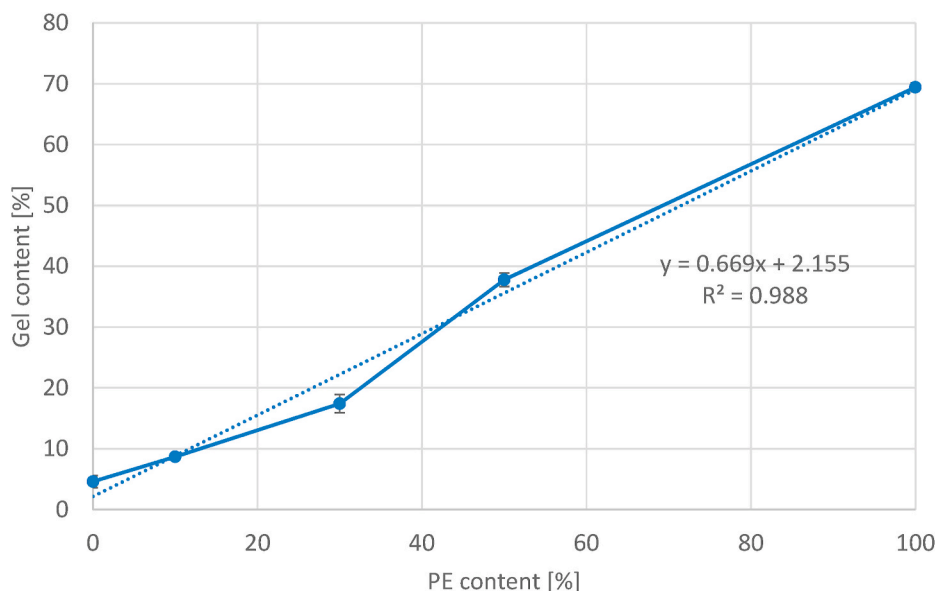


Fig. 19. Calibration curve based on PP-2 + PE mix - series 4.

Table 6

Gel content of rPP and PP/PE blend with peroxide.

Material	Gel content (%), two parallels	Average	% PE estimated from calibration curves
rPP-1 + 2% peroxide	2.9, 7.7	5.3	13 - PE ₁ 7 - PE ₃ 5 - PE ₄
rPP-2 + 2% peroxide	6.4, 7.6	7.0	17 - PE ₁ 11 - PE ₃ 7 - PE ₄
Special blend 1 + 2% peroxide	30.5, 32.6	31.6	69 - PE ₁ 57 - PE ₃ 44 - PE ₄

Table 7

Expected gel content for the special blend 1, all materials extruded with 2% peroxide.

Material	1/6 of average gel content (%)
PP-3	5.13
PP-2	0.77
PP-1	-0.05
PE-1	7.18
PE-2	9.57
PE-3	8.05
Sum	30.7

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

Table 8

Estimated PE content [%] in the two rPP's and the 50/50 blend based on PE₄ calibration curves.

Material	DSC	FTIR	NMR	Gel content ^a
Special blend	55	52	46	44
rPP-1	5	3	3	5
rPP-2	5	^b	3	7

^a Material extruded with 2% peroxide.

^b Contamination of sample gave signal overlapping FT-IR peaks.

the work reported in this paper.

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