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ORIGINAL PAPER

Thermal and Mechanical Properties of Blends Containing PP and Recycled XLPE Cable Waste

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Abstract

Recycled XLPE from cable manufacturing waste and end-of-life cables were mixed with virgin polypropylene (PP) in order to evaluate the potential to be used in new injection molded products. The influence of metal contaminations on the mechanical and thermal properties and how the blends could be stabilized in order to be recycled and give reliable properties over time were studied. The results show that blends of 25–50% XLPE in PP give good mechanical properties with retained or improved impact strength independent of the source of XLPE. Ageing at 105 °C for 6 months showed a more severe material degradation and loss of mechanical properties for blends that contained XLPE with end-of-life cable. Addition of metal deactivator proved to retain the mechanical properties for more than 8 months of ageing at 105 °C. Simulated recycling of 50% XLPE in PP stabilized with a metal deactivator, showed that mechanical properties were preserved.

Keywords Recycling · XLPE · Ageing · Stabilization

Introduction

Plastic cable scrap has been an issue for decades with different views of how to handle the polymeric waste after metal recovery [1, 2]. Most of the plastics from cables are incinerated and some end up as land fill, which contradicts the ambition of creating a sustainable society and a circular economy. Every year large amounts of cables and wires become waste, as much as 4–5 kg/person and about 40% of the weight is made up of plastic. Applied to Western Europe this means 1,000,000 tons plastic each year [3].

As new technology for recycling of cable waste has been developed, the separation processes driven by metal recovery, have resulted in polymer fractions with low amount of metal impurities (< 1%) that are also well separated from each other [4]. Hence, it is possible to separate the "light" fraction cable plastics from "heavier" fractions. This means that higher and lower density polymers can be recovered and used in different applications. Well characterized recycled cable plastics with known composition will give environmental and economic benefits when incorporated in new products [5].

Polyethylene (PE) and crosslinked polyethylene (XLPE) are beside polyvinyl chloride (PVC) and halogen free flame retarding polymers (HFFR), the most commonly used cable plastics. XLPE, which is mainly used in medium and high voltage cables, is crosslinked during the cable production and can therefore not be melt processed during recycling. Production waste from cable manufacturers might not go through the metal-plastic separation, but instead directly to shredding and milling. Other fractions of collected cable waste from building sites or refurbishments contain end-of-life cables of unknown origin. These fractions are processed through granulation with a metal–plastic separation and also through a plastic–plastic density separation.

Some efforts have been made to find methods to recycle XLPE through decrosslinking. Baek [6] demonstrated an extrusion process via a supercritical methanol reaction for decrosslinking silane cross-linked PE. In their study they managed to obtain 100% decrosslinking with only 2 min retention time. Another method used to decrosslink XLPE is based on thermoplasticization and chain scission which is achieved in an extruder providing high shear and high temperature [7]. Although these results are promising, there has been a lack of practical applications for decrosslinked XLPE. The equipment and processes needed are expensive

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and thus would contribute to a higher price for the recovered material. An alternative to recycling by decrosslinking is the mechanical recycling of XLPE milled to flakes or particles. Navratil [8] studied a system of LDPE filled with 10–60% of irradiation cross-linked HDPE from recycled pipes. The E-modulus was improved when the amount of cross linked HDPE was increased in the LDPE that originally had a low stiffness. Qudaih [9] studied the compounding of a virgin LDPE with addition of 5–15% cross-linked LDPE from cable waste. The XLPE was milled to a particle size of about 1 mm. An increase in elastic modulus, yield stress and stress at break was obtained in the study.

Mechanical recycling of XLPE from cable waste in different PE compounds was studied by Boss [4]. Injection molded samples of 50% XLPE in HDPE showed an increase in impact resistance and moderate reduction of stiffness compared to plain pristine HDPE. Extruded samples with 20% XLPE in LLDPE fulfilled the mechanical requirements for standard cable jackets and had retained mechanical properties up to 15 weeks of ageing in 100 °C. These results clearly show the potential of introducing recycled XLPE in various PE products which could contribute to decreased material costs.

Polypropylene (PP) is often chosen if a stiffer polyolefin than PE is desired. The introduction of a recycled fraction such as XLPE holds the potential to decrease the materials cost but the properties of blends with XLPE in PP have not been studied and published to our knowledge. Theoretically, the XLPE particles could be homogeneous distributed into a PP matrix because of the similar non polar nature of XLPE and PP while the materials are considered immiscible per se. It is known from the studies of XLPE in HDPE that the impact strength can be increased and similar results have been obtained when blending XLPE in a homo-PP (unpublished work by the present authors) [9].

Unstabilized polyolefins are prone to degradation by thermally induced oxidation or by UV exposure [10, 11]. Stabilizers are therefore added to virgin polymers to prevent degradation during thermal processing and to prolong the lifetime. Cable plastics are well stabilized in order to give a long service life, often at least 50 years and special stabilizers are added to the plastic in contact with the metallic conductor. Degradation of polyolefins in contact with transition metals e.g. copper is fast and detrimental to the polymers as both decreased activation energy and increased decomposition rate has been observed [12].

Addition of stabilizers to recycled polymers is an important issue since the age and condition of the recycled material in many cases are unknown. Recycled XLPE originating from end-of-life cables will contain metal impurities which make stabilization essential not least for the matrix polymer in blends. Addition of suitable stabilizers is therefore an important part in the materials development and use of recycled cable plastics in order to obtain reliable properties. The thermal stability of polyolefins is commonly measured by oxidation induction time (OIT). For certain stabilizers such as phenolic antioxidants and for phosphites used in combination with phenols, there is a linear relationship between the OIT and the stabilizer concentration in the material [13]. The analysis can be used as a fast method to estimate the stability of a recycled material.

When considering using recycled plastics, lifetime and long term properties are of crucial importance. Accelerated ageing by thermal exposure followed by mechanical testing has been used for a long time, to predict service life of polymers [14]. Exposure at elevated temperatures and materials analyses provide data that can indicate degradation mechanisms. This has been used extensively to study the degradation of PP but was also used for XLPE intended for cables [15].

Jansson [16] studied the degradation and mechanical properties of post-consumer PP exposed to simulated recycling through alternating thermal exposure and reprocessing by extrusion. The intention was to mimic the reality of recycled plastics. The results showed the importance of simulated recycling but also the wide variation between different recycled materials in terms of degradation and contamination. This emphasizes even more the necessity of stabilization when processing and using recycled plastics.

The objective of the present work was to study blends of XLPE and PP and the influence of the origin and content of the XLPE; i.e. compare cable manufacturing waste and a mixed fraction containing manufacturing cable waste and end-of-life-cable. The influence of the levels of contaminations on the properties and how the blends can be stabilized in order to be recycled and give reliable properties over time was of special interest.

Experimental

Materials

Recycled XLPE of two qualities were used in the study: system A consisting of peroxide crosslinked manufacturing waste only and system B which originates from a mix of about 25% manufacturing waste and 75% end-of-life cables. The materials have been processed through the cable granulation process and the plastic separation process called “PlastSep” owned by Stena Recycling, Sweden [4]. The XLPE materials were ground in a PKM 600 mill (Pallman, USA) to powders with particle size about 0.6 mm.

A commercial homo-polypropylene HG 313MO (Borealis) was chosen as matrix for the polymer blends in order to get a high stiffness. A masterbatch (MB) with 10% of the thermal processing stabilizer Irganox B 225 (BASF, Germany) was prepared at first and mixed with the PP matrix during the subsequent compounding. The final concentration of Irganox B 225 was 0.25% with respect to the amount of PP in each compound. Irganox MD 1024 which is a metal deactivator (denoted “Me”) and antioxidant was added to blends with 50% of XLPE system B. List of samples and their compositions are shown in Table 1.

Processing and Ageing

All blends were compounded in a co-rotating twin screw extruder (ZSK 26, Coperion, Germany) with screw diameters of 25 mm and an L/D ratio of 40. The screw configuration included three mixing elements and the rotating speed was 200 rpm. The total output was 7 kg/h and the set temperature was 210 °C over all heating zones. Test bars according to ISO 527-1A were injection molded in an injection molding machine (ES 200/110 HV-L, Engel, Germany) with a melt temperature of 230 °C and a mould temperature of 38 °C and cooling for 10 s. A reference sample of 100% XLPE of system A could not be processed in an extruder and was therefore prepared by pressing a 2 mm thick plate in a closed mold at about 220 °C for 10 min. Test bars according to ISO 527-1A were machined from the plate for mechanical testing. The sample of 100% XLPE of system A was used as a reference for comparison of the mechanical properties.

Accelerated ageing test was performed by exposing specimens in an oven at 105 °C with specimens hanging vertically in the oven with an air flow exchange of about 12 times per hour. The exposure continued for about 6000 h or until the mechanical strength was lost as shown by a clear decrease in strain at break. Simulated recycling by reprocessing five times through the twin screw extruder was performed with the blend 50% BMe5 containing Irganox B225 and Irganox MD 1024.

Materials Characterization and Testing

Thermal analyses were performed by DSC with a Mettler Toledo DSC 1 using aluminum crucibles of 40 µl. The melting behavior was observed by a procedure according to SS-ISO 11357-3: 2011 on samples of 5–10 mg that were cut from the interior i.e. a cross section or fractured surface of the test bars or on the milled XLPE powder particles as received. The analysis was performed in three steps at a constant nitrogen gas flow of 80 ml/min; heating at 10 K/min from 25 to 220 °C, cooling at 5 K/min from 220 to 25 °C and heating at 10 K/min from 25 to 220 °C. The procedure ensures identical thermal history of the samples and the second heating was used for evaluation of the material. The analysis was performed twice on each sample to control reproducibility. OIT was determined with the DSC on three specimens for each sample according to SS-ISO 11357-6:2008 on samples of 2–5 mg. The analysis was performed with a constant gas flow of 50 ml/min with nitrogen during the heating of 20 K/min. After 1 min of stabilizing at 200 °C, the gas was switched to oxygen and the time until start of oxidation (exothermal reaction) was measured.

The degree of crosslinking of XLPE was measured by the gel content using decalin extraction according to ASTM D2765:2006. The metal content in the XLPE powders was analyzed by a stationary X-ray flourescence (XRF) device (Spectro X-Lab 2000, Spectro, Country) using the cuvette method.

Melt flow rate (MFR) of samples was measured before thermal exposure and after mechanical breakdown with a Modular Melt Flow apparatus (Instron Ceast Division, Italy) at 230 °C and a load of 2.16 kg which is standard for PP according to ISO 1133.

Mechanical testing was performed on test bars according to ISO 527-1 on a universal testing machine MTS 20/M (MTS Systems Corporation, USA). The elastic modulus was measured with a testing speed of 1 mm/min and tensile strength at a speed of 50 mm/min. All tests were performed on a minimum of five specimens. The strain-at-break values were evaluated as an indicator for material degradation after accelerated aging at 105 °C. Charpy notched impact resistance was measured according to ISO 179 on the Ceast 9050 impact pendulum (Instron, USA) on ten specimens.

Table 1 Samples compositions

System	XLPE source	Sample	Composition	Stabiliser	Exposure
A	Manufacturing waste	25% A	25% XLPE/75% PP	0.19% Irganox B 225	105 °C
		50% A	50% XLPE/50% PP	0.12% Irganox B 225	105 °C
B	Manufacturing waste and end-of-life cable	25% B	25% XLPE/75% PP	0.19% Irganox B 225	105 °C
		50% B	50% XLPE/50% PP	0.12% Irganox B 225	105 °C
		50% BMe	50% XLPE/50% PP	0.12% Irganox B 225 + 0.2% Irganox MD1024	105 °C
		50% BMe5	50% XLPE/50% PP	0.12% Irganox B 225 + 0.20% Irganox MD1024	Compounding five times

Table 2 Results from gel content and XRF analyses of XLPE materials

	Gel content (%)	Cu (%)	Fe (%)
XLPE:A	75	0.00054	0.005
XLPE:B	52	0.01686	0.028

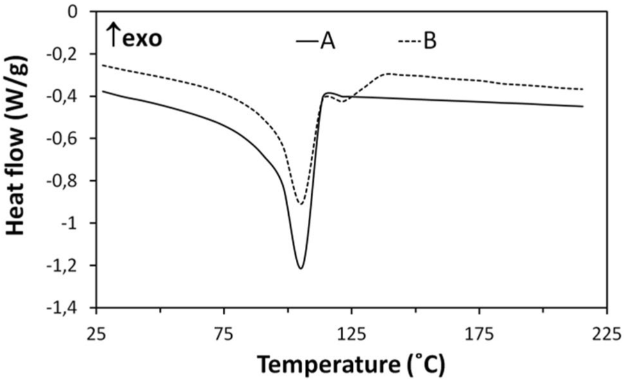

Fig. 1 Results from DSC analysis, showing the second melting for XLPE powders; A manufacturing waste; B: manufacturing waste and end-of-life cables

Scanning Electron Microscopy images were taken with a JEOL JSM-6610 LV instrument (JEOL, Japan) on fracture surfaces that were obtained by breaking a test bar that had been immersed in liquid nitrogen for about 30 s.

Results

Gel and Metal Content in XLPE

The gel content, which is a measure of the degree of crosslinking of the XLPE materials showed that XLPE: A was crosslinked to 75% which is regarded as "fully crosslinked" from a manufacturing point of view. XLPE: B, which mainly originates from "end-of-life" cables was 52% crosslinked. Results from XRF analysis in Table 2, show that XLPE:B contained about 30 times more copper and five times more iron than XLPE:A. There are also aluminum contaminations of higher level in A than in B but iron and copper are the most important that can influence the degradation, which will be discussed further below.

DSC and OIT Analyses

Figure 1 shows the thermal behavior of the XLPE materials during the second melting of the DSC analysis. System A, consisting of manufacturing waste shows a melting peak at 107 °C. The DSC curve for B revealed a melting peak at 106 °C and a separate small melting peak at 123 °C which indicate that the material, in addition to XLPE, might also contain a minor amount of linear polyethylene that could originate from jacketing material.

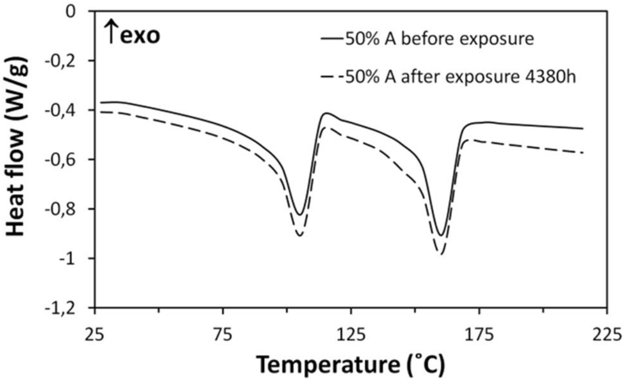

Fig. 2 Second melting of DSC analysis for blend with 50% A before exposure in 105 °C and after loss of mechanical properties at 4380 h of exposure

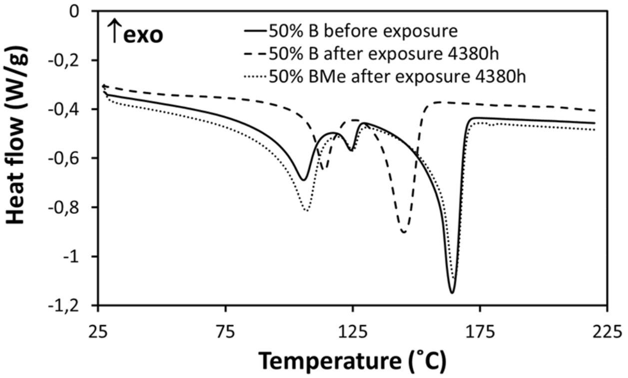

Fig. 3 Second melting of DSC analysis for blend with 50% B before exposure in 105 °C and after loss of mechanical properties at 4380 h of exposure. Results for 50% BMe with 0.2% metal deactivator after exposure to 105 °C for 4380 h is also shown

DSC analyses were made on blends with 50% A in PP and 50% B in PP before thermal exposure and after loss of the mechanical properties that took place after 4380 h exposure at 105 °C. Figure 2 shows the results for 50% A with one melting peak from the XLPE particles and one from the PP matrix. There is no significant difference between the sample before and after exposure although the development of a small shoulder on the low temperature side of the PP peak is visible. Figure 3 shows the results for B after 4380 h exposure. The peak from the crosslinked PE has an increased melting point temperature from 106 to 111 °C and the small melting peak at 123 °C has disappeared while the PP melting peak show a decrease in melting point from about 163 to 148 °C. The blend with

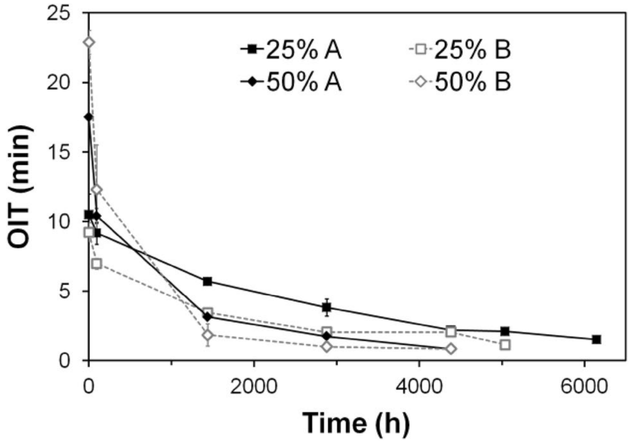

Fig. 4 Oxidation induction temperature ersus time of exposure in oven at 105 °C

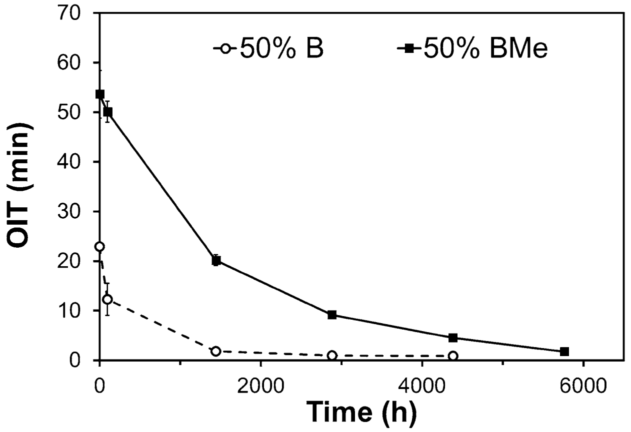

Fig. 5 Oxidation induction time versus time of exposure in oven at 105 °C

Table 3 OIT for blends with 50% B with and without metal deactivator

Blend	OIT (min)
50% B	22.9 ± 4.8
50% BMe	53.6 ± 4.8
50% BMe5	54.9 ± 0.8

Table 4 OIT for blends with 50% B with and without metal deactivator after 4380 h of exposure at 105 °C

Blend	OIT (min) after 4380 h exposure at 105 °C
50% B	0.8 ± 0.3
50% BMe	4.6 ± 0.4

metal deactivator added shows a thermal behavior which is very similar to the material before exposure.

Figure 4 shows the oxidation induction time (OIT) versus time of exposure in 105 °C for samples from the XLPE blends. The OIT decrease rapidly during the first 100 h of exposure since a substantial part of the stabilizer is consumed by thermally induced reactions and oxidation in the sample. The OIT decrease continues at a lower rate after 1000 h of exposure and is around 1 min when the materials finally lose all mechanical strength. It should be noted that the OIT for B is lower than for A at the same concentration of XLPE after exposure of about 1500 h until the breakdown of the material.

The effect of stabilizing by addition of a metal deactivator to a blend of B is shown in Table 3 and Fig. 5. 50% BMe and BMe5 containing 0.2% metal deactivator were compounded one and five times respectively. A large increase in OIT by addition of metal deactivator was observed and the OIT was retained also after compounding five times. Exposure at 105 °C of 50% BME for 4380 h resulted in a low value of OIT, close to 5 min but this is not as low as for the blend without metal deactivator which is shown in Table 4. The decrease of OIT versus time during thermal exposure for the blends with and without metal deactivator is shown in Fig. 5. The decrease of OIT to low values is delayed with addition of metal deactivator.

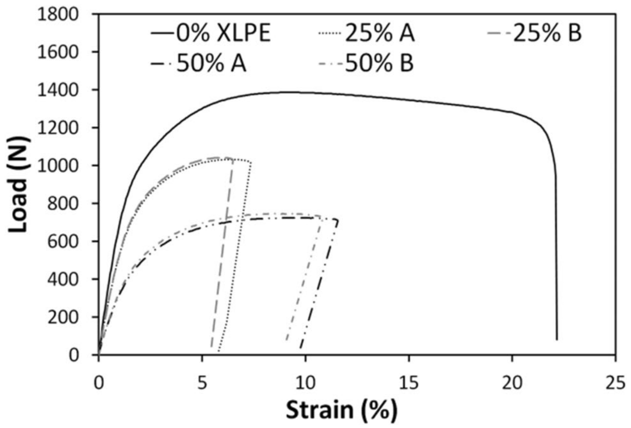

Fig. 6 Behavior during tensile testing of one typical specimen from each blend and the matrix homo PP (0% XLPE)

Mechanical Behavior

The behaviors of the materials during tensile testing are shown in Fig. 6. The ultimate strain of the material decreases significantly when 25% XLPE is added, but interestingly, the strain at break increases when the addition of XLPE is increased to 50%. The sample prepared from 100% XLPE (i.e. A) had a strain at break of nearly 120%, which is shown in Table 5. This sample was

Table 5 Results from mechanical testing of XLPE-PP blends before exposure

Material	E-modulus (MPa)	Stress at break (MPa)	Strain at break (%)	Charpy impact strength, notched (23°) (kJ/m^2)
0% XLPE	1497 ± 26	30.5 ± 0.5	21.2 ± 0.9	2.7 ± 0.1
25% A	1130 ± 14	25.7 ± 0.2	7.8 ± 0.7	2.9 ± 0.2
25% B	1143 ± 13	25.6 ± 0.2	7.0 ± 0.4	2.1 ± 0.3
50% A	653 ± 17	17.8 ± 0.1	11.2 ± 0.6	5.2 ± 0.3
50% B	676 ± 16	17.6 ± 0.9	10.7 ± 1.2	4.8 ± 0.2
50% BMe	717 ± 38	17.9 ± 0.2	11.3 ± 0.7	4.5 ± 0.1
50% BMe5	705 ± 11	18.3 ± 0.2	13.5 ± 1.2	3.2 ± 0.1
100% XLPE: A	181 ± 12	9.5 ± 0.4	119.7 ± 12.7	Non-break

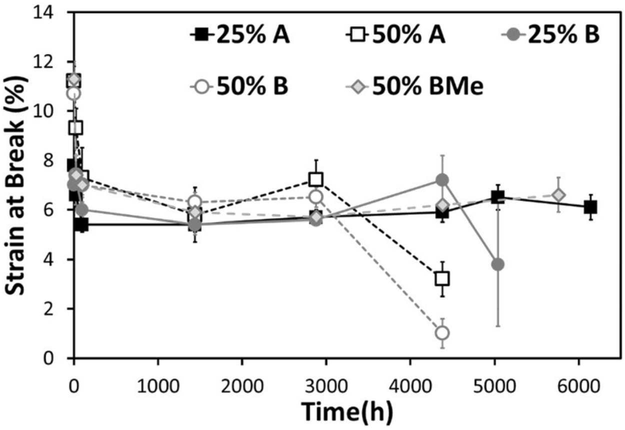

Fig. 7 Strain at break versus time of exposure in oven at 105 °C

Table 6 Results from melt flow rate measurement at 230 °C and 2.16 kg load

Blend	MFI (g/10 min)	MFI after exposure to 105 °C, 4380 h (g/10 min)
50% A	2.8	5.6
50% B	3.7	> 250
50% BMe	3.6	2.6

Table 7 Results from melt flow rate measurement at 230 °C and 2.16 kg load

Blend	MFI (g/10 min)
50% BMe	3.6
50% BMe5	3.3

prepared by a different method which could have an influence on the properties.

The results from the mechanical testing showed that the elastic modulus and the stress at break were almost identical for the blends with A and B for the same concentration of XLPE which can be seen in Table 5. The differences in strain at break and impact strength are small but with the indication of B obtaining lower values. The impact strength increases when the amount of added XLPE increases from 25 to 50%. 50% BMe5 which was compounded five times has lower impact strength than 50% BMe. The sample of 100% XLPE:A did not break when tested for impact strength.

Strain at break versus aging time for samples exposed at 105 °C can be used as an indicator of material degradation and the results are shown in Fig. 7. The blends with 50% XLPE had low strain at break after 4380 h. The degradation of the materials is dramatic and the blend with 50% B was most degraded with a strain at break of only 1%. The blend with 25% B had a rapid decrease in strain at break after 5040 h. The large standard deviation shows that some specimens in the sample were not completely degraded. The material with 25% A had retained strain even after 6144 h which indicates that blends with B degrade earlier than blends with A. The material 50% BMe had retained strain also after 5760 h.

Melt Flow Index

Table 6 shows results from measurements of MFI before and after exposure to 105 °C for 4380 h. There is a moderate increase of MFI for 50% A while the increase for 50% B is dramatic which indicate a severe degradation of the material. The opposite was observed for the blend 50% BMe that obtained a decreased value for MFI after thermal exposure. Table 7 shows that the difference in MFI between 50% BMe and 50% BMe5 is small which indicate that the material was not seriously affected by the reprocessing.

SEM images

SEM images of the materials show homogeneous distributions of XLPE particles in the PP matrix as displayed in Fig. 8 which shows a backscatter electron image of a test

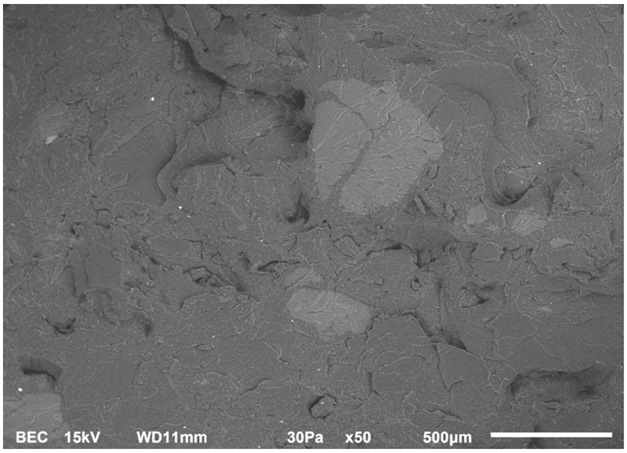

Fig. 8 Backscatter electron image of 50% A with XLPE particles appearing as light grey areas

bar fracture surface of 50% A. The XLPE particles containing carbon black, thus having a slightly higher density than the surrounding PP matrix appear as light grey areas. No particle agglomerates are found which indicate a good distribution of the XLPE in the PP. There are no visible voids in between the particle and the matrix however the edge around the particles is sharp which suggest low interaction between the two materials. The image shows no indication of pull-out particles i.e. there are no visible holes or other signs that the particles have been detached. The image is representative for the structure found in blends with XLPE:A and XLPE:B.

Discussion

The thermal analysis by DSC as shown in Figs. 2 and 3 reveals a large difference in the molecular structure of the blends with 50% A and 50% B after thermal exposure. The results for A show no large difference in behavior before and after exposure. The effect of thermal aging on the blend with B is more dramatic since the melting temperatures have changed which indicates a degradation by chain scission of the XLPE and the PP. Celina [15] studied the degradation of crosslinked polyethylene after thermal ageing by measuring the gel content and the mechanical properties. There was a continuing decrease in gel content with exposure time which indicates the breakdown of the crosslinking structure of the XLPE. This means an increased mobility for the polymer chains which changes the crystallization process. Without the crosslinking points, larger crystalline lamellae can form and thereby an increase in melting temperature can be observed.

The extreme increase of MFI of blend 50% B after oven ageing, see Table 6, indicates a strong reduction of molecular weight of PP by means of chain scission. The strongly reduced molecular weight is reflected in a decreased melting temperature of the PP, see Fig. 3. The decrease in melting temperature is most likely a result of a combination of oxidation and low molecular weight which creates defects in the crystal formation and thereby decreases the lamella thickness i.e. melting point [17, 18]. The chain scission reaction is most likely accelerated by the copper; see Table 2 which increases the rate of degradation of the organic peroxides that leads to the chain scission. The amount of copper in material B was about 30 times higher than in material A which could explain the more severe degradation in samples containing XLPE:B. Addition of a metal deactivator (50% BMe) was shown to efficiently counter act the oxidation reactions of PP maintaining both MFI of the blend, as seen in Table 7, and the melting point of the PP fraction in the blend shown in Fig. 3.

The decrease of OIT versus ageing time shows the consumption of stabilizer during the exposure to heat. The breakdown of polypropylene by chain scission will proceed rapidly once the stabilizers are consumed. OIT show a linear increase with stabilizer concentration for phenolic antioxidants and for phosphites when used in combination with phenols [13, 15]. The stabilizers used in this study are Irganox B 225 which is a combined organic phosphate and a hindered phenolic antioxidant and Irganox MD 1024 is a phenolic antioxidant and the values for OIT will therefore be proportional to the amount of still active stabilizer.

Comparing Figs. 4 and 8 show that the decrease of OIT i.e. consumption of stabilizer takes place before there is any significant reduction of the strain at break. The OIT for blends with B are lower than for blends with A from about 1500 h of exposure until the mechanical strength of the materials was lost as shown by a clear decrease in strain at break. These results correlate well with the fact that the blends with B lost the mechanical properties more dramatically or earlier than blends with A. The higher metal content in B can contribute to these results. Polymer degradation by metal contaminations is a well known problem that initiated research several decades ago. Osawas review article [19] states that transition metals such as copper can cause a fast degradation of polyolefins. A more recent work by Gorghiu shows the same results [20].

Addition of the metal deactivator Irganox MD 1024 delayed the decrease of OIT significantly and retained the mechanical properties over 5760 h (8 months) at 105 °C as seen in Figs. 5 and 8. Similar results have been obtained in other studies when Irganox MD 1024 was added to a PP-clay composite [21]. The values for OIT increased significantly with increasing concentration of metal deactivator and the temperature for start of oxidation also increased. The metal deactivation takes place by complex binding of the detrimental metal ions thus making them ineffective in attacking the formed organic hydroperoxides which would lead to chain scission [22]. The molecular structure of Irganox MD 1024 allows for these types of reactions but it also functions as a process and heat stabilizer due to the sterically hindering phenolic groups [23]. This will also contribute to postpone the degradation of the material. It is possible that a higher concentration of the stabilizer Irganox B 225 could have the same effect as was observed when metal deactivator was added. However, for cable materials in contact with conducting metals, such as copper, addition of specific metal deactivators are necessary. Conventional stabilizers are not considered enough [24].

The mechanical behavior of blends with XLPE in PP shows a lowering of the ultimate strain compared to pure PP. The reason is probably that the interfacial adhesion between the XLPE particles and the PP matrix is low and that XLPE particles may acts as impurities creating local stress concentrations. However, in blends with high concentration of XLPE (50%) the XLPE particles may form a more or less continuous network within the PP matrix and since the inherent strain at break of XLPE is much higher compared to PP (120% vs. 21%, see Table 4) the ultimate strain of the composite may increase, as seen by that 50% XLPE produce a higher ultimate strain than 25% XLPE. The E-modulus decreased linearly with XLPE concentration which is to be expected from the simple rule of mixtures.

The difference in mechanical properties between the blends containing A and B are small considering the difference degree of crosslinking. This is an advantage since it can be assumed that there is a much larger availability of recycled XLPE containing end-of-life cable compared to manufacturing waste.

The impact strength of the blends with 50% XLPE is higher than for homo PP alone. This is due to the high impact strength of XLPE since the crosslinked network in the particles can absorb mechanical energy. Sirisinha [25] found that a higher content of recycled XLPE in HDPE increased the impact strength and the increase was larger with a higher degree of crosslinking in the XLPE particles. Comparing A, with 75% crosslinking and B with 52% crosslinking would therefore lead to the expectation that A would give higher impact strength than B. This is not the case when comparing the results for impact strength as shown in Table 4 as blends with A only has a little higher impact strength than blends with B. This could be due to the incompatibility between PP and XLPE. Even though the SEM images reveal a homogeneous structure there will not be any real molecular interaction in the particle–matrix interface since the materials are immiscible leading to poor interfacial adhesion.

The impact strength for the blend 50% BMe5 which was reprocessed five times by compounding is 30% lower than for the fresh material. Contrary results i.e. a noticeably increase of the impact strength was observed in an unpublished work by the authors when XLPE was mixed with HDPE and reprocessed five times. The blends of XLPE in HDPE also obtained a large increase in strain at break after simulated recycling. This indicates a high degree of molecular interaction between the particles and the matrix. The observed difference between the XLPE/PE blends and XLPE/PP blends is probably due to effects of immiscibility between the XLPE particles and the PP matrix. Further SEM studies of the particle distribution in the matrix could possibly reveal if agglomeration of the XLPE particles in the PP matrix occur with increasing number of compounding cycles.

The value for MFI did not change a lot even after five times of reprocessing and degradation of the material should not be an issue. The results show that blends of XLPE and PP can be recycled several times without losing mechanical properties in any significant way.

The results from mechanical testing showed that the material properties were retained for at least 2880 h in the accelerated aging performed by exposure at 105 °C for blends without metal deactivator. Accelerated aging can be used to estimate the lifetime of a material and according to Dixon [26] an increase in 10 °C doubles the ageing rate. By using the same assumptions and conditions as Dixon the material without metal deactivator would have an estimated lifetime of more than 50 years at 25 °C. When adding the metal deactivator the mechanical properties were retained even after doubling the time to 5760 h. This would give an estimate service life well beyond 50 years. Although 50 year service life seems more than enough for many applications the ageing performance could decrease if there is a deviation in the amount of metal impurities. In order to ensure that the material can withstand fluctuation in the content of metal impurities a metal deactivator could be advantageous.

Conclusions

Recycled XLPE from manufacturing waste (A) and from a mixture of manufacturing waste and end-of-life cables (B) were blended with PP by compounding and injection molding. The mechanical properties of the blends showed similar values and the origin of the recycled XLPE was not considered to have any significant influence.

The thermal behavior and mechanical properties after ageing showed a large difference between the blends. The XLPE:B containing end-of-life cable was severely degraded which was observed by a decrease of the melting temperature of 15 °C for the PP matrix and a large increase in the MFR. This can be explained by the fact that recycled plastic from end-of-life cables has a higher content of metal impurities compared to plastic from manufacturing waste. A high amount of metal impurities, especially copper can increase the rate of degradation in polyolefins.

Addition of a metal deactivator to the blend containing XLPE: B showed that the thermal behavior and mechanical properties were retained even after 5760 h of exposure at 105 °C.

Simulated recycling by compounding as much as five times showed that the mechanical properties were overall maintained but the impact strength was decreased by 30%. The results reveal that compounding several times only generates minor deterioration of the material.

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References

1. Bevis M, Irving N, Allan P (1983) Conserv Recycl 6:3–10
2. Hagström B, Hampton RN, Helmesjo B, Hjertberg T (2006)) IEEE Electr Insul Mag 22:21–30
3. Christéen J (2007) Swedish cable waste for recovery in China or Sweden, Master thesis report, LIU-IEI-TEK-A–07/00097—SE, Linköping
4. Boss A, Boström JO, Nilsson PH, Farkas A, Eriksson A, Rasmussen E, Svenningsson E, Dalesjö M, Johansson A (2011) In: Proceeding of 8th international conference on insulated power cables, Versailles, France, June 19–23, B.2.6
5. Zackrisson M, Jönsson C, Olsson E (2014) Adv Chem Eng Sci 4:221–232
6. Baek BK, Shin JW, Jung JY, Hong SM, Nam GJ, Han H, Koo CM (2015) J Appl Polym Sci 132:1–7
7. Tokuda S, Horikawa S, Negishi K, Uesugi K, Hirukawa H (2003) Furukawa Rev 23:88–93
8. Navratil J, Manas M, Mizera A, Bednarik M, Stanek M, Danek M (2015) Radiat Phys Chem 106:68–72
9. Qudaih R, Janajreh I, Vukusic SE (2011) Advances in sustainable manufacturing. In: Proceedings of the 8th global conference on sustainable manufacturing, Abu Dhabi City, Abu Dhabi, Nov 22–24, 2010, Seliger G (ed) Springer Nature, 231–237
10. Schwarzenbach K (2009). In: Zweifel H, Maier RD, Schiller M (eds) Plastics additives handbook, chap 1, 6th edn. Hanser Publishers, Munich, pp 3–9
11. Gugumus F (2009) In: Zweifel H, Maier RD, Schiller M (eds) Plastics additives handbook, chap. 2, 6th edn. Hanser Publishers, Munich, pp 139–152
12. Day M, Cooney JD, MacKinnon M (1995) Polym Degrad Stab 48:341–349
13. Pauquet JR, Todesco RV, Drake WO (1993) In: Proceeding of the 42nd international wire and cable symposium, Nov 15–18. St Louis, USA, IWCS, 1993, 1–9
14. Celina M, Gillen KT, Assink RA (2005) Polym Degrad Stab 90:395–404
15. Celina M, George GA (1995) Polym Degrad Stab 48:297–312
16. Jansson A, Möller K, Gevert T (2003) Polym Degrad Stab 82:37–46
17. Hocquet S, Dosiére M, Tanzawa Y, Koch MHJ (2002) Macromolecules 35:5025–5033
18. Fatou JG, Mandelkern L (1965) J Phys Chem 69:417–428
19. Osawa Z (1988) Polym Degrad Stab 20:203–236
20. Gorghiu LM, Jipa S, Zaharescu T, Setnescu R, Mihalcea I (2004) Polym Degrad Stab 84:7–11
21. Fitaroni LB, de Lima JA, Cruz SA, Waldman WR (2016) Polym Test 53:165–173
22. Hendrickson L, Connole KB (1995) Polym Eng Sci 35:211–217
23. Grabmayer K, Wallner GM, Beißmann S, Braun U, Steffen R, Nitsche D, Röder B, Buchberger W, Lang RW (2014) Polym Degrad Stab 109:40–49
24. Schwarzenbach K (2009) Zweifel H, Maier RD, Schiller M (eds) Plastics additives handbook, chap 1, 6th edn. Hanser Publishers, Munich, pp 61–62
25. Sirisinha K, Chuaythong P (2014) J Mater Sci 49:5182–5189
26. Dixon RR (1980) IEEE Trans Electr Insul 15.4:331–334