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Tensile properties of LDPE/electrical cable waste blends prepared by melt extrusion process

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Propiedades de resistencia a la tracción de las mezclas de residuos de LDPE/cables eléctricos, preparadas mediante el proceso de extrusión por fusión

Propietats de resistència a la tracció de mescles de residus de LDPE/cables elèctrics, preparats per mitja del procés de extrusió per fusió

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SUMMARY

In this study low density poly-ethylene (LDPE)/electrical cable waste blends were prepared using a single-screw extruder at pilot plant level. The cable waste was mainly composed of LDPE, synthetic rubbers, flexible poly-vinyl chloride (PVC) and traces of conductive metal. Recycled LDPE was recovered by using the gravimetric separation approach. Heterogeneous extruded filaments were obtained because of the presence of not-melted waste particles that caused the interruption of the extrusion process. In order to improve the mixing and the homogeneity of the extruded filaments, LDPE waste was collected using nest sieves with opening mesh of 1.68 and 0.59 mm. The mechanical properties of the blends were related to the LDPE waste content and processing. In general, the mechanical parameters corresponding to the heterogeneous extruded filaments were notoriously lower than the LDPE because of large and not-melted waste particles caused the premature failure of the material. The blends containing sieved LDPE waste particles showed higher values in stiffness and ductility with respect to the rest of the blends.

Keywords: Recycling; mechanical properties; processing.

RESUMEN

En este estudio, las mezclas de residuos de polietileno de baja densidad (LDPE)/cable eléctrico se han preparado usando un extrusor de rosca única a nivel de planta piloto. Los residuos de cables estaban compuestos básicamente de LDPE, goma sintética, cloruro de polivinilo flexible (PVC) y trazas de metal conductor. El LDPE reciclado se recubría usando el método de separación gravimétrico. Se obtenían filamentos extruidos heterogéneos debido a la presencia de partículas residuales no fundidas que causaban la interrupción del proceso de extrusión. Para mejorar la mezcla y homogeneidad de los filamentos extruidos, se recogían residuos de LDPE usando tamices o cribas con una abertura de malla de 1.68 y 0.59 mm. Las propiedades mecánicas de las mezclas se relacionaban con el contenido residual y el procesamiento del LDPE. En general, los parámetros mecánicos correspondientes a los filamentos extruidos heterogéneos eran bastante inferiores a los del LDPE debido a que las partículas residuales grandes y no fundidas causaban el fallo prematuro del material. Las mezclas que contenían partículas residuales de LDPE tamizadas mostraban valores superiores en rigidez y ductilidad con respecto al resto de las mezclas.

Palabras clave: Reciclado; propiedades mecánicas; procesamiento.

RESUM

En aquest estudi, les mescles de residus de polietilè de baixa densitat (LDPE)/cable elèctric s'han preparat fent servir un extrusor de rosca única a nivell de planta pilot. Els residus de cables estaven composts bàsicament per LDPE, goma sintètica, clorur de polivinil flexible (PVC) i traces de metall conductor. El LDPE reciclat es recobria fent servir el mètode de separació gravimètric. La obtenció de filaments extruïts hetero-

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genis era deguda a la presencia de partícules residuals no foses que provocaven la interrupció del procés de extrusió. Per millorar la mescla i homogeneïtat dels filaments extruïts es recollien residus de LDPE mitjançant tamisos o garbells amb una obertura de malla de 1.68 i 0.59 mm. Les propietats mecàniques de les mescles es relacionaven amb el contingut residual i el processament de LDPE. En general, els paràmetres mecànics corresponents als filaments extruïts heterogenis eren bastant inferiors als de LDPE degut a que les partícules residuals grans i no foses provocaven la fallada prematura del material. Les mescles que contenien partícules residuals de LDPE tamisades mostraven valors superiors en rigidesa i ductilitat respecte la resta de mescles.

Paraules clau: Reciclat; propietats mecàniques; processament.

INTRODUCTION

It is well known that urbanisation, industrialisation and population growth affect the plastic generation. The global plastics production has grown continuously for more than 50 years. Thus, the worldwide production in 2014 rose to 311 million tonnes, meaning a 3.9% increase compared to 2013, and approximately 28% respect to 20041. China (26%), Europe (20%) and the North American Free Trade Agreement NAFTA (19%) are top of the rankings for global plastics production[1].

Plastic materials are used in an expanding range of products with diverse uses in packaging, construction, medicine, electronics, automotive, appliances and consumer products[2]. According to the Association of Plastics Manufacturers in Europe [1], the Building & Construction segment represents the 20.1% of the total plastic demand and, within this segment, the 18% is demanded for manufacturing electrical cables, which makes it of interest and potentially attractive to the plastic recycling sector.

Electrical cables are constituted of a core conductor material like copper or aluminium, and an insulation material composed of PVC, LDPE and elastomers. In the past, the market for wire recycling from electrical cable waste was entirely based on the high commercial value of the conducting metal, while plastic materials were often neglected. Currently, the potential to increase the recycling of plastics from electrical cable waste is really high because of significant environmental impacts and economic savings[3].

It is well studied that the plastic materials can be recovered by using several methods like chemical recycling, energy recovery and mechanical recycling[4–13]. However, the later method is widely used since it is relatively easy, economical and possible to scale to industrial processes. It refers to operations that aim at recovering plastic waste via mechanical processes like the melt extrusion process, which is a continuous process that includes mixing, cooling, pelletizing and, depending on the final product, forming.

In general, the recycled materials are typically used in applications with mechanical requirements lower than virgin polymers because of the mechanical properties of the recyclates are not spectacular, since polymers can suffer degradation from heat, mechanical stress, oxidation or ultraviolet radiation during their lifetime and reprocessing[8,14,15].

The aim of this work is to evaluate the influence of the plastic cable waste concentrations on the tensile properties of the LDPE blends, which were obtained by means of the melt extrusion process. The results section of this manuscript is divided in three parts related to the mechanical performance: the first one analyses the effect of the residual waste content; the second part evaluates the influence of a second reprocessing of extrusion and the third part studies and compares the mechanical parameters by using sieved waste particles.

MATERIALS

In this work LDPE Lupolen 1800H from LyondellBasell with a density of 0.919 g/cm^3 and a melt flow index (MFI) (190°C/2.16 kg) of 1.5 g/10 min was used. The LDPE has a tensile modulus and yield strength of 200 and 9 MPa respectively, with an elongation at break higher than 50%.

The electrical cable waste was supplied by a certified company for the waste management of electrical cables located in Catalonia, Spain. According to this company, the composition by weight of the cable waste provided should be: 60% PVC (1.4 g/cm^3), 30% LDPE (0.92 g/cm^3), 9% synthetic rubber (1.2 g/cm^3) and 1% metal fraction.

EXPERIMENTAL

Metal-free cable plastic waste

The metal fraction contained into the cable plastic waste was removed before the extrusion process, which resulted in a tremendous effort and patient since the very small metallic wires were separated manually from the cable waste.

LDPE recovery

Once the metal fraction was removed, PVC and LDPE were separated each other by using the gravimetric separation technique, which is relatively easy, economical and simple to do. First of all, the metal-free cable waste was placed in a beaker with water, which was used as the suspending medium because of its density (ρ = 1 g/cm^3). The floating portion was considered as the residual LDPE waste and labelled as R in this work. The non-floating portion was discarded because it was assumed to be composed of PVC and synthetic rubbers.

Melt-extrusion process

Blends of virgin LDPE and R (LDPE/R) were mixed in a pilot-scale extrusion line using a single-screw extruder (IQAP-LAP) with a screw diameter of 30 mm and an L/D ratio of 25. The screw rotation speed was set at 30 rpm and the processing temperatures were between 100°C in the feed section and 160°C in the extrusion die. At the end of the extruder, the extruded filament was cooled in a water bath and pelletized in a granulating cutting machine (Figure 1).

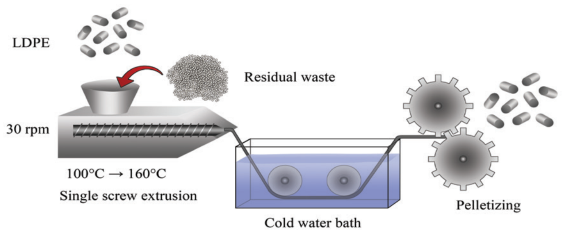

Figure 1. *Schematic representation of the single-screw extrusion process line used to prepare the LDPE/electrical cables waste blends.*

It is worth noticing that both virgin LDPE and R were dried previous to the extrusion process in an oven with forced air circulation (JP Selecta) at 80°C for 24 h.

Specimens and mechanical properties

ASTM tensile test dog-bone specimens of virgin LDPE and LDPE/R blends were obtained in an injection moulding machine (Mateu Solè METEOR 70/22) with a clamping force of 22 tons. The injection temperature profile of 185 to 160°C from hopper to nozzle was employed. The wall temperature of the mould was kept at 30°C. The material was injected into the mould at an injection speed of 45 mm^3/s with a maintenance pressure of 50 bar and a holding time of 11 s. The cooling cycle was kept constant at 45 s.

Uniaxial tensile tests (ASTM D-638 standard) were carried out in a universal testing machine (Galdabini Sun 2500) equipped with a 5 kN load cell. The tests were performed at a crosshead rate of 50 mm/min and at room temperature (23 ± 2°C). Young's modulus (E), yield strength (σ_y) and tensile at break (σ_b) were obtained from the engineering stress versus strain curves, and the elastic deformation (ε_b) was measured using a video extensometer (Mintron OS-65D).

The broken surfaces were observed in a stereo microscope (Carton) and the optical images were captured using an adapted digital camera (ProgRes CT3).

RESULTS AND DISCUSSIONS

LDPE recovery

The metal fraction removed from the electrical cable waste was approximately 0.8 wt.%, which is very close to the value stated by the supplier. On the other hand, by applying the gravimetric separation technique it was found the cable waste contained 23 wt.% of LDPE, represented by the floating portion (R), and 77 wt.% of PVC and synthetic rubbers represented by the non-floating portion. The results are not in concordance with the information provided by the supplier. Nevertheless, the gravimetric separation method is highly useful and currently used for industrial proposes, which is the main address of this work.

Mechanical properties: one-step of extrusion process

For the first part of this work, three LDPE/R blends were prepared after mixing virgin LDPE with 7.5, 15 and 25 wt.% of R (LDPE/7.5R1, LDPE/15R1 and LDPE/25R1) in a single-screw extruder. The code R1 indicates the blends were extruded once, as presented in Table 1.

The materials were not difficult to mix with different concentrations of **R** because the control panel sensors of the extruder did not show variations in the values of internal pressure, maintaining the pressure in approximately 8 MPa for all the blends. However, the major drawback was presented at the outside of the extruder, where the extruded filament constantly broke, causing the extrusion line to stop. The previous was attributed to the presence of immiscible particles that caused heterogeneities into the extruded filament and promoted its breaking during the collecting at the outside of the extruder. The heterogeneities were physically evident and shorter extruded filaments (**Figure 2a**) were collected as the R content increased.

Table 1. *Mechanical properties of the virgin LDPE, LDPE/R1 and LDPE/R2 blends*

	Material	E (MPa)	σ_y(MPa)	σ_{max}(MPa)	σ_b(MPa)	ε_b (%)
	LDPE	145.20 ± 1.82	8.65 ± 0.32	14.19 ± 0.14	13.92 ± 0.13	173.73 ± 14.93
one-step of extrusion	LDPE/7.5R1	78.60 ± 1.68	7.36 ± 0.14	11.96 ± 0.14	11.65 ± 0.16	142.65 ± 8.52
	LDPE/15R1	78.32 ± 1.41	7.25 ± 0.26	11.34 ± 0.21	11.12 ± 0.36	123.41 ± 12.31
	LDPE/25R1	78.96 ± 1.23	7.18 ± 0.37	10.69 ± 0.28	10.52 ± 0.31	114.85 ± 16.35
Two-steps of extrusion						
	LDPE/7.5R2	69.53 ± 1.35	7.55 ± 0.23	12.04 ± 0.62	11.73 ± 0.50	124.75 ± 5.70
	LDPE/15R2	65.10 ± 1.60	7.31 ± 0.41	11.02 ± 0.33	10.75 ± 0.24	80.87 ± 6.60

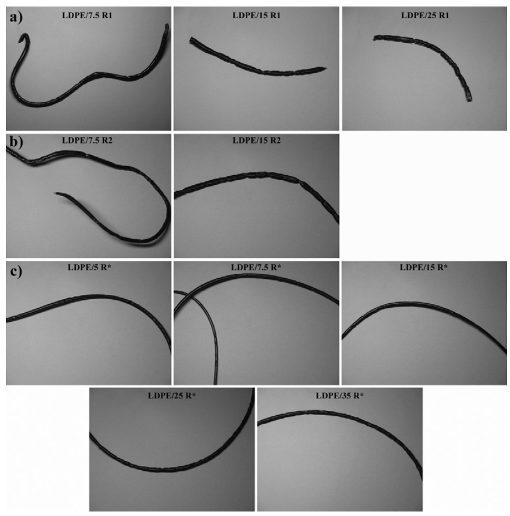

Figure 2. *Photographs of the extruded filaments at the outside of the extruder: a) LDPE/R1, b) LDPE/R2 and c) LDPE/R* blends*

Figure 3 shows the representative engineering stress – strain curves obtained during the tensile tests of LDPE and LDPE/R1 blends.

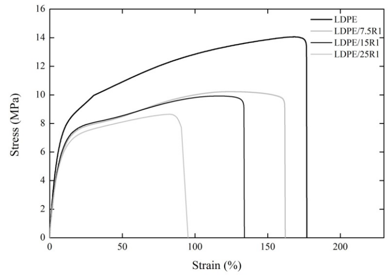

Figure 3. *Stress – strain curves of the virgin LDPE and LDPE/R1 blends.*

All the curves exhibited an initial linear elastic region followed by a diffuse yielding, which was attributed physically to a not well-defined necking on the specimens during the tensile tests. During the plastic deformation, the stress – strain curves showed a continuous increase in strain at low stress values (more evident for the blends) followed by the failure of the specimen. Both the maximum stress and the maximum strain were reduced with the addition of R; hence, the area under the curve of the virgin LDPE is clearly higher than the LDPE/R1 blends.

The representative broken specimens corresponding to the virgin LDPE and the LDPE/R1 blends are shown in Figure 4. For all specimens, large plastic elongation was not developed and the necking or localized deformation was not really noticeable. The diffuse necking was ascribed to the injection moulding conditions that induced changes in the microstructure of the LDPE in terms of crystallinity[16]. Other traces of plastic deformation mechanisms like whitening were not observed during the tensile tests.

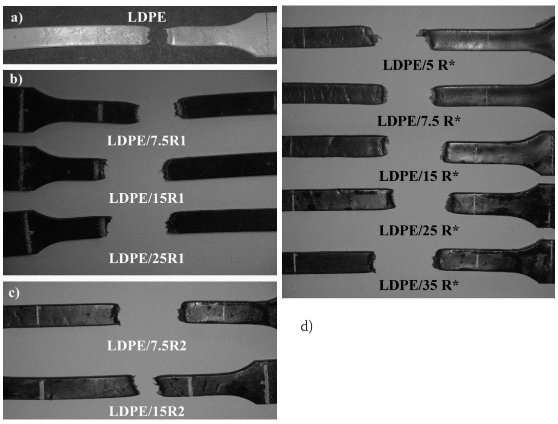

Figure 4. *Photographs of the broken specimens after the tensile test: a) virgin LDPE, b) LDPE/R1, c) LDPE/R2 and d) LDPE/R* blends.*

According to the Table 1, the mechanical parameters such as Young's modulus, tensile strength and ductility of the LDPE/R1 blends were significantly lower respect the virgin LDPE, which was an expected behaviour due to the presence of recycled material that limits the performance of the LDPE. However, respect to the R content, both the stiffness and the strength of the LDPE/R1 blends did not show significant variations at higher contents of R. The most notorious differences were found for the tensile and elongation at break. Both parameters tended to decrease gradually as the R content increases. Thus, the blends with the minimum and the maximum R content (LDPE/7.5R1 and LDPE/25R1 respectively) showed a reduction of S_b close to 16 and 25% respectively compared to the virgin LDPE. Similarly, the ductility of the blends dropped down up to approximately 33% respect to the LDPE.

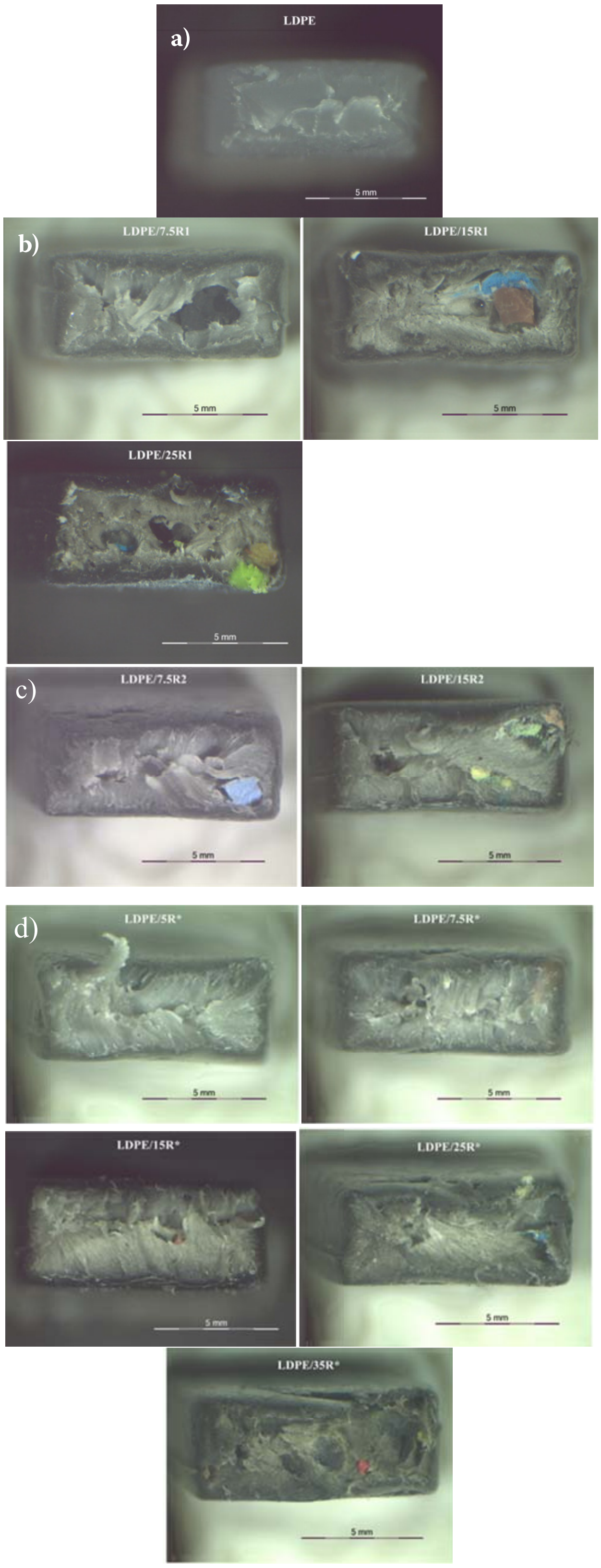

Figure 5. *Pictures taken from the failure surfaces of: a) virgin LDPE, b) LDPE/R1, c) LDPE/R2 and d) LDPE/R* blends.*

In order to explain the tendencies observed, the failure surfaces of the broken specimens were taken into consideration. **Figure 5** shows the failure surfaces of the virgin LDPE and the LDPE/R1 blends.

LDPE (**Figure 5a**) showed some traces of ductile tearing on the broken surface typical of semi-crystalline polymers. On the other hand, the broken surfaces of the LDPE/R1 blends revealed interesting features (**Figure 5b**). In the first instance, several not-melted waste particles with diverse dimensions were easily to observe. The presence of not-melted particles is attributed to the heterogeneity of distinct materials with different densities that compose the electrical cable wastes. As expected, the higher content of R, the higher the number of not-melted particles. Moreover, a considerable number of voids of different sizes were also observed on the failure surfaces of the specimens. The voids were certainly a result to the decohesion of the unmelted particles from the LDPE during the tensile test.

Mechanical properties: second-step of extrusion process

It is well known that the single-screw extrusion is not an efficient mixing process. However, it is relevant to find some alternatives to obtain blends with higher quality in mixing using single-screw extrusion. In this section, two additional blends were prepared by processing for a second time the surplus LDPE/7.5R1 and LDPE/15R1 extrudates; hence, each extrudate was pelletized and reprocessed following the same processing parameters and conditioning explained in section 3.3.

The new blends were labelled as LDPE/7.5R2 and LDPE/15R2 (**Table 1**) and were prepared in order to clarify if more uniform extruded filaments are possible to obtain through a second extrusion process and its influence on the mechanical properties of the blends. **Figure 6** shows the representative σ vs ε curves for the LDPE and the LDPE/R2. It is possible to appreciate a considerable change in the shape of the tensile curves respect to the LDPE/R1. In first instance, the strength at break is notorious higher with a hardening-like behaviour. The most notorious is the reduction on ductility that the LDPE/R2 present in comparison with the LDPE/R1 blends.

The LDPE/R2 extrudates (**Figure 2b**) showed similar heterogeneities than the LDPE/R1 blends at the outside of the extruder. The heterogeneities were more evident by increasing the content of R, promoting the interruption of the extrusion line.

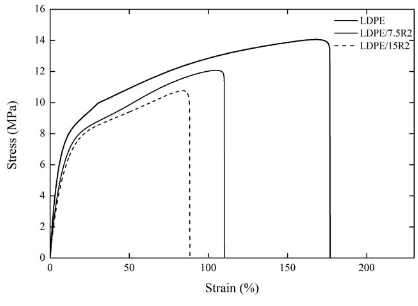

Figure 6. *Stress – strain curves of the virgin LDPE and LDPE/R2 blends.*

Figure 5c shows representative pictures of the failure surfaces from the broken LDPE/R2 specimens. As can be seen, the second extrusion process does not seem to modify the size of the unmelted waste particles.

During the tensile tests, the LDPE/R2 specimens showed fairly similar failure mechanisms than the LDPE/R1 (**Figure 4c**); hence, the shape of the stress-strain curves was similar as well.

The mechanical properties of the LDPE/R2 are listed in **Table 1**, and it is easy to appreciate that the Young's modulus shows a dramatic reduction respect to the virgin LDPE and LDPE/R1 blends, which was attributed to the thermo-mechanical degradation causing chain scission [17,18].

An unexpected result was obtained in the tensile stress of the LDPE/R2 blends, which does not exhibit significant changes with respect to their corresponding LDPE/R1 blends. The previous could be attributed to the not-melted and larger waste particles can be composed of not only LDPE but also PVC and rubbers, where the recycled LDPE should be interacting with the virgin LDPE because of the affinity between each other, acting more like composite materials than blends.

The elongation at break of the LDPE/R2 blends decreases by increasing the content of R, showing similar tendencies to that observed by the LDPE/R1 blends. However, the most notorious changes on ductility were observed in the LDPE/15R2 by decreasing close to 35% with respect to the LDPE/15R1 and up to 53% in reference to the virgin LDPE. The combination of thermal degradation and the presence of unmelted particles of diverse sizes led to the dramatic reduction in the ductility shown by the LDPE/R2 blends[8]by gel permeation chromatography (GPC).

Mechanical properties: Effect of the sieved waste particles

In order to obtain homogeneous particle size distribution, portions of R were selected by using nest sieves with opening mesh of 1.68 and 0.59 mm. R was put on the sieves and shaken by hand in order to select smaller particles than 2 mm and eliminate dust. The collecting of residual particles that remained between the sieves was labelled as R*. These homogeneous particles were dried at the same conditions indicated in the section 3.3 and mixed with virgin LDPE in the single-extruder in order to prepare LDPE/R* blends with concentrations of 5, 7.5, 15, 25 and 35 wt. % of R*. The parameters during the extrusion process and conditioning were the same as presented in section 3.3.

During the extrusion process, large and homogeneous extruded filaments of LDPE/R* blends were possible to extrude without interruptions, even with the blend having 35 wt.% of R*, which means the sieved waste particles do not hinder the extrusion of the LDPE/R*, as presented in **Figure 2c**. In this manner, the extruded filaments were water-cooled and pelletized continuously through the extrusion line.

Figure 6 shows the engineering stress – strain curves developed for the virgin LDPE and the LDPE/R* blends during the uniaxial tensile tests.

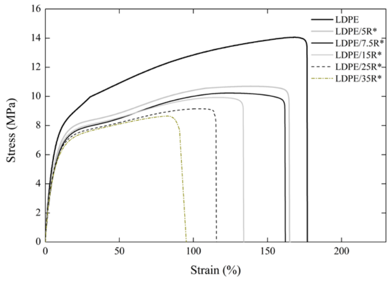

Figure 6. *Stress – strain curves of the virgin LDPE and LDPE/R* blends.*

The shape of the stress – strain curves of the LDPE/R* blends did not show relevant differences with respect to the corresponding curves developed by the LDPE/R1 blends.

The LDPE/R* specimens showed a diffuse necking during the tensile tests similar to the LDPE/R1 and LDPE/R2 blends, without any other traces of plastic deformation mechanism, as compared in **Figure 4d**. As expected, higher contents of R* represented lower areas under the stress – strain curves, that resulted in lower mechanical performance of the sieved blends. **Table 2** summarises the mechanical properties of the LDPE/R* blends obtained through the tensile curves. Notoriously, the Young's modulus was not so affected by the addition of R*, since the reduction in stiffness of the LDPE/R* was only up to 18% lower than the virgin LDPE. This result contrasts to those obtained for the LDPE/R1 and LDPE/R2 blends, and it could be associated to the sieved particles are mainly composed of recycled LDPE.

Table 2. *Mechanical properties of the virgin LDPE and LDPE/R* blends*

|	Material	E (MPa)	σ_y(MPa)	σ_{max}(MPa)	σ_b (MPa)	ε_b(%)
	LDPE	145.20 ± 1.82	8.65 ± 0.32	14.19 ± 0.14	13.92 ± 0.13	173.73 ± 14.93
one-step of extrusion	LDPE/5R*	123.47 ± 1.85	7.72 ± 0.63	10.69 ± 0.18	10.37 ± 0.21	162.17 ± 9.85
	LDPE/7.5R*	121.50 ± 2.18	7.67 ± 0.89	10.23 ± 0.13	9.69 ± 0.87	158.72 ± 13.56
	LDPE/15R*	122.12 ± 2.56	7.30 ± 0.64	9.92 ± 0.16	9.26 ± 0.93	132.92 ± 6.27
	LDPE/25R*	120.22 ± 2.14	7.04 ± 0.97	9.15 ± 0.28	8.80 ± 0.67	125.29 ± 7.26
	LDPE/35R*	120.18 ± 1.89	6.75 ± 0.83	8.65 ± 0.35	8.46 ± 0.48	92.26 ± 4.96

Respect to the R* content into the LDPE/R* blends, the Young's modulus did not offer relevant variations. However, the stress at yield as well as the tensile and elongation at break decreased continuously by increasing R*. The reduction on ductility was more evident for the LDPE/35R* blend.

The broken surfaces of the LDPE/R* blends are compared in **Figure 5d**. The observations revealed that relatively large particles were not appreciable in comparison with the previous blends (**Figures 5b** and **5c**), even with the highest R* content (25 and 35 wt.%). On the other hand, comparing the broken surfaces of the sieved blends in relation to the R* content, a ductile tearing similar to the observed in the neat LDPE surface was revealed for the LDPE/5R* blend. For this blend, very small and well-dispersed black points were observed at higher magnifications. By increasing the R* content, different features on the broken surfaces like the less evident ductile tearing, the presence of slightly larger particles and the development of several micro voids were observed.

When comparing the mechanical properties of the LDPE/R* with the rest of the blends (**Figure 7**), it is easy to appreciate that the stiffness of the sieved residual blends are close to the virgin LDPE, in contrast to the LDPE/R1 and LDPE/R2 blends (**Figure 7a**). It is important considering that R could be formed by PVC, synthetic rubbers and LDPE. The portions of non-rigid PVC and rubbers contained into the larger particles R should be promoting the reduction in stiffness. In contrast, the sieved particles are relatively easy to separate by using the gravimetric separation technique; hence R* seems containing basically just recycled LDPE, with high affinity and ready to melt with virgin LDPE, allowing better mixing and more homogeneity than the LDPE/R1 and LDPE/R2 blends, according to the observations performed in **Figure 5**.

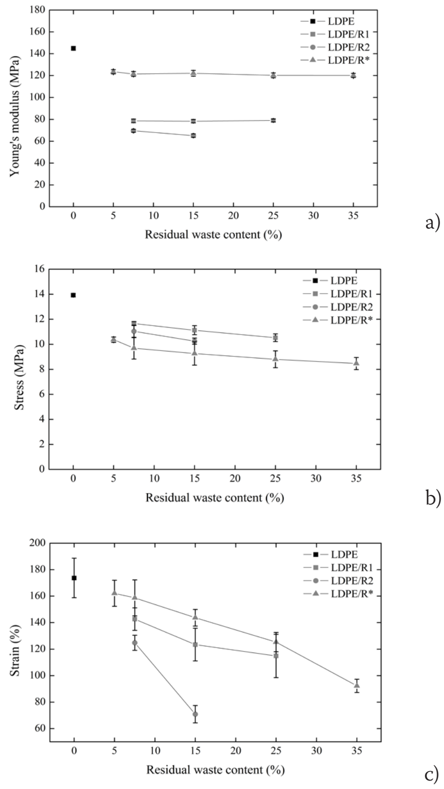

Figure 7. *Mechanical properties of the virgin LDPE and the blends: a) Young's modulus, b) tensile stress and c) strain.*

Figure 7b shows that the maximum stress of the LDPE/R* was notoriously lower than the LDPE/R1 and LDPE/R2 blends, which could be attributed to the larger particles are acting as fillers because they contain not only different materials but also portions of recycled LDPE that favour their cohesion with the virgin LDPE.

With respect to the plastic deformation of the blends (**Figure 7c**), it was expected the ductility decreases as the residual waste content increases. However, the differences in ductility between the LDPE/R* respect to the LDPE/R1 and LDPE/R2 blends are clearly evident. The larger and heterogeneous not-well melted particles should be acting as defects into the LDPE/R1 blends, causing the failure of the specimens. Meanwhile, the second step of single-screw extrusion causes the degradation of the LDPE/R2 blends; hence the combination of polymer degradation and larger not-melted particles promote the suddenly failure of the LDPE/R2 specimens respect to LDPE/R1 and LDPE/R* blends.

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CONCLUSIONS

Blends of LDPE/electrical cable waste particles were prepared by means of the melt-extrusion process in order to evaluate and compare the mechanical performance respect to the waste particles content.

During the processing of the blends, it was observed the addition of the waste particles promoted the interruption of the extrusion line because of heterogeneities developed by the presence of larger and not-well melted waste particles. In contrast, sieved waste particles allowed the extrusion of homogeneous filaments, irrespectively of the waste content, and avoided the extrusion line to stop.

Larger waste particles are composed by portions of non-rigid PVC, synthetic rubbers and recycled LDPE that promoted the notorious reduction in stiffness of the blends. Nevertheless, the affinity of the recycled LDPE portion with the virgin LDPE favoured the cohesion of the waste particles, which acted as fillers inside the virgin LDPE. The presence of the waste material led to the reduction in ductility, and the reprocessing, through a second-step of extrusion process, resulted in the degradation of the blends.

The collected sieved waste particles were composed of recycled LDPE and were well-mixed with the virgin LDPE. Stiffness of the blends was not so affected by the presence of the sieved particles and the reduction on ductility of these blends was not dramatic as compared with the rest of the blends analysed. Strength was lower in the blends with sieved particles because of the absence of larger particles with affinity portions that reinforced virgin LDPE.

REFERENCES

1. Manufacturers, A. of plastic. *Plastics-The facts*; Brussels, 2015.
2. Hopewell, J.; Dvorak, R.; Kosior, E. Plastics recycling: challenges and opportunities.
3. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* **2009**, *364* (1526), 2115–2126. Achilias, D. S.; Roupakias, C.; Megalokonomos, P.; Lappas, A. Recycling techniques of polyolefins from plastic wastes. *Glob. NEST J.* **2008**, *10* (1), 114–122.
4. Achilias, D. S.; Roupakias, C.; Megalokonomos, P.; Lappas, a. a.; Antonakou, V. Chemical recycling of plastic wastes made from polyethylene (LDPE and HDPE) and polypropylene (PP). *J. Hazard. Mater.* **2007**, *149* (3), 536–542.
5. Andrade, F. A.; Al-Qureshi, H. A.; Hotza, D. Measuring the plasticity of clays: A review. *Appl. Clay Sci.* **2011**, *51* (1-2), 1–7.
6. Goto, M. Chemical recycling of plastics using sub- and supercritical fluids. *J. Supercrit. Fluids* **2009**, *47* (3), 500–507.
7. Gao, F. *Handbook of plastics recycling*; F La Mantia, Ed.; John Wiley & Sons, Ltd., 2004; Vol. 53.
8. Jin, H.; Gonzalez-Gutierrez, J.; Oblak, P.; Zupančič, B.; Emri, I. The effect of extensive mechanical recycling on the properties of low density polyethylene. *Polym. Degrad. Stab.* **2012**, *97* (11), 2262–2272.
9. Kalfoglou, N. K.; Chaffey, C. E. Effects of extrusion on the structure and properties of high-impact polystyrene. *Polym. Eng. Sci.* **1979**, *19* (8), 552–557.
10. Liu, X.; Bertilsson, H. Recycling of ABS and ABS/PC Blends. *J Appl Polym Sci* **1999**, *74*, 510–515.
11. Merrington, A. Recycling of Plastics. In *Applied Plastics Engineering Handbook*; Kutz, M., Ed.; William Andrew Publishing, 2011; pp 177–192.
12. Sánchez, C.; Hortal, M.; Aliaga, C.; Devis, A.; Cloquell-Ballester, V. A. Recyclability assessment of nano-reinforced plastic packaging. *Waste Manag.* **2014**, *34* (12), 2647–2655.
13. Qin, L.; Ding, Y.-M.; Zhu, G.-C.; Yu, H.-C.; Yang, W.-M. Heat Flow Analysis and Efficiency Optimization of Rotational Molding Equipment for Large Plastic Products. *Int. Polym. Process.* **2015**, *30* (2), 194–201.
14. Navarro, R.; Ferrándiz, S.; López, J.; Seguí, V. J. The influence of polyethylene in the mechanical recycling of polyethylene terephtalate. *J. Mater. Process. Technol.* **2008**, *195* (1-3), 110–116.
15. Shen, L. *Plastic recycling*; Elsevier, 2014.
16. Leyva-Porras, C.; Esneider-Alcalá, M. A.; Toxqui-Terán, A.; Márquez-Lucero, A.; Aguilar-Martínez, J. A. Effect of Molding Parameters on Young's Modulus of an Injection Molded Low-Density Polyethylene (LDPE). *Ind. Eng. Chem. Res.* **2013**, *52* (16), 5666–5671.
17. Martín-Alfonso, J. E.; Franco, J. M. Influence of polymer reprocessing cycles on the microstructure and rheological behavior of polypropylene/mineral oil oleogels. *Polym. Test.* **2015**, *45*, 12–19.
18. Kulshreshtha, A. K.; Vasile, C. *Handbook of Polymer Blends and Composites*, 3rd ed.; Anand K. Kulshreshtha, C. V., Ed.; Handbook of Polymer Blends and Composites; Rapra Technology, 2003.