

The role of functional polymers in rubber powder/thermoplastic composites^{*)}

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Abstract: Low density polyethylene (LDPE), ethylene-vinyl acetate copolymer with 10–14 wt % (EVA-1) and 24–30 wt % vinyl acetate (EVA-2) contents, respectively, and ethylene-vinyl acetate-maleic anhydride terpolymer (OREVAC) were combined with rubber powder in the composition range: 100/0, 80/20, 70/30, 50/50, 30/70, 20/80. Two different rubber powders were used: ground rubber tire (GRT) and ethylene-propylene-diene (EPDM) rubber powder (RP), both of which were prepared by high temperature shear deformation. In the case of RP, changes in the crosslink density were also considered. The mechanical properties, melt flow index and morphology of the polymer/rubber powder composites were studied. Specimens were either prepared by compression or, for selected compositions, through injection molding. Improved elongations at break were observed for the OREVAC/rubber powder and EVA/rubber powder composites that were attributed to an enhanced interfacial adhesion between the dispersed rubber particles and matrix polymer. Composites with a rubber powder content as high as 70 wt % still showed good processability and elongation at break values greater than 100 %, which are basic requirements of traditional thermoplastic rubbers.

Keywords: rubber powder, thermoplastic polymers, mechanical properties, melt flow index, morphology.

Rola polimerów funkcjonalnych w termoplastycznych kompozytach z udziałem proszków gumowych

Streszczenie: Polietylen małej gęstości (LDPE), kopolimery etylen-octan winylu z udziałem 10–14 (EVA-1) lub 24–30 % mas. (EVA-2) octanu winylu oraz terpolimer etylen-octan winylu-bezwodnik maleinowy (OREVAC) zmieszano ze sproszkowaną gumą w stosunku 100/0, 80/20, 70/30, 50/50, 30/70, 20/80. Użyto dwa rodzaje proszków gumowych: zmieloną gumę opon samochodowych – GRT i sproszkowany kauczuk etylenowo-propylenowo-dienowy (EPDM) – RP, otrzymanych w warunkach wysokiej temperatury pod wpływem odkształceń ścinających. W wypadku stosowania RP brano również pod uwagę jego gęstość usieciowania. Badano właściwości mechaniczne, wskaźnik szybkości płynięcia oraz morfologię otrzymanych kompozytów. Próbkę do badań przygotowano metodą wytłaczania, a próbki wybranych kompozycji – także metodą wtryskiwania. Zaobserwowano zwiększenie wytrzymałości na rozciąganie próbek kompozytów proszek gumowy/OREVAC i proszek gumowy/EVA, co wiązało się z efektywniejszą adhezją pomiędzy zdyspergowanymi cząstkami napełniacza gumowego i polimerową matrycą. Kompozyty zawierające więcej niż 70 % mas. proszkowego napełniacza gumowego wykazywały dobrą przetwarzalność, a ich wytrzymałość na rozciąganie była większa niż 100 %, co spełnia warunek stawiany tradycyjnym termoplastycznym kauczukom.

Słowa kluczowe: proszek gumowy, polimery termoplastyczne, właściwości mechaniczne, wskaźnik szybkości płynięcia, morfologia.

One of the various problems of the 21st century is waste disposal management [1–4]. A great deal of waste rubber is produced every year in the world. The main sources of waste rubber products are discarded tires, pipes, belts,

shoes, edge scraps and waste products that are produced in rubber processes and others. The three-dimensional crosslinked structure of waste rubber makes it infusible, insoluble and difficult to recycle.

Typical recycling methods have been developed to treat waste rubber: combustion, landfilling, biodegradation, and recycling. Among them, recycling is the most attractive. Recycling is a major issue for most plastic processors and waste disposal authorities in the new century. However, the technology for recycling rubbers is complex and costly.

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The choice of the process is based on the requirements of the final product, such as particle size distribution and structure of the particles. The search for better technologies that will allow larger quantities of waste rubber to be incorporated into new products continues and several new approaches have been successful.

One of the promising methods developed in the last two decades is high temperature shear deformation (HTSD) [1, 5]. This technique is based on the degradation of a material in a complex strained state by the action of uniform compression pressure and shear forces under elevated temperatures. HTSD makes it possible to obtain fine powders, thus allowing the valuable properties of elastomer materials to be realized to a considerable extent.

Considerable efforts have been devoted to finding new applications for ground rubber tire (GRT). Fine GRT particles may be used as fillers and property modifiers in thermoplastic, elastomer and thermoset blends. Although the use of GRT as a filler in polymer composites is a potentially attractive approach, it is fraught with a number of difficulties. Karger-Kocsis *et al.* [4] recently published a comprehensive review regarding the difficulties of producing high quality GRT filled compounds. The mechanical properties of such composites depend on the content of GRT, polymer matrix type, adhesion between the GRT and the polymer matrix, as well as the particle size and their dispersion and interaction between GRT and the matrix. However, the incorporation of GRT particles into a number of polymer matrices significantly deteriorates the mechanical properties of the composites due to very weak interfacial adhesion between the GRT particles and the matrix-forming polymer [4–12].

The effect of mixing conditions on the mechanical properties of thermoplastic rubbers based on isotactic polypropylene (IPP) and GRT prepared from tread rubber by the method of HTSD has been studied [13]. Melt blending of IPP and GRT was used in a Brabender internal mixer at 190 °C for 10 min (rotor speed of 100 rpm) and

the method of HTSD in a rotor disperser (temperature 190 °C).

The mechanical properties of the blend were shown to be independent of mixing conditions (Figs. 1, 2).

Depending on the amount of crumb rubber, three regions that differ in the mechanism of deformation of thermoplastic rubbers are distinguished: < 0.1, 0.1–0.75, and > 0.75 parts by volume. According to Bazhenov *et al.* [9], the successive change of deformation a mechanism from plastic macro-heterogeneous deformation to brittle fracture and then to macro-homogeneous deformation takes place when the GRT content in the blend increases.

Thus, the content of GRT is an important factor, which influences the structure and properties of composites. So, when the content of GRT in the composite is lower than 10–20 wt %, the properties of the composite are satisfactory, while when the content is higher than 20 wt %, the properties of composite are unsatisfactory.

It is very interesting to explore the possibility of modifying the surface of GRT particles so that new reactive groups are introduced for enhanced miscibility with the thermoplastic phase. For the surface modification of GRT, physical and chemical methods can be used. The choice of the process is based on the requirements of the final product.

Rajalingam and Baker [14] reported the surface treatment of GRT by electron beam radiation to generate new oxygen-containing functional groups that promote adhesion to the plastic phase. Shanmugaraj *et al.* reported UV modification of GRT powder [15].

The effects of various compatibilizers to promote the adhesion between GRT and the polymer matrix were studied. Rajalingam *et al.* [6] reported the use of several compatibilizers such as ethylene-*co*-glycidyl methacrylate polymer to improve the adhesion between GRT particles and linear low-density polyethylene (LLDPE). Rodriguez [16] found that the addition of silane coupling agents improved the mechanical properties of GRT/plastic composites. Oliphant and Baker [7] and Pramanik and Baker [17] reported that most of the deleterious effects of add-

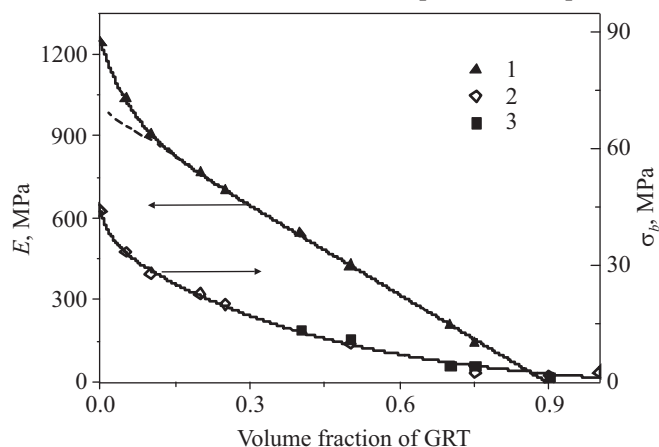


Fig. 1. Elastic modulus (E) and tensile strength (σ_b) of the IPP/GRT blend as functions of the GRT volume fraction for the materials blended: 1, 2 – in a Brabender mixer, 3 – by the method of HTSD [13]

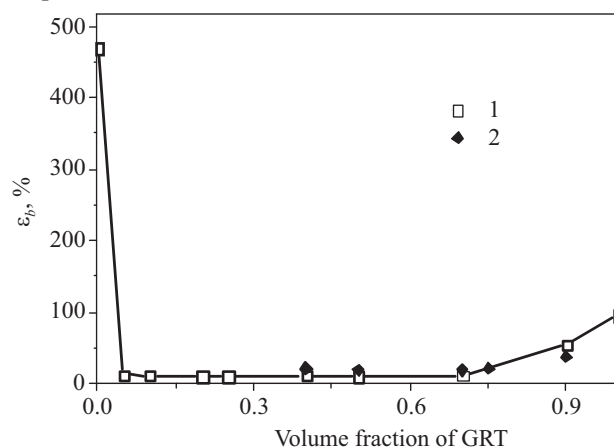


Fig. 2. Elongation at break (ϵ_b) of the IPP/GRT blend as a function of GRT volume fraction for the materials mixed: 1 – in the Brabender mixer, 2 – by the method of HTSD [13]

ing GRT to LLDPE could be overcome by precoating the GRT particles with ethylene acrylic copolymer, which increases the impact energy through a coupling action. The role of surface modified-rubber powders in the toughening of the epoxy polymers has been studied by Bagheri *et al.* [18]. Naskar *et al.* [19, 20] studied thermoplastic elastomeric compositions based on maleic anhydride-grafted and chlorinated GRT with polyolefins and PVC.

Many processes have been carried out to improve the mechanical behavior, such as the control of GRT particle morphology and the devulcanization of GRT particles, using various physical and chemical processes [21, 22].

In the present article, composites based on thermoplastic polymers and rubber powder (RP) have been prepared without using an expensive treatment of the RP particles or additives. The aim of this research is to study the effect of a RP content above 50 wt % on the mechanical properties and melt flow index (MFI) of composites based on different functional polymers. The morphology and structure of the composites were investigated using a scanning electron microscope (SEM). The preliminary experiments showed that the composites based on LDPE would have poor mechanical properties when the content of GRT reached 30 wt %.

EXPERIMENTAL PART

Materials

Commercial polymers used in the experiments are listed in Table 1.

Crosslinked ethylene-vinyl acetate (EVA) copolymers are widely used in the rubber market. The general effects of crosslinking on the EVA properties are: stability at higher temperatures (thermal resistance), slightly better flame resistance, higher tensile strength, abrasion resistance, resistance to environmental stress cracking, and solvent resistance.

Two different rubber powders were used:

- ground rubber tire (GRT) with a particle size of 0.315–0.630 mm was prepared from truck tire treads;
- second rubber powder (RP) with a particle size of 0.315–0.630 mm was prepared from EPDM vulcanizates.

Rubber crumb was provided by Chehov regeneratniy zavod (Moscow province, Russia) with a particle size of

0.5–1.5 mm. The rubber crumb originated exclusively from truck tire treads. Truck tire treads contain a number of different rubbers (polyisoprene, polybutadiene rubber, *etc.*), carbon black filler, antioxidants, and additional additives.

Then, this crumb was subjected to grinding by passing through a lab-scale rotor disperser designed at our Institute (Fig. 3).

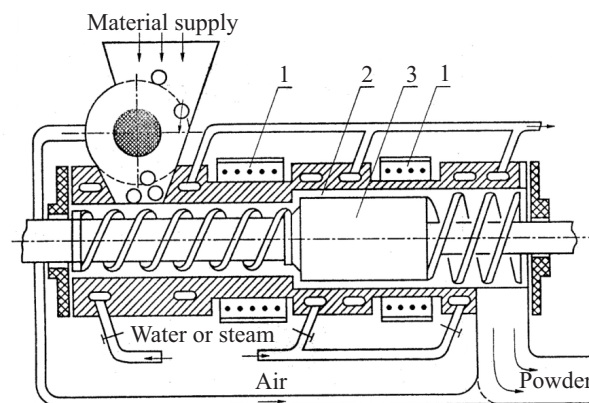


Fig. 3. Schematic diagram of rotor disperser: 1 – heating elements, 2 – concentric transport gap of the dispersion chamber, 3 – grinding rotor

This disperser is based on a lab-scale, single-screw extruder providing an intensive shear during processing (the screw diameter was 32 mm, the length to diameter ratio was 11, and the screw rotation was 45 rpm) [1, 5]. The rotor disperser was equipped with a head designed as a cam element rotating inside a channeled cylinder. The crumb rubber resided in the disperser for about 5 min at 150–155 °C.

Dutral TER 4044 (EPDM 4044, Polimeri Europa, Italy) elastomer was used. The EPDM vulcanization was carried out using a vulcanization system (VS): sulfur (1.0–4.0 phr), tetramethylthiuram disulfide (0.73 phr), di(2-benzothiazolyl) disulfide (0.25 phr), zinc oxide (2.53 phr), and stearic acid (1.0 phr). VS were introduced into EPDM in a Plastograph® EC mixer (Brabender®, Germany) at 30 °C for 10 min at a rotor rate of 100 rpm.

Vulcanization was carried out on a Carver CH 4386.4010 laboratory press (Carver® Inc., USA) for 10 min at 190 °C and 10 MPa. As was shown previously, under such conditions, the maximum degree of rubber crosslinking is attained [23].

Table 1. Polymers used in experiments

Materials	Grade	MFI g/10 min	Source
Low density polyethylene	LDPE	1.4	Kazanorgsintez (Russia)
Ethylene-vinyl acetate copolymer, content of vinyl acetate (VA) 10–14 wt %	EVA-1	3.8	Sevilen (Kazan, Russia)
Ethylene-vinyl acetate copolymer, content of vinyl acetate (VA) 24–30 wt %	EVA-2	> 13.6	Sevilen (Kazan, Russia)
Ethylene-vinyl acetate-maleic anhydride terpolymer OREVAC® T 9318	OREVAC	6.0–8.0	ARKEMA (France)

Rubber powder (RP) was prepared by the HTSD method *via* four-fold passing of material through a rotor disperser [24].

After grinding, the produced powders were subjected to sieve analysis using standard sieves (Ecros Laboratory, Sankt-Petersburg, Russia). Rubber powder with a particle size of 0.315–0.630 mm was used to prepare GRT or RP/polymer composites.

The powder particles were of an asymmetric form and had a surface area of 750–1200 cm²/g. Two characteristic regions with a distinct boundary were observed at the surface of the particles. Rugged surfaces were caused by plastic whereas smooth surfaces resulted from brittle fractures [24].

Composite preparation

Composites with different ratios of components, *viz.* GRT/polymer = 20/80, 30/70, 50/50, 60/40, 70/30, 80/20 wt % were prepared by mixing the components in a Plastograph EC (Brabender GmbH & Co. KG, Dusseldorf, Germany) at 160 °C, 100 rpm for 10 min. The mixing was continued until the recorded torque reached an equilibrium value. The mixing time was minimized to avoid degradation of the polymers. Rubber powder and different polymers were also mixed without the addition of additives under the same processing conditions.

There was no difficulty in incorporating GRT, even at high loading, into polymer matrices.

Sample preparation

Compression molded samples were obtained using a Carver laboratory machine (Carver® Inc., USA) at a temperature of 180 °C and a pressure of 10 MPa for 10 min. After their cooling, dumbbell specimens with a gauge length of 35 mm, a width of 5 mm and a thickness of 1.0 mm were cut from the sheets.

Injection molded samples were obtained using an injection molding machine (DSM Xplore, Netherlands)

with a thermal profile of 170–190–210 °C and a packing pressure of 60 MPa. These parameters were chosen after a number of trials optimizing the mold filling and the overall quality of the sample.

Methods of testing

– The mechanical properties of all the investigated blends were measured using an Instron machine, model 1122 (Instron, UK) on specimens obtained by injection molding or cut from compression molded sheets.

Load-extension curves were converted to stress-strain plots by dividing the measured load on the specimen by the original cross-sectional area of the specimen and the measured elongation by the original gauge length.

Tensile strength (σ_b), elongation at break (ϵ_b), and Young's modulus (E) were determined. The Young's modulus was calculated from the initial slope of the stress-strain curve. The average value and standard deviation of the tensile properties were calculated using at least 7 samples.

– Melt flow index values were obtained on an IIRT-5 unit (Russia) with the use of a capillary 8 mm in length and 2 mm in diameter at 190 °C for LDPE and OREVAC, 150 °C for EVA-1 and EVA-2 and loads of 2.16 kg.

– The morphology of the samples was analyzed using a scanning electron microscope JSM7001F JEOL (Japan), at accelerating voltages of ~ 1 kV [25]. For analysis, the samples were prepared by fracturing the composites under liquid nitrogen, without any treatment of the surface.

RESULTS AND DISCUSSION

Mechanical properties

It is known that stress-strain behavior is a strong indicator of phase coupling between composite components. A better phase coupling is pronounced if not only the matrix but both components can attribute to the mechani-

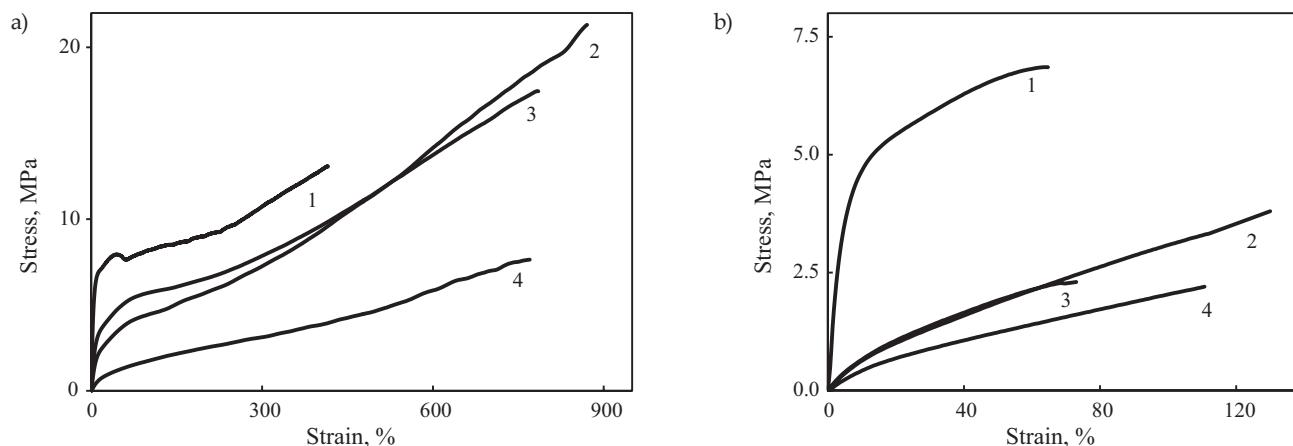


Fig. 4. Stress-strain curves of: a) neat polymers: 1 – LDPE, 2 – OREVAC, 3 – EVA-1, 4 – EVA-2, b) their composites: 1 – GRT/LDPE = 30/70, 2 – GRT/OREVAC = 70/30, 3 – GRT/EVA-1 = 70/30, 4 – GRT/EVA-2 = 70/30

Table 2. Effect of polymer matrix on the mechanical properties: Young's modulus (E), tensile strength (σ_b), elongation at break (ϵ_b) and melt flow index (MFI) of composites

Polymer matrix	Composition GRT/polymer wt %	Method of molding	E MPa	σ_b MPa	ϵ_b %	MFI g/10 min
LDPE	0/100	Compression molding	140	12.3	380	1.4
	20/80		150	7.8	80	2.1
	30/70		110	6.6	70	1.8
EVA-1	0/100	Compression molding	55	16.4	780	3.8
	30/70		28	4.7	155	5.4
	50/50		25	4.0	115	3.1
	70/30		11	2.3	75	0.5
EVA-2	0/100	Compression molding	7.4	6.3	790	Flow
	30/70		6.5	2.4	230	Flow
	50/50		5.8	2.4	170	13.6
	70/30		6.4	2.5	135	1.0
	80/20		4.3	1.6	90	0.1
	50/50 70/30	Injection molding	8.4 6.6	2.7 2.7	160 140	12.6 1.0
OREVAC	0/100	Compression molding	30.5	20.6	880	6.0–8.0
	60/40		17.0	5.1	180	1.4
	70/30		11.0	3.8	130	0.3
	80/20		7.5	3.0	120	No flow
	60/40 70/30 80/20	Injection molding	14.5 13.6 8.0	5.0 4.5 4.1	170 140 155	1.4 0.3 No flow

cal behavior because of stress transfer across the interface. Therefore, significant changes can be expected by comparing the composites containing various amounts of GRT and polymer matrix [20].

The tensile behavior of the neat polymers (LDPE, OREVAC, EVA-1, and EVA-2) and their composites is shown in Fig. 4.

Figure 4 illustrates the variation in stress-strain behavior of polymers as measured at a constant rate of strain. All these polymers are ductile. The LDPE curve shows a yield stress, strain softening and strain hardening. The OREVAC, EVA-1, and EVA-2 samples deform homogeneously as indicated by the continuous increase of stress with strain. There was no necking.

The addition of GRT significantly degraded the mechanical properties. Detailed mechanical properties of all the composites are summarized in Table 2.

It is observed that incorporation of GRT in the polymer matrix decreases the tensile strength, Young's modulus, and elongation at break of all the composites. However, the magnitudes of the tensile strength, Young's modulus, and elongation at break are significantly different and depend on the polymer matrix. Therefore, the GRT/LDPE composites have very poor mechanical properties, especially elongation at break. The elongation at break ϵ_b is seen to drop by about 80 % even at 20 wt % filler loading. The ϵ_b continues to drop until 30 wt % filler. Thus, the Young's modulus E and tensile strength σ_b decrease steadily with increasing GRT content. At 30 wt % GRT, the tensile strength σ_b decreased by about 46 % and the Young's modulus E by about 21 %. The poor adhesion between GRT and LDPE makes it easy for the propagation of cracks and leads to a large degradation in the mechanical properties.

To improve the adhesion between GRT particles and polymer matrix, some interactions must form at the interface.

A potentially even more attractive route is the use of matrices that increase the interaction (adhesion) between the matrix and the GRT particles. The effect of three functional polymers (EVA-1, EVA-2, OREVAC) on the mechanical properties and MFI of GRT/polymer was investigated, and the results are listed in Table 2. Data in Table 2 indicate that elongation at break decreases with increasing GRT content up to 80 wt %. Changes in tensile strength and Young's modulus followed the same trend. All the composites have higher elongation at break compared with the composites without functional polymers at 70 wt % GRT. This can be explained by the assumption that the functional polymers increase the interaction (ad-

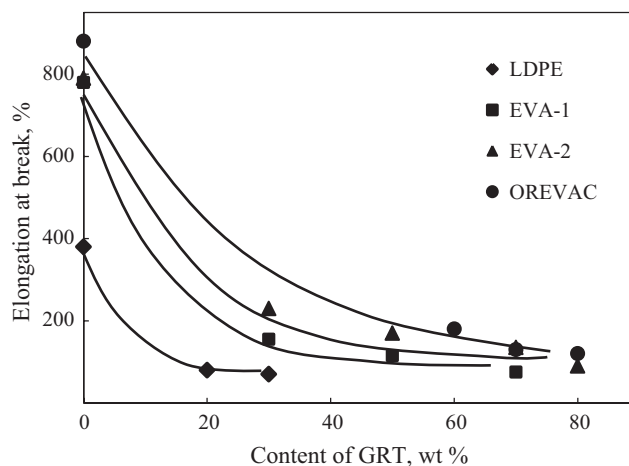


Fig. 5. Elongation at break of GRT/polymer composites as a function of the content of GRT

Table 3. Effect of rubber powder (RP) on the mechanical properties: Young's modulus (E), tensile strength (σ_b), elongation at break (ϵ_b) and melt flow index (MFI) of composites

Polymer matrix	Composition RP/polymer	Method of molding	E MPa	σ_b MPa	ϵ_b %	MFI g/10 min
OREVAC	EPDM-1 crosslinking degree of EPDM $n = 2.4 \cdot 10^{-4} \text{ mol/cm}^3$ [26] 70/30	Injection molding	4.6	4.6	460	No flow
	EPDM-2 crosslinking degree of EPDM $n = 3.2 \cdot 10^{-4} \text{ mol/cm}^3$ [26] 70/30	Compression molding	4.9	3.3	240	No flow

hesion) between the matrix and the GRT particles. The highest elongation at break was obtained with the composition containing OREVAC (Fig. 5).

The elongation at break of the GRT/OREVAC composites containing 70 wt % GRT is more than two times that of GRT/LDPE = 30/70. Composites on the basis of HDPE with a content of GRT more than 30 wt % cannot be obtained. The enhancement in elongation at break may suggest the formation of an interfacial region. The possible chemical interaction between OREVAC and GRT may lead to improved compatibility, and also to dispersion of the GRT in the matrix, thereby improving the product's elongation at break.

Specimens GRT/EVA-2 = 70/30, and 80/20, and GRT/OREVAC = 60/40, 70/30, and 80/20 were prepared by injection molding and compression molding (Table 2).

With a further increase in GRT content to 80 wt %, the modulus and tensile strength decreases, and the elongation at break was practically unchanged. However, these materials have no fluidity.

The highest value of elongation at break of 460 % was achieved for a composite based on RP (EPDM) and OREVAC at a ratio RP/OREVAC = 70/30 (Table 3).

At the same time, composites GRT/OREVAC and GRT/EVA for the same ratio of components have an elongation at break of 130 % and 110 %, respectively.

Thus, the values of the mechanical characteristics depend on the composition of RP. Impurities in the powder and the rubber crosslinking degree of rubber significantly affect the properties of the final material. Therefore, the elongation at break is lower when GRT is used compared to EPDM-based RP. Consequently, a different mechanical behavior between composites can be attributed to the difference of bonding between the rubber powders and polymer matrix. In order to maximize effectiveness, it was desired for the greatest percentage of GRT possible to be used in the composites.

Thus, the presence of polar groups in the vinyl acetate EVA increases the interfacial interaction between the matrix and rubber particles. The growth of the number of vinyl acetate groups in EVA-2 over EVA-1 improves the value of elongation at break and the MFI at the same ratio of components GRT/polymer = 70/30.

Morphology

SEM was used to visualize the interphase between the polymer matrix (LDPE, EVA-1, EVA-2, and OREVAC) and the imbedded rubber particles. SEM micrographs of the cryogenic fractured surfaces of composites are shown in Figs. 6–8.

The holes indicate the domains of GRT particles. The arrows for the particle are indicated in the SEM pictures. It is clear that the rubber particles are dispersed in the matrix. It is observed that the particles have an irregular shape. The presence of both very large and very small particles suggests a large particle size distribution. It can be observed that the matrices OREVAC, EVA-1 and EVA-2 have a significant influence on the size and shape of the particles (Figs. 6–8).

Generally, the elongation at break of composite filled GRT increases if there is sufficient adhesion between the matrix and GRT. It can be seen in Table 2 that an increase in elongation at break was achieved for all the composites based on OREVAC, EVA-1 and EVA-2 compared to the composite based on LDPE.

Particularly, the best elongation at break was significantly increased up to 120–155 % for GRT/OREVAC = 70/30. This is due to sufficient adhesion between the matrix phase and the dispersed phase; hence, efficient stress transfer from the matrix to the dispersed phase occurred, resulting in an increase of elongation at break.

The interfacial tension between the matrix and GRT is very important for phase morphology, and the added functional group plays a major role in reducing interfacial tension and thereby forming a finer morphology. At the same time, the average dimensions of the dispersed phase decrease, and interfacial adhesion between the OREVAC, EVA and GRT was also improved.

Melt flow index

It is well known that the addition of particles to a polymer increases the melt viscosity [27–29]. For filled systems with larger particles, the response to deformation is determined by a hydrodynamic interaction and not by particle-particle interactions. With an increasing content of the filler, the interparticle interactions increase weakly

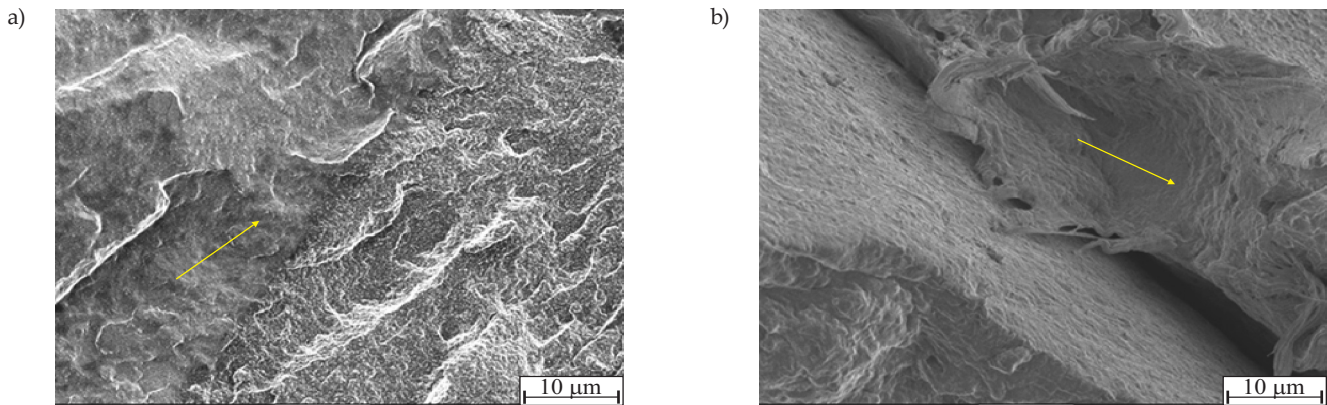


Fig. 6. SEM micrographs of the cryogenic fractured surface of GRT/LDPE: a) before, b) after tension; the arrows for the particle are indicated in the SEM pictures

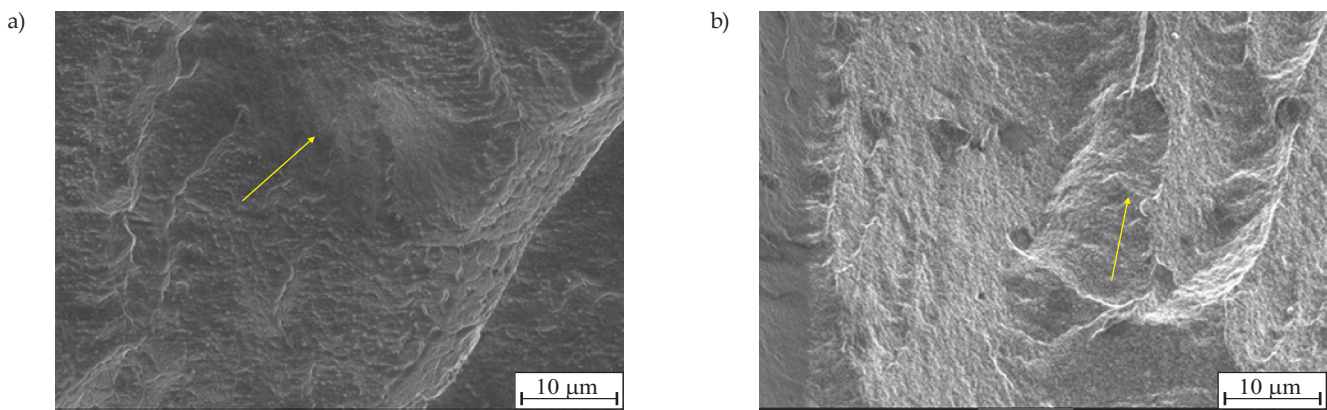


Fig. 7. SEM micrographs of the cryogenic fractured surface of: a) GRT/EVA-1 = 70/30, b) GRT/EVA-2 = 70/30; the arrows for the particle are indicated in the SEM pictures

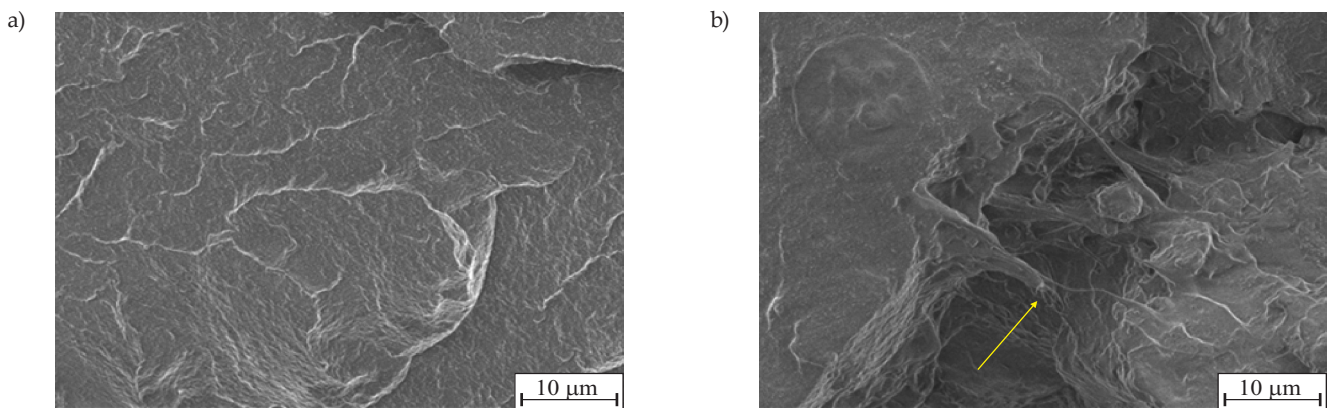


Fig. 8. SEM micrographs of the cryogenic fractured surface of GRT/OREVAC: a) before, b) after tension; the arrows for the particle are indicated in the SEM pictures

at first and then rather strongly as the content becomes greater.

Therefore, the melt viscosity is necessary in specifying optimum compounding conditions. As can be seen from Table 2, the GRT content does not cause significant changes in the viscosity of GRT/LDPE composites within experimental error. The melt flow index of GRT/LDPE composites can be explained in terms of the extremely low adhesion in these systems. This may be attributed to the high crosslink density of a tire, which does not allow any interfacial interpenetration, resulting in a sharp

interface. Surfaces of the specimens were observed using SEM and the results are shown in Figs. 6–8, where different states of adhesion can be observed.

Although a small amount of plastic deformation formed in the unmodified composites, there were substantial vacuole and debonding regions, indicating poor adhesion between the GRT particles and the polymer matrix, as well as the stress concentration around them, as shown in Figs. 6–8.

On the other hand, the melt flow index of the other composites decreased with greater filler content (Table 2).

The decreasing of *MFI* is ascribed to the formation of an interfacial region.

CONCLUSIONS

In this work, methods of using ground rubber tire in the development of new materials on a laboratory scale are discussed. A series of GRT/polymer composites were prepared. The addition of GRT to polymer matrices resulted in a significant decrease in mechanical properties due to its large particle size and poor adhesion. The composites, in which the GRT content was as high as 70 wt %, were characteristic of good processibility.

An improved elongation at break is observed for GRT/OREVAC and GRT/EVA composites and this can be attributed to an enhanced adhesion between GRT and polymer matrix. The melt flow index demonstrated the flowability and processability of the composites. The GRT/polymer composites exhibited two-phase morphology with filler particles dispersed through the matrix. The results of this work can be used to guide manufacturers in developing GRT/polymer composites with superior properties.

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