

Effect of expanded glass bead particle size on the mechanical, surface roughness and optical properties of low-density polyethylene composites

Aneta Tor-Świątek^{1*} , Anna Jakimińska¹ 

¹ Department of Technology and Polymer Processing, Faculty of Mechanical Engineering, Lublin University of Technology, ul. Nadbystrzycka 36, 20-618 Lublin, Poland

* Corresponding author's e-mail: a.tor@pollub.pl

ABSTRACT

This study investigated the effect of expanded porous glass bead particle size on the mechanical, surface, and optical properties of low-density polyethylene (LDPE) composites. Two granulations of the filler with a range of particle sizes were inserted into the LDPE matrix at 10% wt. The composites were characterized using static tensile tests, under sudden impact loading, surface roughness measurements, and colourimetric analysis on the CIELAB scale. The results showed that filler significantly modified the mechanical performance, surface morphology, and optical properties of LDPE. The filler reduced tensile properties and increased surface irregularity compared with the unfilled polymer. Clear changes in colour parameters were also observed, including lowered lightness and changes in chromatic coordinates. The magnitude of these changes depended on filler particle size. The results show that filler particle size is an important factor influencing the mechanical, surface, and optical properties of LDPE composites and should be considered when designing materials that require a balance between mechanical performance and surface appearance.

Keywords: polymer composites, low-density polyethylene, ceramic, expanded glass beads.

INTRODUCTION

Due to their excellent mechanical properties and ease of processing, polyethylenes have found widespread applications in many areas, including medicine, packaging, cable, machinery, toy, and construction industries [1]. It is no surprise, then, that polyolefin-based composites, including polyethylene, constitute a large, distinct group of materials. Currently, research is being conducted worldwide using low- and high-density polyethylene as a matrix, to which various modifiers [2, 3] and fillers [1, 4–6] are added, including powders [7, 8] and fibrous materials [9].

The use of mineral material as a filler allows to give new mechanical, rheological, structural and functional properties to the designed products, but it is necessary to take into account the quantity, geometry and size of the filler [10–12]

due to the processing [13], including the construction of processing tools, the process itself and technological parameters, as well as the structure and functional properties [14–15] of the products themselves [16–17].

The literature review indicates that there is relatively little research on extruded polyolefin composites, especially polyethylene composites containing recycled glass, particularly in the form of porous glass beads. Studies conducted on this topic have included thermal, physical, and tribomechanical analysis of the extruded filament [18], mechanical and microstructural properties [19]. 3D amplitude analysis and parameters of worn surfaces [20], the effect of UV degradation on physical properties [21], and rheological studies [24].

Unal et al. in their work [19] showed that adding glass beads to pure polypropylene (PP)

decreased tensile and impact strength while increasing elastic modulus and elongation. Adding polyolefin rubber (POE) and glass beads to the PP matrix reduced the decrease in tensile strength but mitigated the decreases in elastic modulus and impact strength, and significantly increased elongation. Furthermore, the interfacial bonding between the PP matrix and the glass beads was weak, whereas the bonding between the POE rubber and the PP matrix was strong, indicating improved compatibility.

Studies by Deleanu et al. [20] demonstrated that composites with 2.5% to 5% glass bead content exhibited reduced wear compared to 50% glass bead content, with a correlation between increased wear and roughness at higher sliding speeds. Furthermore, they demonstrated that relatively good surface quality was maintained with glass bead content ranging from 10% to 30% at sliding speeds of 0.5 to 1 m/s. The studies also indicated that the concentration of glass beads in the surface layer reduced wear, despite increased roughness in some composites.

In their study, Pandey and Gupta [18] found that the HDPE/WGP composite exhibited the best performance at a WGP content of 10 wt%, making it suitable for low- to moderate-load wear-resistant applications, such as gears and bearings, across various industrial environments. The addition of WGP increases the composite's melting point due to limited polymer chain mobility, while both crystallinity and enthalpy of fusion decrease with increasing WGP content.

Extensive rheological studies conducted by Liang's group [22] have shown that the rheological properties of polyethylene composite materials filled with glass beads are crucial for predicting their processing. The study confirmed that the melt flow follows a power-law relationship and that the apparent shear viscosity follows the Arrhenius equation as a function of temperature. Furthermore, it was observed that at constant temperature and shear rate, the apparent shear viscosity slightly increases as the glass bead volume increases. In their studies, they demonstrated that the elastic modulus of polymer composites filled with inorganic particles is significantly dependent on factors such as filler size and content, particle geometry, and interface morphology. A quantitative characterization model, based on Eshelby's method and Mori's work, was proposed that effectively relates the modulus to the aforementioned factors. The authors found that the predictions

from their proposed equation closely matched experimental data for low-density polyethylene composites filled with glass beads.

Liang et al. [23, 24], demonstrated the effect of glass bead granulation on the rheological properties. The flow properties of plasticized LDPE filled with glass beads at 150 °C were studied using a capillary rheometer to determine the effect of particle size and extrusion rate on the flow behaviour. The results showed that the shear viscosity of LDPE decreased linearly with increasing wall shear stress and changed slightly with increasing bead diameter at different shear stress levels. Specifically, the effect of bead size on the melt flow properties of LDPE/glass bead composites was negligible at lower concentrations of fine beads, possibly due to relatively weak interfacial adhesion between the particles and the matrix, resulting from the smooth, spherical surfaces of the beads.

These studies highlight the importance of understanding the interactions between fillers and the polymer matrix to improve the mechanical properties of composites. Dynamic mechanical analysis is a valuable tool for assessing the viscoelastic properties of polymeric materials, providing insight into their structure and performance.

Wei Yang [10, 26], also conducted research on the rheological and mechanical properties of polyethylene composites reinforced with glass beads.

Embery [25] analyzed the effects of glass beads on the linear and nonlinear rheology and processability of plasticized polyethylenes with different flow properties, namely LDPE and HDPE. The beads were additionally coated with a compatibilizer, and the composite was extruded. The authors found that the presence of glass beads increased viscosity across all shear rates. The increase at low rates was consistent with the Kreiger-Dougherty relationship for LDPE. For HDPE composites, the increase in viscosity was lower than that predicted by the developed K-D model. It was found that the different results obtained for filled HDPE may stem from differing compatibilizer effects on the polymer properties. Nonlinear rheological studies in shear and extension were also conducted. For nonlinear shear, the same increase in viscosity was obtained as in the linear measurements at small strains. At larger strains, the increase in LDPE viscosity was different. It was stated that the changes may be due to the formation of voids around the glass beads. balls at larger deformations.

Wei Yang et al. [27] investigated the tensile and impact properties of linear low-density polyethylene (LLDPE) filled with glass beads. They found that the tensile behaviour of LLDPE composite samples filled with beads did not differ significantly from that of pure LLDPE, although the composite samples exhibited significantly improved mechanical properties. A relatively small range of bead sizes was found to improve the mechanical properties of the tested LLDPE. The elastic modulus and elongation at break remained the same for different filler contents, while the yield strength increased significantly at 20% filler content. Furthermore, a gradual increase in impact strength was observed as filler content increased, culminating in a 40% improvement. Finally, it was found that bead size plays a significant role in composite reinforcement, and that the main factor influencing the composite's mechanical properties was the distribution of beads in the matrix. Morphological studies of the samples showed that, despite the lack of surface treatment on the beads, the filler exhibited good interfacial adhesion with the LLDPE matrix.

In [26], the authors studied LLDPE composites filled with glass beads of varying particle size and mass content. The composite was prepared by extrusion, and samples for mechanical testing (EWF test) were injected. They found that the fundamental work of fracture of LLDPE composites filled with glass beads was lower than that of pure LLDPE. The work of fracture was not affected by the diameter of the beads. The non-fundamental work of fracture (plastic work) also decreased with the addition of filler, indicating lower energy absorption during the fracture process. The authors observed a slightly greater effect of glass bead content on fracture behaviour than the effect of filler diameter alone.

This paper presents research on the influence of the type and amount of recycled glass beads on static mechanical properties and under sudden impact loading, as well as selected surface properties, including geometrical structure (surface roughness) and optical (colour).

MATERIALS

In the tests, low-density polyethylene LDPE MALEN E FABS23D022 (produced by Basell Orlen Polyolefins Sp. z o.o.) in granulate form was used as the matrix. According to the manufacturer, the polymer properties were: density 923 kg/m³, MFR (190 °C/2.16 kg) 1.95 g/10 min, modulus of elasticity 250 MPa, tensile strength 18 MPa, elongation at break 450%, Shore's hardness 48°Sh D, gloss 65. The material contained an anti-blocking additive at 170 ppm and a lubricant (Oleamide) at 500 ppm.

Poraver ceramic spheres were used as a filler; they are lightweight and made from recycled, porous, expanded glass bead. The chemical composition and percentage of individual components of the filler, as quoted by the manufacturer, are: SiO₂ – 70–75%, Na₂O – 10–15%, CaO – 7–11%, Al₂O₃ – 0.5–5%, MgO – 0–5%, K₂O – 0–4%. All components were measured by the XRF method. Two filler gradations were used to produce composite samples at 10% wt. each. The type, properties of the gradation materials, and sample marking are presented in Table 1.

METHODS

Composite samples were obtained by tape extrusion on a laboratory single-screw extruder

Table 1. Gradations, sample name and selected physical properties of LDPE and ceramic filler granules (manufacturers data)

Property	LDPE	Filler Poraver granulation, mm	
		0.25–0.5	0.5–1.25
Sample name	A	B	C
Filler amount, %wt.	0	10	10
Granular size [mm]	3–4	0.25–0.5	0.5–1.25
Bulk density [kg/m ³]	750	340 +/- 30	270 +/- 30
Particle density [kg/m ³]	923	700 +/- 80	500 +/- 80
Crushing resistance [N/mm ²] According to DIN EN 13055-1	-	>2.6	>2.0
Water absorption [%]	Under 0.01	21	18

(W25). The extruder die used was 2.3 cm wide and 0.14 cm thick.

Mineral fillers were inserted into the LDPE during mechanical mixing prior to processing. Temperatures in the plasticizing system zones were 32 °C, 170 °C, 170 °C, and 190 °C; extruder die temperature was 200 °C; screw speed was 200 rpm; extrusion pressure was 0.7 MPa; coolant temperature was 17 °C.

Mechanical static tests were carried out in accordance with the applicable standard PN-EN ISO 572. Samples with type 1A were cut out with the ZCP 020 manual press. Tensile strength, elastic modulus, and elongation at break were measured using the Zwick Roell Z010 machine at a test speed of 50 mm/min (Figure 1a). Five measurements were performed for each series of samples.

Tests under sudden impact loading such as impact tensile measurements (method A) were carried out in accordance with the PN-EN ISO 8256:2006 standard. Also, samples were cut using the ZCP 020 manual press. The property was measured using a Comatech Testing Machine type 639F (Figure 1b). The hammer speed was the same for all analyses and was 2.9 m/s, and its energy was 5 kJ. Five measurements were performed for each series of samples. A paddle-shaped specimen with a length of 60 mm and an attached transverse yoke is placed in the device's holder. Then, the impact hammer is released; it strikes the yoke, stretching the specimen.

Surface roughness tests were performed using the inductive profilometric method on a laboratory stand equipped with a TR200 profilometer,

Ta-610 measuring table, TS-100 measuring head, and software (Figure 1c). Tests were conducted in accordance with the PN-EN ISO 4287 and PN-ISO 4288 standards. Samples were tested at three locations (three measurements in each location), and average values of vertical amplitude parameters (R_z , R_a , R_q) and horizontal distance (S_m) were determined. A cut-off wavelength of 0.25 mm, linear measurement length of 3L, and measurement range of $\pm 80 \mu\text{m}$ were used.

Colour analysis of LDPE/glass spheres composites was carried out using an X-Rite Ci 4200 benchtop sphere spectrophotometer (Figure 1d). The colour assessment was carried out using the CIE Lab colour space, which describes colour in Cartesian coordinates. The individual colour parameters were measured three times for each sample. Next, the average values of each measured quantity were determined. The following parameters were determined: L – brightness ranging from 0 to 100, a – represents red (0~+128) or green chromaticity (−128~0), b – the colour of yellow (0~+128) or blue chromaticity (−128~0), C – chroma parameter, and ΔE – total colour change.

RESULTS AND DISCUSSION

Mechanical

Static tensile testing revealed that using 10 wt.% filler granules affects both stiffness and mechanical strength of LDPE composites. Filler

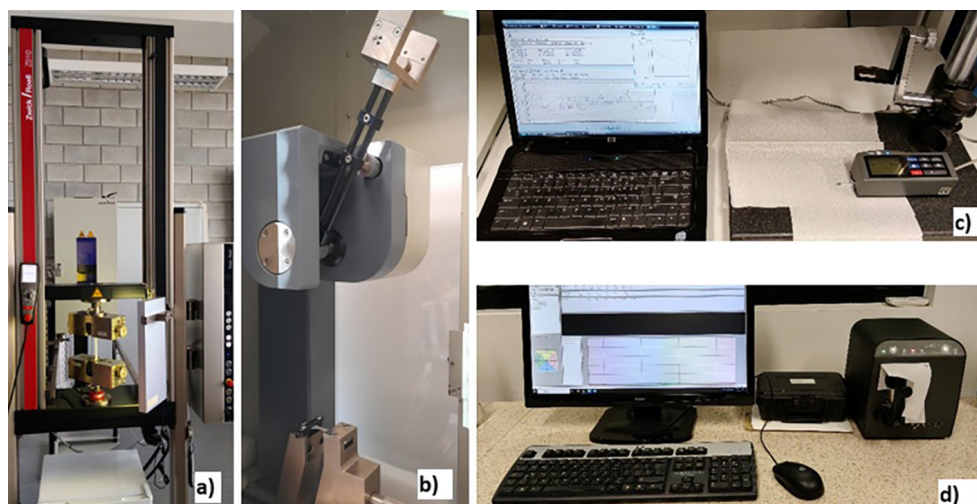


Figure 1. General view of the test setups used in the research of composite samples: a) test stand for determining mechanical properties under static tension; b) impact tensile testing station; c) roughness testing station; d) colour testing station

grain size also considerably modifies the material's response to loading.

The average elastic modulus E_t (Figure 2) for pure LDPE. The average elastic modulus E_t (Figure 2) for pure LDPE (sample A) was about 133 MPa. Adding 0.25–0.5 mm filler (sample B) increased the modulus to about 156 MPa, a 17% increase over the base material. Similar stiffness was achieved for the composite with a larger filler fraction (sample C), where average E_t reached about 155 MPa, a 16% increase over pure LDPE.

The tensile strength results (Figure 3) did not show a similar trend. The average value for sample A was approximately 9.13 MPa. For composite (B), this value decreased by approximately 19%, and for sample C by 17% compared to pure LDPE. The results suggest that the presence of the

porous filler constitutes stress concentration sites, accelerating the initiation of tensile cracking.

Significantly larger differences were observed for strain at break ϵ_b (Figure 4). Pure LDPE had an average elongation of about 387%, while composites decreased to about 38% (sample B) and 51% (sample C). This represents a reduction in ductility by about 90% and 87%, respectively, compared to the base material. Such a large reduction in plastic deformation indicates a transition from highly ductile to brittle material. Comparing the two composites, the larger filler granulation slightly improves strength and elongation at break compared to the finer filler, but the differences are minor.

The addition of a lightweight filler granulation increased the composite's stiffness owing

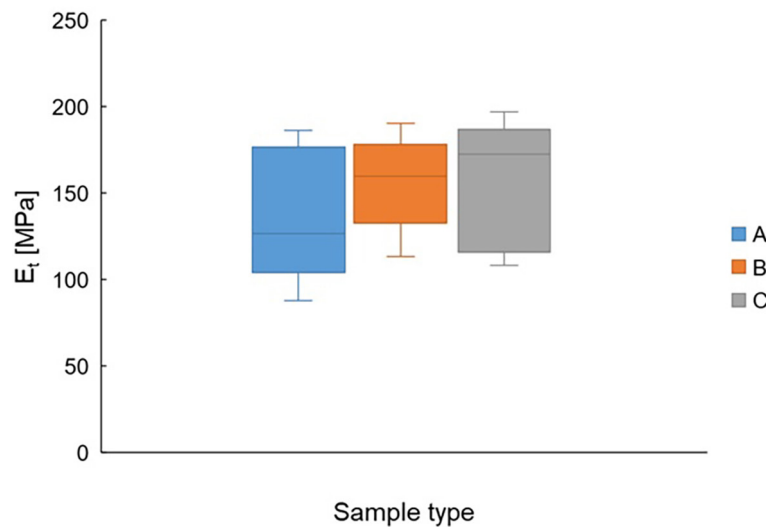


Figure 2. Results of elastic modulus of composite samples

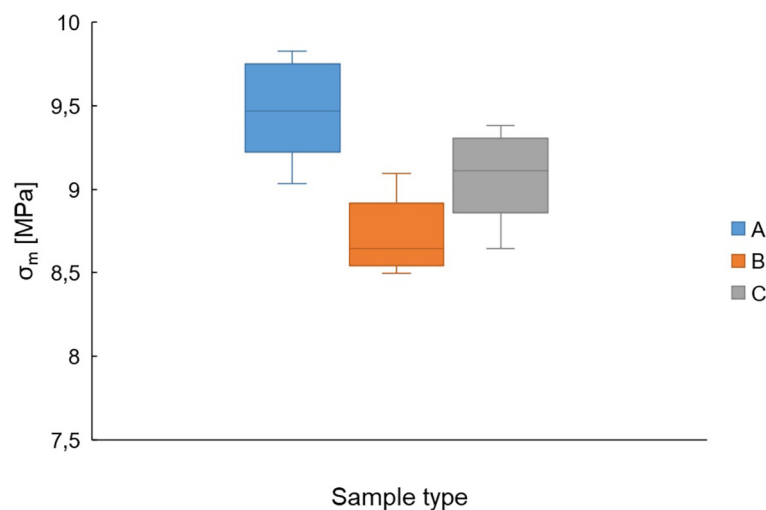


Figure 3. Results of tensile strength of composite samples

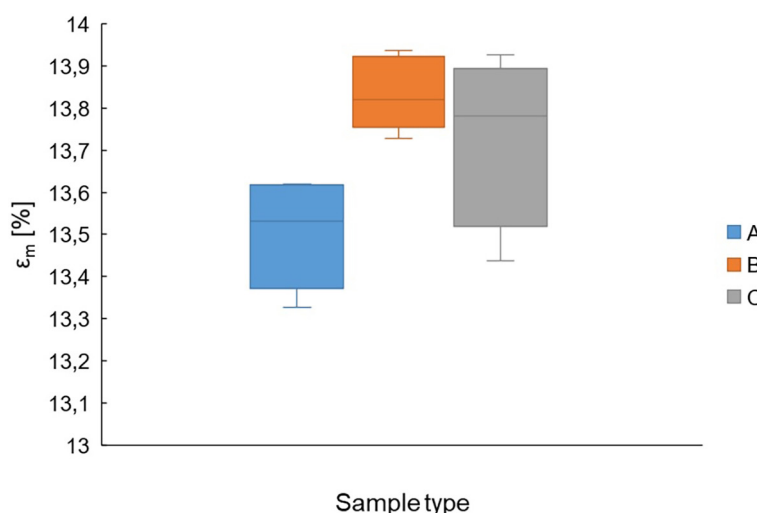


Figure 4. Results of strain at break of composite samples

to the higher elastic modulus of the porous glass bead compared with the LDPE matrix. At the same time, the presence of porous particles limited the material's ability to undergo plastic deformation and reduced its tensile strength. This mechanism is typical of particle composites, where the interface between the polymer and filler becomes a stress concentration point. In the case of glass bead, an additional factor is the porous grain structure, which can promote the earlier initiation of microcracks. Despite the increase in elastic modulus, there was a significant decrease in elongation at break. The slightly better mechanical properties of the composite containing a larger filler fraction may be due to the smaller interfacial area per unit volume and fewer potential crack nucleation sites. The addition of 10 wt.% filler increased the elastic

modulus by approximately 13%, indicating an increase in the composite's stiffness. At the same time, the relatively high standard deviations indicate considerable variation in mechanical properties among individual samples, which is typical of composites with particulate and granular fillers. The addition of filler led to a considerable reduction in the composite's deformability. The elongation at break decreased by approximately 90%, showing a change in the fracture mode from ductile to a significantly more brittle fracture. This result is consistent with the behaviour of composites containing rigid, porous mineral particles that initiate local stress concentrations.

The addition of glass beads to the LDPE matrix significantly reduced the material's resistance to sudden impact tensile loads (Figure 5). For pure LDPE (sample A), the average impact

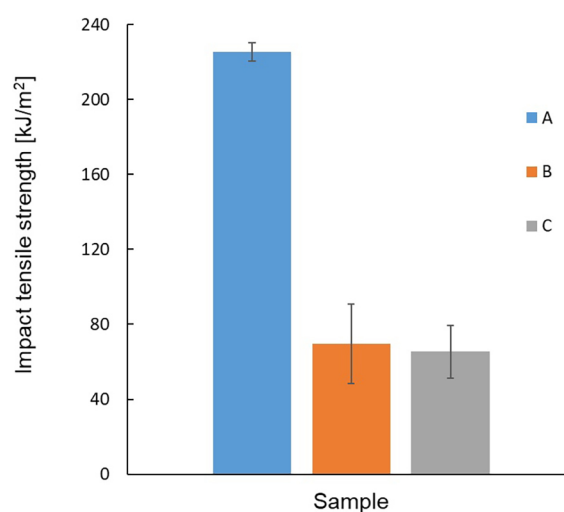


Figure 5. Results of impact tensile strength of composite samples

tensile strength was 225.38 kJ/m². For the composite (sample B), this value decreased by 69.12% compared to the base material. For sample C, the average value was further reduced by 71.01% compared to pure LDPE. The increase in the scatter of results after the adding of the filler is especially significant. The coefficient of variation increased from only 2.12% for LDPE to 30.44% for sample B and 21.69% for sample C. This may indicate greater heterogeneity in the composite structure and a local influence of the glass bead distribution on damage initiation and propagation during impact loading.

To assess the effect of glass bead granulation on mechanical properties, a one-way analysis of variance (ANOVA) was conducted at a significance level of $\alpha = 0.05$ (Table 2). Elastic modulus (E), tensile strength (σ_m), elongation (ϵ_m), and impact tensile strength were analyzed. When a significant effect was found, the Tukey's HSD post hoc test was made to identify differences between groups.

The analysis showed no significant effect of the modified granulation on elastic modulus ($F = 0.441$; $p = 0.6532$). Statistically significant differences were found for tensile strength ($F = 9.375$; $p = 0.0035$), elongation at maximum stress ($F = 17.047$; $p = 0.00043$), and impact tensile strength ($F = 371.139$; $p < 0.0001$). Tukey's test showed that for σ_m , samples A and B differed significantly, while sample C did not differ significantly from the others. For ϵ_m , samples B and C differed significantly from pure LDPE (A), while there was no significant difference between B and C. The strongest effect was observed for impact tensile strength – both composites (B and C) showed significantly lower values than pure LDPE, while the difference between the two filler types was not statistically significant.

The observed reduction in tensile strength and elongation at break is consistent with previous studies on glass-filled LDPE. Liang et al. [22]

indicated that the incorporation of glass beads into LDPE resulted in a reduced strain at break, while the tensile modulus increased with increasing filler content. The authors attributed the changes in mechanical properties to the presence of the stiff glass phase and the resulting modification of the composite morphology. The effect of particle size must also be considered. In this study, the two filler types differed in particle size, allowing the effect of filler geometry to be assessed independently of the polymer matrix. The differences between samples B and C indicate that particle size influences the mechanical response, although the magnitude of this effect depends on the specific mechanical property. This observation is consistent with literature reports indicating that the effect of glass particle size on the mechanical properties of LDPE is not universal. Liang et al. found that the effect of glass bead diameter on the tensile strength of LDPE was relatively small, whereas other studies [27] showed a more pronounced effect of particle size, particularly when particle size is small and particle distribution and interfacial adhesion become the main factors.

The results obtained from the impact tensile test provide additional information on the effect of glass beads on the material's ability to absorb applied energy. The impact tensile strength of unfilled LDPE was significantly higher than that of both composites. This indicates that the addition of this type of filler reduces the material's ability to dissipate energy under high-strain-rate loading. The reduced impact resistance may be related to the presence of stiff and relatively brittle porous glass beads in LDPE. Under sudden loading, the difference in strain behaviour between LDPE and the filler can promote local stress concentrations at the interface. If interfacial adhesion is insufficient, debonding and subsequent crack propagation can occur, reducing the energy required for fracture. Therefore, filler particles can shift the dominant failure mechanism

Table 2. ANOVA results for Mechanical properties of composite material

Mechanical property	A – solid LDPE	B – Poraver 0.25–0.5 mm	C – Poraver 0.5–1.25 mm	F-ratio	p-value
E_t [MPa]	137.77 ± 39.20 ^a	156.24 ± 27.85 ^a	155.59 ± 37.72 ^a	0.441	0.6532
σ_m [MPa]	9.33 ± 0.30 ^a	8.60 ± 0.23 ^b	8.96 ± 0.26 ^{ab}	9.375	0.0035
ϵ_m [%]	13.50 ± 0.13 ^a	13.83 ± 0.09 ^b	13.82 ± 0.07 ^b	17.047	0.00043
Impact tensile strength [kJ/m ²]	225.38 ± 4.77 ^a	69.60 ± 21.19 ^b	65.33 ± 14.17 ^b	371.139	<0.0001

Note: Values are mean ± standard deviation. Different superscript letters (a, b) within a row indicate statistically significant differences according to Tukey's HSD test ($p < 0.05$).

from extensive plastic deformation of the material to localized damage and crack propagation.

This is supported by research by Yang et al. [27], who showed that the impact performance of glass bead-filled LLDPE is strongly dependent on filler concentration, particle size, and particle distribution. This suggests that a stiff filler can either reduce or improve impact resistance depending on the composite morphology.

Roughness

To assess the effect of adding 10 wt.% filler of varying granulation on the surface development of LDPE composites, basic roughness parameters were analyzed: Ra, Rq, Rz, Rp, and Sm. Sample

A (solid LDPE) served as the reference material. The measurements represented the tested surface, presented in Figures 6–8 as profilographs. Figure 9 presents the average values of the individual roughness parameters.

The average Ra value (Figure 9a) for the reference sample was 0.658 μm . The addition of 10 wt.% glass bead with a granulation of 0.25–0.5 mm (sample B) increased this parameter to 2.922 μm , corresponding to a 344.1% increase compared to sample A. For sample C, containing filler with a granulation of 0.5–1.25 mm, the Ra value reached 4.230 μm , an increase of 542.9% compared to pure LDPE (sample A). Compared to sample B, the Ra value increased by an additional 44.8%, showing a clear effect

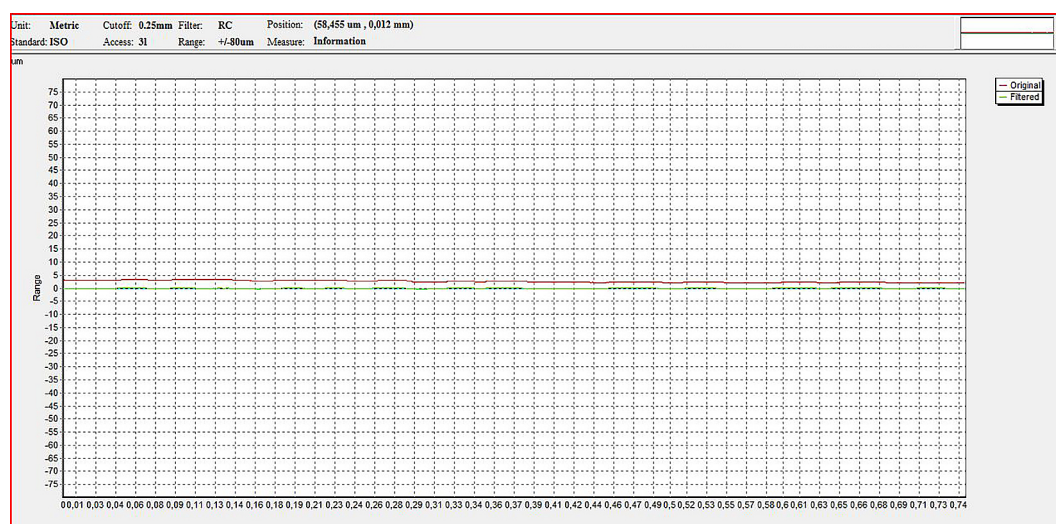


Figure 6. Profilograph of selected sample A – solid LDPE

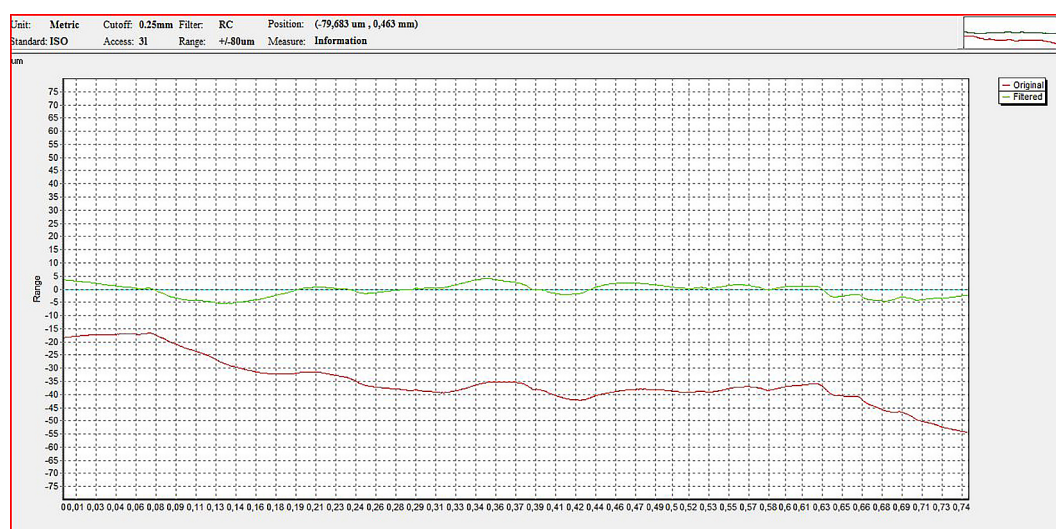


Figure 7. Profilograph of selected sample B

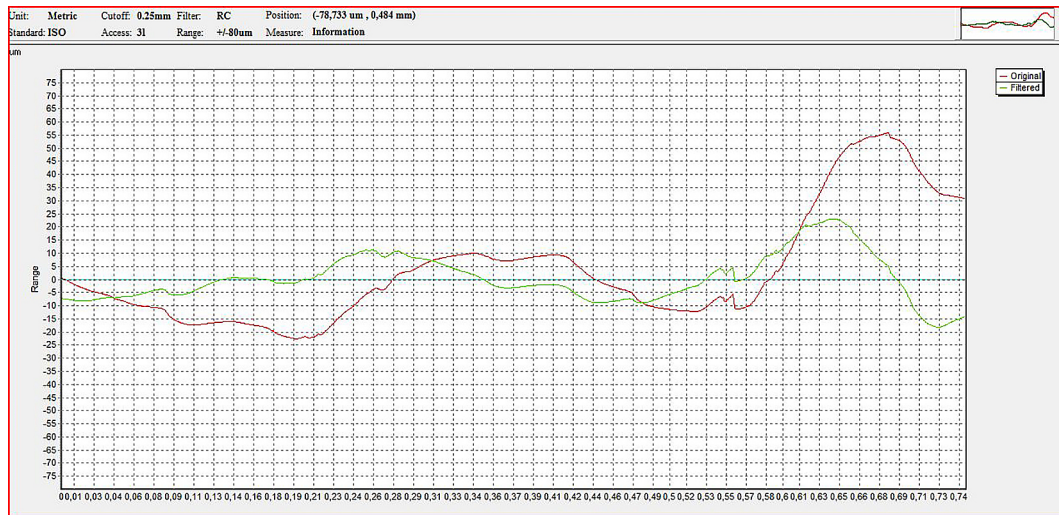


Figure 8. Profilograph of selected sample C

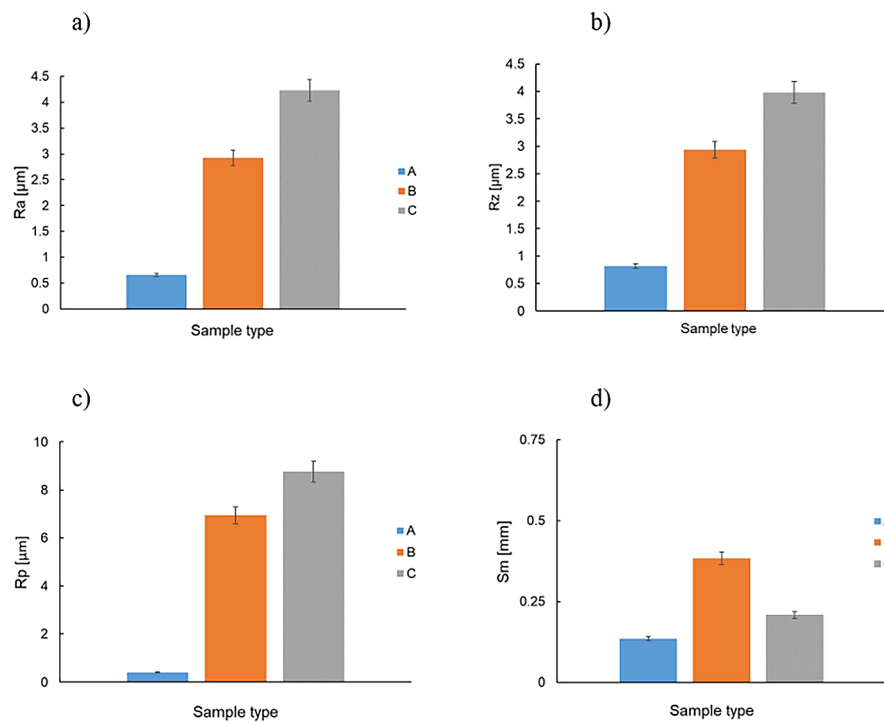


Figure 9. Results of roughness parameter measurements: a) Ra – average roughness of a surface; b) Rz – total surface roughness height; c) Rp – maximum roughness peak height; d) Sm – average distance between surface roughness elements

of increasing grain size on the development of surface microgeometry. The Rz parameter (Figure 9b), describing the total surface roughness height, increased from 0.822 μm for pure LDPE to 2.935 μm for sample B and 3.975 μm for sample C. This represents an increase of 257.1% and 383.6%, respectively, compared to the reference sample. Compared with sample B, the Rz parameter increased by an additional 35.4%. The largest differences were observed for the Rp

parameter (Figure 9c), defining the maximum roughness peak height. For sample A, the average value was 0.408 μm , while for samples B and C, it was 6.949 μm and 8.757 μm , respectively. This corresponds to an increase of 1602.2% for sample B and 2045.2% for sample C compared to pure LDPE. At the same time, increasing the filler granulation from 0.25–0.5 mm to 0.5–1.25 mm resulted in a further increase in the Rp parameter by 26.0%.

A different relationship was observed for the S_m parameter (Figure 9d), which determines the average distance between surface elements. For sample A, this value was 0.135 mm. In sample B, the parameter increased to 0.383 mm, representing an 183.7% increase over the reference material. For sample C, the S_m value was 0.208 mm, representing a 54.1% increase over sample A but a 45.7% decrease over sample B. This result suggests that larger filler grains lead to the formation of higher yet more concentrated surface irregularities.

The overall results clearly indicate that the addition of glass beads significantly increases the geometric surface structure of LDPE composites, and that increasing filler granulation additionally intensifies this effect. The R_p parameter demonstrated the greatest sensitivity to the presence of filler, while the smallest relative changes were observed for the S_m parameter.

The results show that both the presence of the filler and its grain size substantially affect the surface topography of LDPE composites. With increasing granulation, the amplitude parameters (R_a , R_z , and R_p) increase systematically, showing a progressively rougher surface structure of the composites.

This mechanism can be explained by the larger size of the filler particles, which are more difficult to fully surround with molten polyethylene during processing. As a result, some grains remain partially exposed on the sample surface, causing increased unevenness height and increased amplitude parameters. At the same time, larger grains generate more localized but higher unevenness, which is particularly well reflected in the R_p parameter. The results are consistent with the influence of particle size in lightweight mineral fillers on the development of the surface geometry of polymer composites, as observed in the literature [28–30].

Colour

The analysis of colour parameters showed a clear influence of filler granulation on the change

in the optical properties of the composite surfaces. The results of testing the average values of individual colourimetric parameters are summarized in Table 3.

Compared to the base material (sample A), both tested composites exhibited negative ΔL values, indicating a significant darkening of the sample surfaces. For composite B, the ΔL value was -17.23, while for composite C, it reached -21.59, corresponding to a 25.36% increase in the absolute brightness difference. Positive Δa values of 0.57 and 1.07 were observed for samples B and C, respectively, showing a reddish colour shift. The Δa value for the larger fraction of glass beads was 87.72% greater than for sample B. The Δb values for samples B and C indicate a yellowish colour shift, with sample C showing a 12.95% smaller effect. The ΔC value between the composite samples B and C decreased around 35%. At the same time, the change in ΔH between B and C indicates a change in the direction of the shade shift with increasing glass bead granulation. The total colour difference determined by the ΔE parameter increased by 12.77% between sample B and C. The results show that increasing the filler granulation primarily leads to greater surface darkening, a stronger redshift, and a larger total colour difference relative to the base material (sample A).

The addition of glass beads significantly changed the colour of the tested samples. The most pronounced change was observed for the lightness parameter ΔL for samples B and C (values -17.23 and -21.59 respectively). Thus, both composites exhibited significant darkening compared to the base material (Figure 10). Furthermore, this effect was more pronounced for the larger fraction of glass beads—sample C. Similar behaviour was observed for polymer composites containing glass-based reinforcement, where the introduction of an inorganic phase caused changes in the CIELAB coordinates, particularly in the lightness range [31]. Previous studies on glass fiber-reinforced polymer composites also showed

Table 3. Research results of colourimetric measurements of composites

Sample	CIE Lab values					Chromatic aberration and DE values					
	L	a	b	C	h	ΔL	Δa	Δb	ΔC	ΔH	ΔE
A	70.87	-0.31	-1.4	1.44	257.71	-	-	-	-	-	-
B	53.64	0.26	2.45	2.47	83.9	-17.23	0.57	3.86 Y	1.03	-3.76 G	8.61
C	49.28	0.77	1.96	2.11	68.63	-21.59	1.07	3.86 Y	0.67	3.47 R	9.71

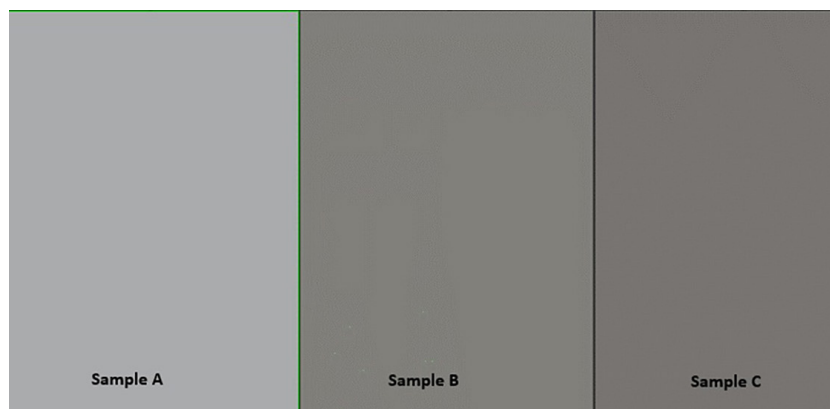


Figure 10. Photometric images of the specimens

that changes in the L parameter can be the main reason for the overall colour difference ΔE [32].

Positive Δa values obtained for samples B and C (0.57 and 1.07, respectively) show a shift towards the red colour, while positive Δb values (3.86 and 3.36) show a shift towards the yellow colour. Larger filler granulation resulted in a stronger red component but a slightly lower yellow component. The total colour difference, ΔE , increased over 12 % between samples B and C. The observed increase may indicate the influence of filler particle size on the optical properties of the composite, most likely resulting from differences in surface inhomogeneity and light scattering associated with the porous expanded glass particles [33].

It should be noted that the effect of particle size on composite properties is not necessarily identical for different types of properties. Studies of glass-bead-filled LDPE composites have shown that particle diameter may have a relatively limited effect on mechanical properties, whereas the filler itself substantially modifies the response of the polymer matrix [22–23].

The observed colour changes may be related to changes in surface topography caused by the incorporation of the filler. Both composite materials exhibited a pronounced decrease in lightness relative (ΔL) to the reference LDPE, for samples B and C. The absolute difference in lightness was therefore 25.36% higher for the larger glass bead fraction. Previous studies on polymer composites have demonstrated that surface condition and roughness can notably affect measured CIELAB colour coordinates and the overall colour difference ΔE . In particular, changes in surface morphology can modify how incident radiation is reflected and scattered [34].

The higher ΔL parameter observed for sample C may be related to greater surface heterogeneity due to the larger particle size of the glass beads. The porous structure of the expanded glass used in the study may further promote multiple scattering of light at the polymer-glass interface and on the uneven sample surface. Such scattering effects can influence the measured brightness and chromaticity of the composite surface. Previous studies have shown that changes in light scattering are closely correlated with changes in colour coordinates, and ΔL is a significant parameter influencing the overall colour difference [35, 36].

Although the larger filler fraction resulted in a 25.36% increase in the absolute difference in lightness and a 12.77% increase in ΔE , the change in chromaticity ΔC decreased by 34.95%. This suggests that increasing particle size affected the optical response mainly by changing lightness rather than by increasing colour saturation. The results show that in the investigated LDPE/glass bead composites, particle size may affect the optical properties by modifying surface morphology [37] and light-scattering behaviour [38, 39].

CONCLUSIONS

The study showed that introducing glass beads into the LDPE matrix considerably alters the material's mechanical and surface properties. Compared to pure LDPE (sample A), using both the 0.25–0.5 mm (sample B) and 0.5–1.25 mm (sample C) fractions modifies the material's properties under static and sudden impact loading and affects surface roughness and optical properties.

The addition of porous glass beads as a filler results in a deterioration of the strength properties

compared to solid LDPE, indicating the limited load-bearing capacity of the LDPE–glass beads system. This effect can be ascribed to the discontinuity of the composite structure, the presence of a rigid inorganic phase, and phase borders between the polymer matrix and the filler. During sudden impact loading, differences among the individual filler fractions further underscore the importance of particle size and its distribution within the matrix.

The introduction of the filler also significantly altered the surface topography. Compared with pure LDPE, increasing filler particle size increased surface inhomogeneity. This is important for the composite's functional properties, as increased roughness can affect both adhesion and the reflection and scattering of radiation at the surface.

Colourimetric analysis confirmed the significant effect of porous glass beads on the optical properties of the composites. Compared to the baseline sample (sample A), the composites exhibited a decrease in brightness L relative to the reference material by 24.32% (sample B) and 30.46% (sample C). For the larger filler fraction, the absolute difference in brightness was 25.36% greater than for sample B. Simultaneously, the total colour difference ΔE increased by 12.77%. The results show that increasing the particle size of the porous glass bead filler primarily leads to greater changes in brightness and total colour difference, whereas the change in chromaticity (ΔC) is smaller for the larger fraction.

A combined analysis of the roughness and colour results indicates a possible relationship between glass bead granulation, surface topography, and optical properties. Larger particles may cause greater surface inhomogeneity, thus altering the light reflection and scattering conditions. It should be emphasized, however, that based on the results obtained, such a mechanism is probable, although direct confirmation might require correlation analysis between the roughness parameters and ΔL and ΔE .

The obtained results allow to present general conclusions:

1. Pure LDPE exhibits the best mechanical properties, while the addition of filler leads to a reduction in strength parameters. This is due to the presence of a stiff, discontinuous filler phase and limited stress transfer at the matrix–filler interface.
2. Filler particle size influences the composite response, and this effect depends on the type of property being tested. Therefore, it cannot be

assumed that a larger fraction of glass beads always causes a proportional change in all material properties.

3. A filler in the form of porous glass beads increases surface roughness compared to pure LDPE. Larger filler granulation promotes the formation of a more heterogeneous surface topography.
4. The filler used causes a significant darkening of the surface. For a larger fraction of glass beads, the absolute difference in brightness was 25.36% greater. The colour change is also chromatic. Positive Δa values indicate a red shift, while positive Δb values indicate a yellow shift. The overall colour difference increases with filler particle size. A larger fraction of glass beads causes a greater change in brightness but not in chromaticity.
5. The comparison of roughness and colourimetry results suggests that modification of surface topography may be one of the factors responsible for changes in the optical properties of composites. Increased surface inhomogeneity can alter light scattering and consequently affect the colourimetric parameters L and ΔE .
6. From a material design perspective, the selection of porous glass bead granulation should be based on the required performance properties.

The results show that incorporating porous glass beads into the LDPE matrix effectively modifies the mechanical, surface, and optical properties of the composite. However, the modification is accompanied by a deterioration of mechanical performance and a pronounced increase in surface heterogeneity. Increasing the filler particle size from 0.25–0.5 mm to 0.5–1.25 mm resulted in a 25.36% increase in the absolute difference in lightness and a 12.77% increase in the total colour difference ΔE . The simultaneous changes in surface roughness and colour parameters show that the optical response of the composites is related to the modified surface topography and light-scattering conditions. Therefore, particle size should be considered an important design parameter when optimizing LDPE/glass bead composites for applications in which mechanical performance, surface quality, and appearance are all relevant.

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