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Transforming Wheel Waste into Functional Composites: Effect of Ground Tire Rubber and Hollow Glass Microspheres on Low-Density Polyethylene

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Keywords:
Weather generators; Climate changes; Meteorological parameters; GCM; Scenarios.

Highlights:

- *Develop new hybrid composites using recycled ground tire rubber and virgin materials.*
- *LDPE/GTR/HGMS composites were successfully prepared by injection molding method.*
- *The 10% GTR and 3% HGMS hybrid composite showed optimal results.*
- *Hardness and impact strength values improved by adding GTR and HGMS.*

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Abstract: Disposal of used bicycle wheels poses a significant environmental challenge. This study explores a recycling approach by incorporating ground rubber particles from used tires with low-density polyethylene (LDPE). The present study investigates the effect of GTR on the physical and mechanical properties of LDPE with the addition of hollow glass microspheres (HGMS), as a hybrid composite. This composite has useful properties for engineering applications that combine the properties of the composite materials. The composites were formulated with GTR ratios (10%, 20%, and 30%) and HGMS ratios (0%, 1.5%, 3%, 4.5%, and 6%). The materials were processed using a single-screw extruder and an injection molding machine under specific mixing conditions, i.e., 130 °C, 0.6 MPa, and 160 °C. The composites were subjected to comprehensive tests to study their microstructure, physical, and mechanical properties on a large scale. The TGA test showed that the inclusion of varying amounts of GTR insignificantly affected the onset temperature of weight loss, and it had no effect on the final degree of loss and stability. In contrast, the addition of HGMs increased the onset temperature of failure to 300 °C. The addition of HGMs resulted in the highest percentage of residual material compared to the percentage of residual material at 0% HGM. The manufactured composites were analyzed using scanning electron microscopy (SEM), which revealed the microstructure of the composite. The examination particularly emphasized the weak bond between the base material and the additives. The investigation showed a consistent distribution of the additives throughout the base material, with specific clusters of empty glass spheres. A negative correlation was found between the density of the composite and the percentage of void content and water absorption. Mechanical tests showed that tensile and flexural strengths decreased with increasing GTR levels by about 27% for tensile strength and 29% for flexural strength at 20% and 30% GTR. However, the presence of additives significantly affected the hardness and impact strength values, with significant improvements at higher levels of HGMS by up to 15% for impact strength. The hybrid composite containing 10% GTR and 3% HGMS showed encouraging results. The results revealed that the composite has promising potential for use in technical industries, especially automotive rubber supports, providing a sustainable option for managing waste generated from car wheels.

تحويل نفايات العجلات إلى مركبات وظيفية: تأثير مطاط الإطارات الأرضية والكريات الزجاجية المجوفة على مادة البولي إيثيلين منخفض الكثافة

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الخلاصة

ان التخلص من عجلات الدراجات المستعملة يشكل تحديًا بيئيًا كبيرًا. تستكشف هذه الدراسة نهج إعادة التدوير من خلال دمج جزيئات المطاط المطحونة من الإطارات المستعملة مع البولي إيثيلين منخفض الكثافة .(LDPE) نهدف إلى دراسة تأثير GTR على الخصائص الفيزيائية والميكانيكية لـ LDPE مع تأثيرات إضافة كرات زجاجية مجوفة (HGMS) وباعتباره مركب هجين يمتلك خواص مفيدة للتطبيقات الهندسية تجمع هذه الخواص بين خواص المواد المتكونه منه المتراكب. تمت صياغة المركبات بنسب GTR (١٠٪ و ٢٠٪ و ٣٠٪) ونسب HGMS (٠٪ و ١,٥٪ و ٣٪ و ٤,٥٪ و ٦٪). تمت معالجة المواد باستخدام آلة بثق أحادية اللولب وآلة قولبة بالحقن في ظل ظروف خلط محددة (١٣٠ درجة مئوية و ٠,٦ ميجا باسكال و ١٦٠ درجة مئوية). خضعت المركبات لاختبارات شاملة لدراسة بنيتها الدقيقة وخصائصها الفيزيائية والميكانيكية على نطاق واسع. خلال اختبارTGA ، لاحظنا أن إدراج كميات متفاوتة من GTR كان له تأثير ضئيل على درجة حرارة بداية فقدان الوزن ولم يكن له تأثير على الدرجة النهائية للفقد والاستقرار. في المقابل، أدى إضافة HGMs إلى زيادة درجة حرارة بداية الفشل إلى ٣٠٠ درجة مئوية. أدى إضافة HGMs إلى أعلى نسبة من المواد المتبقية مقارنة بالنسبة المئوية للمواد المتبقية عند ٠٪ .HGMتم تحليل المركبات المصنعة باستخدام المجهر الإلكتروني الماسح(SEM) ، والذي كشف عن البنية الدقيقة للمركب. أكد الفحص بشكل خاص على الرابطة الضعيفة بين المادة الأساسية والمواد المضافة. أظهر التحقيق توزيعًا ثابتًا للمواد المضافة في جميع أنحاء المادة الأساسية، مع مجموعات محددة من الكرات الزجاجية الفارغة. تم العثور على ارتباط سلبي بين كثافة المركب ونسبة محتوى الفراغ وامتصاص الماء. أظهرت الاختبارات الميكانيكية أن قوى الشد والانحناء انخفضت مع زيادة مستويات GTR بنحو ٢٧٪ لقوة الشد و٢٩٪ لقوى الانحناء عند ٢٠٪ و٣٠٪ .GTRومع ذلك، فإن وجود المواد المضافة أثر بشكل كبير على قيم الصلابة وقوة التأثير، مع تحسن كبير عند مستويات أعلى من HGMS بنسبة تصل إلى ١٥٪ لقوة التأثير. أظهر المركب الهجين الذي يحتوي على ١٠٪ GTRو ٣٪ HGMSنتائج مشجعة. تشير النتائج إلى أن المركب لديه إمكانات واعدة للاستخدام في الصناعات التقنية، وخاصة الدعامات المطاطية للسيارات. وهذا يوفر خيارًا مستدامًا لإدارة النفايات الناتجة عن عجلات الدراجات.

الكلمات الدالة: مطاط العجلات المعاد تدويره، بولي إيثيلين منخفض الكثافة، الكرات الزجاجية المجوفة، الخواص الميكانيكية، خواص الشد.

1.INTRODUCTION

Waste tires present significant and hazardous environmental concerns worldwide. Many resources are dedicated to pursuing economically feasible and ecologically sustainable methods for recovering and reutilizing used tires [1, 2]. Upcycling is a method of recycling that involves using shredded waste tires in polymer blends to produce goods of additional value. These products can be used for various purposes, such as playground equipment, anti-corrosion, and highway curb barriers. Ground tire rubber (GTR) is a product obtained by grinding tires using various technologies. It consists of a significant quantity of excellent quality natural and synthetic rubbers. These rubbers may be used as important raw materials in producing polymers, such as thermoplastics, thermosets, and rubbers [3, 4]. Transforming the whole tire into GTR involves many steps, including shredding, separating the steel and textile components, granulating the tire, and classifying the resulting material. GTRs are manufactured by mechanical grinding at room temperature, at room temperature in the presence of moisture, at elevated temperatures, and at very low temperatures. Before being ground to finer mesh sizes, i.e., smaller particle sizes, the tire is first chopped into relatively big pieces and then shredded into smaller fragments. Ambient grinding is often performed using a mill of the two-roll cracker type. Despite being referred to as "ambient," the temperature may go to 130°C during milling. The attainable particle size and particle size distribution of GTR are determined by the milling sequences and the kind of mill used [2, 5]. Waste tires consist of synthetic and natural rubbers appropriate for strengthening composites. Incorporating recycled tires into virgin matrices reduces the cost of the end items and the consumption of virgin resources. An instance of using waste tires as lightweight additives in asphalt is seen in the construction of roadways. This technique enhances the quality of the road surface by minimizing the formation of grooves, enhancing its capacity to withstand temperature changes, and improving its durability against deterioration [6]. Scrap tires are used in construction to enhance the durability of concrete compositions by serving as fillers in cement mortar. These fillers increase resistance against bending, dynamic loading, and cracking [7]. In addition, thermal insulation and acoustic qualities are being enhanced while reducing moisture absorption and permeability. The combination of discarded tires with polymers, such as thermoplastics, thermosets, and rubbers, produces cost-effective and environmentally friendly composite mixtures. These mixtures can be economically feasible substitutes for equivalent products [7, 8]. Shredding old tire waste into smaller particles increases the surface area, dispersing fillers more evenly throughout the material and enhancing the bonding of rubber chains, resulting in stronger bonds. Waste tire shredding, also known as tire shrinking or downsizing, is the process of reducing the size of tires [6]. Glass microbeads are little glass spheres manufactured for a diverse range of uses, such as thermal insulation surface coatings, synthetic foams, adhesives, printed circuit board substrates, fan blades, caulking materials, PVC, and other applications. Glass microspheres generally have dimensions ranging from 1 to 1000 µm. However, their sizes may vary from 100 nm to 5 mm in diameter. Microspheres are spherical particles that may be categorized as either solid or hollow [7]. Hollow glass microspheres (HGMs) are used as fillers in many applications because they can be integrated into a diverse array of polymer matrices as substitutes or in conjunction with other substances. The distinctive characteristics of HGMs, such as their low weight and exceptional resistance to crushing, are a direct consequence of their composition, which comprises an unreactive gas core surrounded by a rigid glass shell [9]. HGMs are known as glass bubbles and sometimes small balloons, with sizes ranging from 10 to 300 micrometers. Glass bubbles are usually composed of borosilicate glass, soda, and lime, providing low density, strong heat resistance, and chemical durability. The crushing strength of hollow balls is directly affected by the thickness of their walls. As expected, the greater density of the balls leads to a corresponding increase in their crushing force. The lightweight hollow glass spheres possess chemical stability, are non-combustible, non-porous, and exhibit exceptional water resistance [10]. A study was done by Bodude et al. [11] on the combination of low-density polyethylene with rubber grains measuring 150 µm. The ratios of the mixture ranged from 5% to 25%, increasing in increments of 5%. The casting technique was used to analyze the mechanical characteristics of the polyethylene base. Several mechanical tests were conducted, including tensile strength, impact resistance, bending resistance, and hardness. The findings indicated that including crushed rubber particles at a maximum weight ratio of 20% produced a composite material with a 65% greater modulus of elasticity and a 22% higher hardness in comparison to the original components. Nevertheless, the composite material showed a 28% decrease in bending strength when compared to the basic material while exhibiting almost the same impact energy. The lack of strong bonding between the matrix phases and reinforcements might cause this issue. Khan et al. [12] prepared a composite of low-density polyethylene (LDPE/GTR) and studied the mechanical properties. They also demonstrated the effect of adding tire waste (GTR) to the base polyethylene material. The tire waste was added in different proportions under 220 °C and 200 bar manufacturing conditions. At a pressure of 200 bar, tests were conducted, and it was found that the tensile strength decreased as the content of (GTR) increased. However, the impact strength and elongation ratio increased. With the enhanced impact and elongation ratios, this material is well-suited for applications like gym mats or the car sector. The characteristics of LDPE compounds were examined by Kiss et al. [13] with varying ultrafine ground tire rubber (uGTR) and fine rubber (fGTR) content. The findings showed that the tensile qualities diminished as the elongation increased, likely due to the property arising from the greater surface area and the influence of size. Additionally, there was a modest drop in the tensile strength. The scanning electron microscope (SEM) pictures provided visual information on the state or quality of the materials. The use of uGTR resulted in superior interphase adhesion and hardness. The amount of material dropped as the GTR concentration increased. However, the hardness was high in the case of UGTR samples. The mixes containing uGTR exhibited improved interfacial adhesion between the phases as a result of the much larger surface area, enhancing mechanical characteristics compared to fGTR. Stagnaro et al. [14] incorporated microspheres (HGMs) into polyethylene via melt mixing at three weight ratios: 5%, 10%, and 20%. Characteristics of unaltered and altered hierarchical graphene materials. The adhesion between the filler and the base material was analyzed using a scanning microscope (SEM), and the mechanical characteristics of the composites were compared to those of the base material. The findings indicated that the most significant enhancement in characteristics, such as yield strength, modulus of elasticity, and elongation, occurred at a concentration of 5%. The results demonstrated a weight reduction of up to 17% with exceptional aesthetics. Chimene et al. [15] examined the impact of particle size and content of hollow glass microspheres on raw and recycled polyethylene. Testing revealed that these factors influenced the density, tensile modulus, and storage properties. The modulus increased in correlation with the glass content as it experienced creep. The recovery exhibited a substantial drop, with the composites being more strongly impacted by the lower particle size due to their larger surface area. A significant disparity was noted between the virgin and recycled LD-PE, mainly attributed to the pollution present in the latter. Nevertheless, the data indicated this result. Recycled polyethylene may serve as a substitute for virgin polyethylene. Enhanced with glass particles, particularly when reduced dimensions are used, this substance may be utilized in several applications. Cosse et al. [16] studied the polyethylene (PE)/HGM characteristics, containing 1% and 5% weight/weight of HGM, respectively. The composite materials were fabricated using two processing techniques: single-screw extrusion and twin-screw extrusion. Based on morphological investigation, matrix/filler adhesion was found to be inadequate for all samples. The most optimal dispersion of HGM was achieved in samples that underwent twin-screw extrusion. The mechanical characteristics were influenced by both the chosen processing technique and the concentration of the included hollow glass spheres. The modulus of elasticity, tensile strength, and strain in the systems experienced a drop of 20%, 10%, and 23%, respectively. Manufactured with a two-screw extruder, the impact force was the only instance with a growth above 300%. The presence of a significant amount of hollow glass spheres reduced the mechanical strength of the Syntactic foams, with a fall ranging from 5% in modulus of elasticity to 50% in strain. The present work aims to utilize ground tire rubber (GTR) in combination with polyethylene (PE) to produce enhanced thermoplastics. Specifically, this research aims to demonstrate the impact of integrating rubber granules from recycled tires on the properties of low-density polyethylene (LDPE). By incorporating hollow glass microspheres (HGMS) as reinforcing elements, the study explores the potential to improve the mechanical characteristics of the composite material while reducing its weight. These LDPE/GTR/HGMS composites are intended for various engineering applications, including automotive bumpers, cable covers, hydraulic motor cushions, and head shields. Such applications require materials with excellent impact resistance, flexibility, stiffness, and lightweight properties, which can be achieved cost-effectively. Additionally, the study contributes to environmental preservation through recycling practices.

2.EXPERIMENTAL WORK

2.1.Materials

The low-density polyethylene (PE-TASNEE LD4025AS) material used was obtained from the Saudi Manufacturing Company. The specific properties of this material are tabulated in Table 1. Waste tire granules were obtained from a private laboratory and underwent a screening process to produce granules with a size of 150 µm to 300 µm. The density investigated was 1.2 g/cc. In addition, the user obtained hollow glass microspheres (HGMs) with a density of 1.27 g/cc and a granular size of <53µm. Figures 1 and 2 depict the constituent elements and scanning electron microscope (SEM) images of the HGMs, respectively.

Table 1 The Physical Characteristics of the Polyethylene Used.

Typical Propeties			
Physical	**Method**	**Unit**	**Values**
Density	ISO 1183	g/cm³	0.925
Melting Flow Rate (190° C/2.16 Kg)	ISO 1133	G/min	4.0
Melting Temperature	ISO 3146	°C	111
Vicat Softening Temperature (A50(50 °C/h 10N)	ISO 306	°C	92

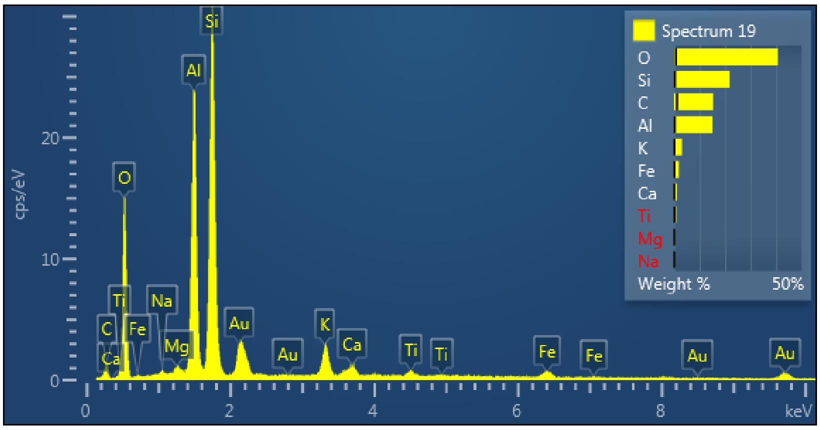


Fig. 1 Components of Hollow Glass Microspheres (HGMS).

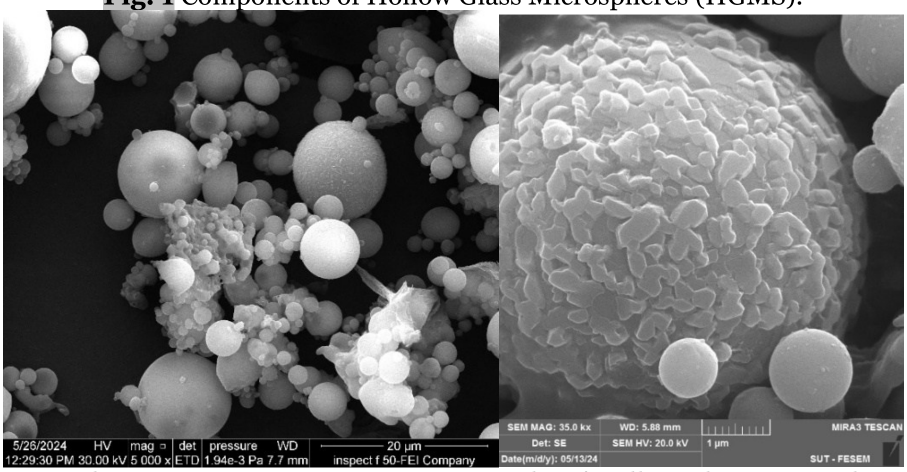


Fig. 2 Scanning Electron Microscopy (SEM) Micrographs of Hollow Glass Microspheres (HGMS).

2.2.Preparation of the Samples

The rubber powder (GTR) was sieved using special sieves to obtain granular sizes from 150 to 300 µm. Then, the polyethylene granules, hollow glass balls, and rubber granules were weighed using a high-precision balance with an accuracy of 0.0001 g, as shown in Table 2. These materials were fed into the single-screw extruder machine (SJ25 made in China). Under specific operating conditions, with a temperature of 130 °C and a specific screw rotation speed of 10 rpm, the mixture is placed in an injection machine (XCX-40G of Chinese origin) and compressed to 0.6 MPa at a temperature of 160 ºC and for 30 sec in pre-prepared molds. This process followed international standards for producing specimens for hardness, impact, tensile, and bending tests, as shown in Figure 3.

Table 2 Compositions of the Samples Produced.

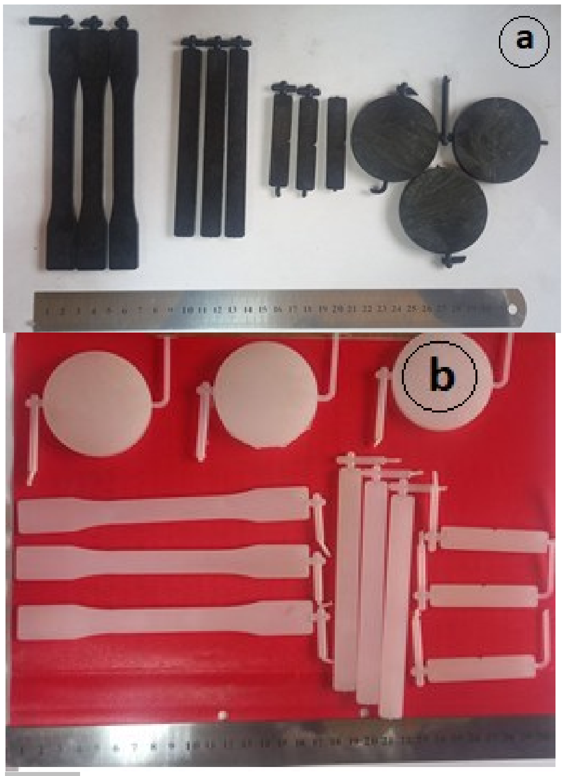


Fig. 3 Samples Produced (a) LDPE+10% GTR, (b) Pure LDPE.

2.3.Testing Methods

2.3.1.Density, Void Content, and Water Absorption

The density of the composite material, which is manufactured by combining polyethylene, rubber, and hollow glass, was determined according to international standards (ASTM D792) [17]. The void content formed in the composite material was also measured according to the international standard (ASTM D2734) [18]. The water absorption rate was measured according to ASTM standards. D570 [19].

2.3.2.Hardness Test

To assess the hardness of samples made from composites (PE-GTR-HGM) by international standards (ASTM D2240) [20], a hardness testing apparatus (SHORE D) was used.

2.3.3.Tensile Test

The tensile test was conducted using (LARYEE) testing equipment manufactured in China. The tensile samples were produced following the international standard ASTM D638 [21].

2.3.4.Flexural Test

The flexural test was conducted using (LARYEE) testing equipment manufactured in China. The tensile samples were produced following the international standard ASTM D790 [22].

2.3.5.Izod Impact Test

The composite specimens for impact testing were produced using equipment of Chinese origin (Time Group Inc.), following the international standards described in ASTM D256 [23].

3.RESULTS AND DISCUSSION

3.1.Thermogravimetric Analysis (TGA)

Three steps can be seen in the TGA diagrams, shown in Figure 4. During the first stage, a slight decrease in weight was observed in all the samples being examined. This stage ended at a temperature ranging between (250 to 350) °C. However, the onset of loss fluctuates depending on tire rubber addition rates. By adding 10%, as in Fig. 4 (a), the starting value was 105 °C. Including 6% glass pellets increased the weight loss temperature to 300 °C, as shown in Fig. 4 (b). In contrast to the present findings, a 30% GTR concentration insignificantly affected the onset of weight loss in the composite differences, ascribed to the higher thermal stability of polyethylene than GTR. It is worth noting that including glass pellets insignificantly affected the onset temperature of weight loss, resulting in a slight increase of only 128 °C, as shown in Fig. 4 (d) [24, 25]. These slight decreases are due to the evaporation of moisture and volatile chemicals in the compounds. The second step is the main stage, where the polyethylene and rubber begin to thermally decompose. As a result, the collapse of the polymer chains led to a significant weight loss of (92% and 71%) for 10%GTR and (0% and 6%) HGM, respectively, and (88% and 78%) at 30%GTR for the same HGM ratios. In the third stage, which started for all samples after 475 °C, the decomposed materials decomposed further due to continued heating, leaving only inorganic and carbonaceous materials. For the samples with HGM ratios, the proportion of non-degradable additives remained constant [25, 26].

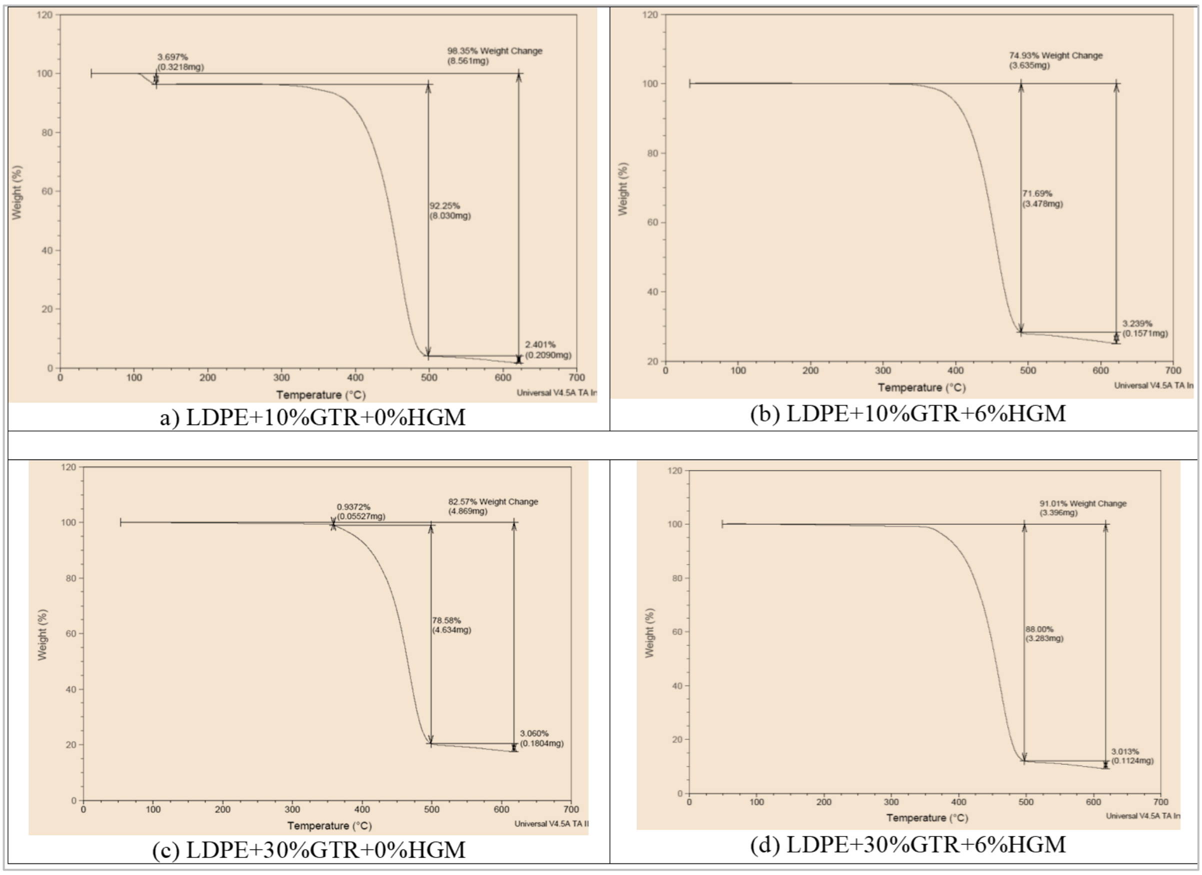
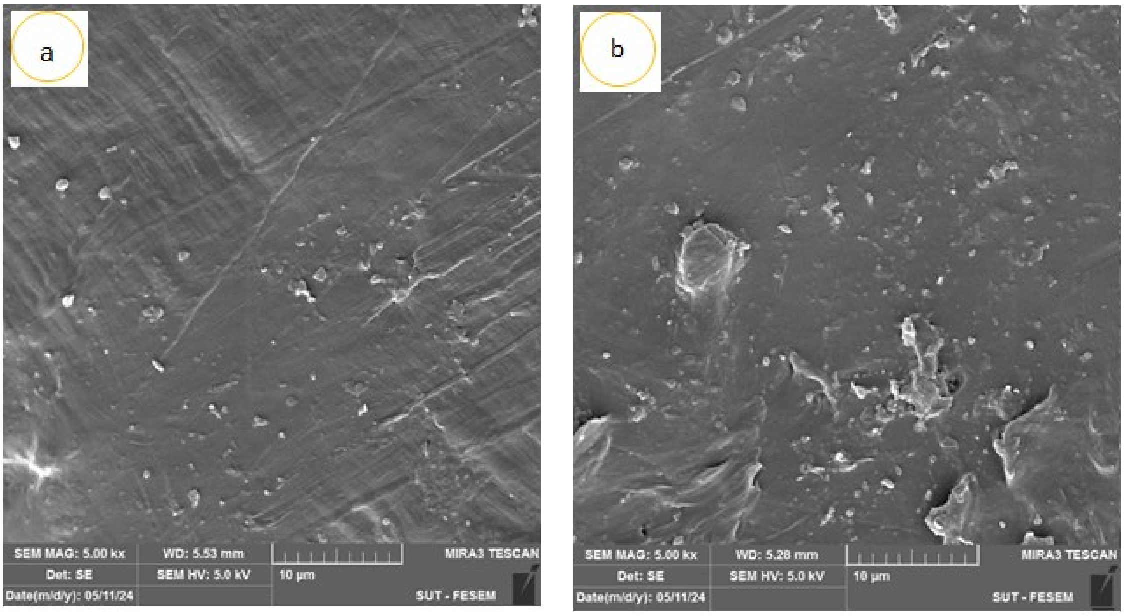


Fig. 4 Thermogravimetric Analysis (TGA) of the Prepared Composites.

3.2.Internal Structure—Micrographs Analysis

The scanning electron microscope images, shown in Fig. 5, visually represent the combination of GTR's large particle size and restricted specific surface area. However, images (a, b) cannot distinguish between tire waste particles and base materials. The combination of these materials results from their ability to flow easily. Figures 5 (c, d) show the presence of voids in the composite material, which indicates weak bonding between the composite molecules and shows reasonable dispersion of both GTR and HGM additives. Although there was some aggregation, the small particle size of HGM enabled it to infiltrate the base material and GTR, filling the gaps created during the production process. This observation is consistent with [13, 27].



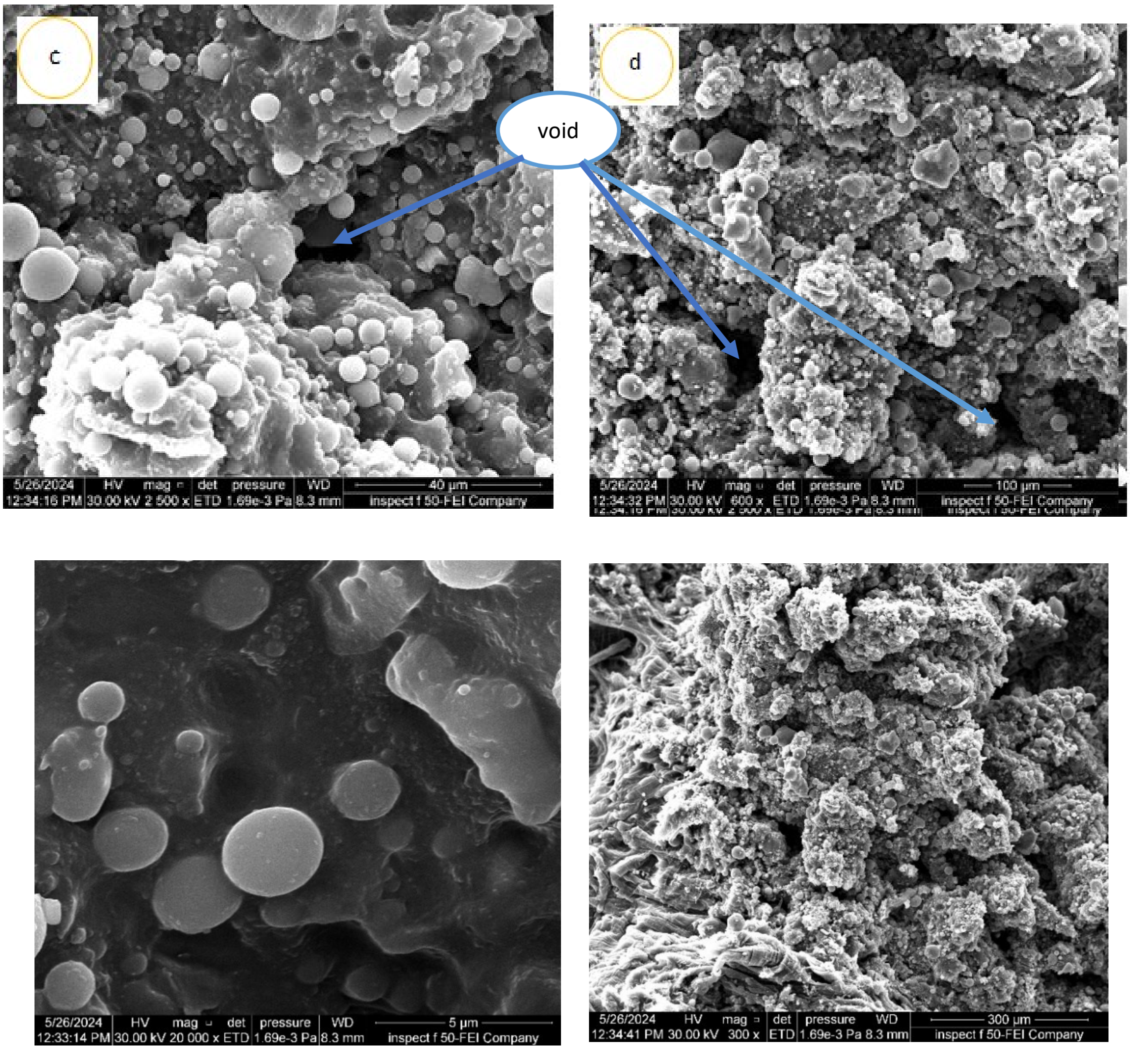


Fig. 5 Scanning Electron Microscopy (SEM) Micrographs of (a, b) LDPE/10%GTR/3%HGMS, (c, d) LDPE/30%GTR/3%HGMS.

3.3.Density, Void Content, and Water Absorption

The variability in the density of the constituents used in the production of the compound clearly impacts the density of the outcome, as seen in Fig. 6. Incorporating GTR and HGMs with densities beyond that of the LDPE matrix substantially elevates the composite material's density, aligning with the documented rise in theoretical density, as seen in Table 3. This outcome is in line with [24].

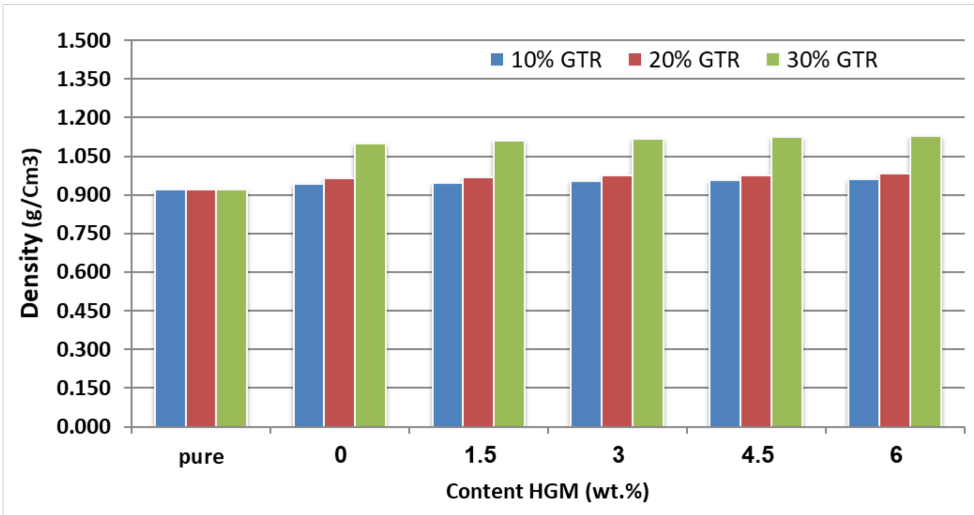


Fig. 6 The Density of the Investigated Materials as a Function of GTR and HGMs Content.

Table 3 The Theoretical Density (Td) (g/cc) with Addition Ratios for Each of (GTR and HGMs).

% HGMS	(Td) (g/cc) at 10% GTR	(Td) (g/cc) at 20%GTR	(Td) (g/cc) at 30%GTR
Pure (LDPE)	0.925	0.925	0.925
0	0.947	0.969	1.113
1.5	0.951	0.974	1.118
3	0.955	0.978	1.124
4.5	0.959	0.982	1.129
6	0.963	0.986	1.135

Figures 7 and 8 illustrate the percentages of void content and water absorption, respectively, revealing a clear correlation between these parameters. The content of additives, GTR, and HGMs was inversely proportional to the void content ratios, indicating an increase in the composite's density, as shown in Fig. 6. A slight increase in void content at 30% GTR is observed, likely due to weaker bond strength with the matrix and differing rates of thermal shrinkage during cooling of LDPE and GTR. Nonetheless, HGMs effectively reduced void content and absorption rates due to their uniform distribution, although some aggregates were visible in SEM images. This behavior occurred when HGMs successfully filled the voids between the PE matrix and GTR particles, as evidenced in electron scanning microscope (ESM) images. This behavior aligns with the previous research of [28].

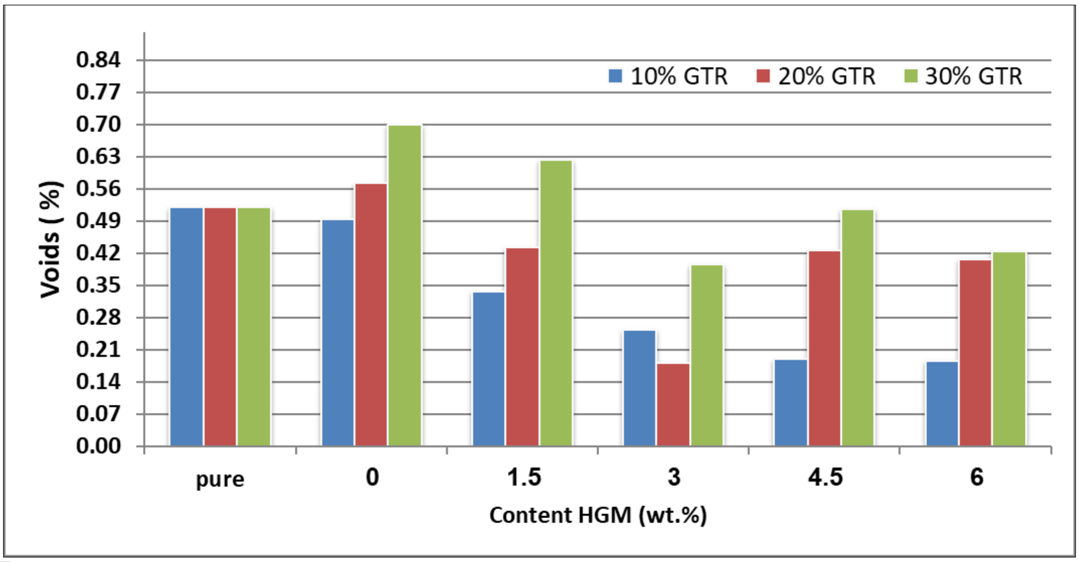


Fig. 7 The Void Content of the Investigated Materials as a Function of GTR and HGMs Content.

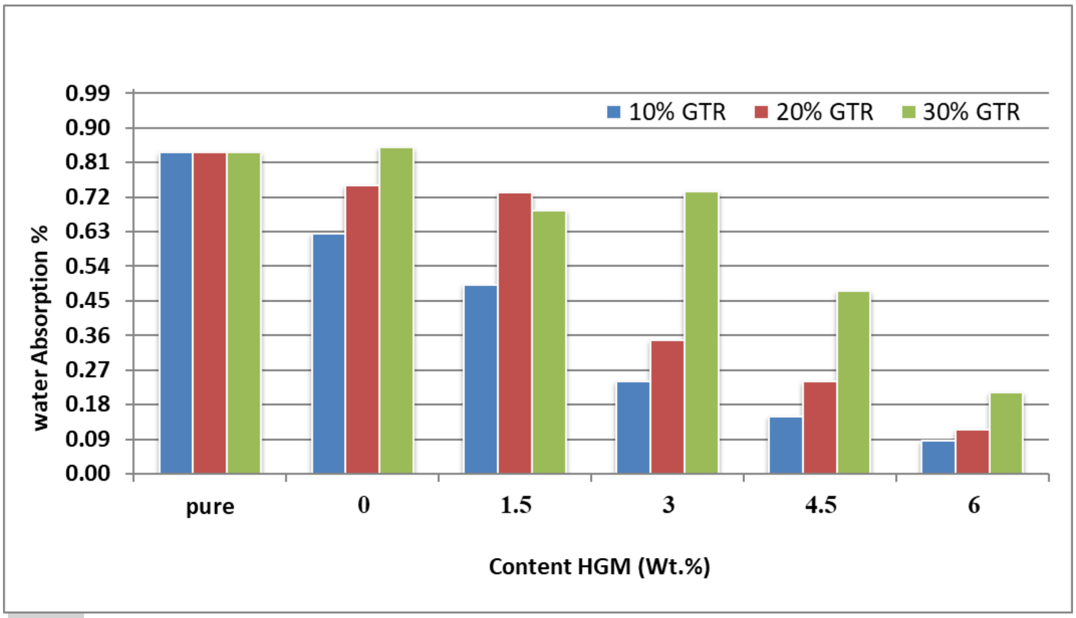


Fig. 8 The Water Absorption of the Composites as a Function of GTR and HGMs Content.

3.4.Hardness Test

Including ground tire rubber (GTR) reduced the hardness of the low-density polyethylene (LDPE) base material, as indicated by the Shore D hardness measurements in Fig. 9. A decrease in hardness values was observed with increasing GTR content at 10%, 20%, and 30%. This reduction can be attributed to the higher elasticity of the rubber, which diminishes the composite's ability to resist deformation under pressure. Additionally, the weak bonds between the LDPE and GTR further reduce hardness [26, 29]. Figure 9 shows a positive relationship between hardness levels and the concentration of hollow glass spheres. This improvement can be attributed to the incorporation of hollow glass spheres, which reach 8% after the decline in hardness values due to the addition of GTR, as shown in Fig. 1. The high hardness of the composite was further enhanced by the uniform dispersion of these spheres, as observed in the SEM images. This dispersion helps distribute loads evenly across the material, resulting in lower stress concentrations and improved ability to withstand pressure. This principle is evident in the data presented in Ref. [30].

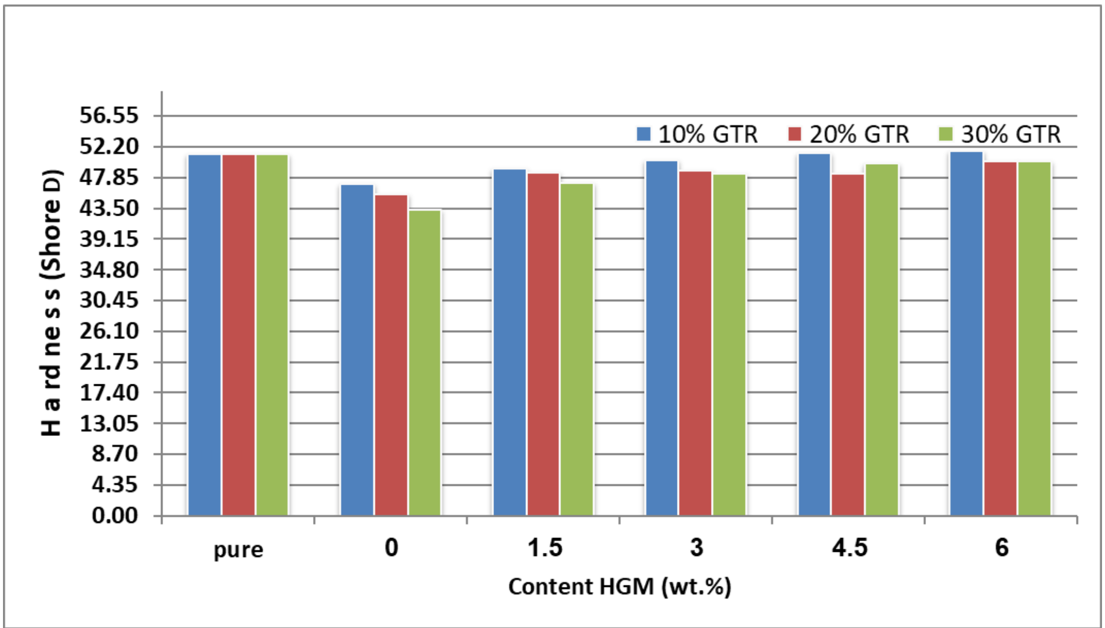


Fig. 9 The Hardness of the Investigated Materials as a Function of GTR and HGMs Content.

3.5.Tensile Properties

Incorporating waste tires (GTR) substantially decreased tensile strength. Figure 10 demonstrates that the increase in GTR concentration led to a more noticeable drop. The decline may be attributed to many causes, including inadequate compatibility between the foundation material and the voids, which serve as areas of vulnerability and creation. The material is prone to failure when exposed to mechanical stress, as seen in the scanning electron microscope (SEM) pictures depicted in Fig. 5. Furthermore, rubber has a lower modulus of elasticity compared to polyethylene, resulting in a reduced capacity of the composite material to endure stress before fracturing and experiencing further degradation. This behavior happens when the process of recycling (GTR) is exposed to the atmosphere during its use and processing. This result agrees with [12, 13]. By examining Fig. 10, the tensile strength values increased with the concentration of hollow glass balls (HGMs). This increase was slight, reaching 3% after deterioration, after adding GTR due to the ability of these balls to distribute the composite materials evenly. They also effectively reduced the presence of voids inside the composite, as shown in Fig. 6. In addition, it showed resilience against some applied forces, thus reducing the overall stress on the composite. However, this increase in tensile strength did not reach the values of the base material due to the weak adhesion strength with the base material. Also, a decrease was noticed in tensile strength at 6% HGMs due to the increase in the aggregates that form the center of concentration of stresses, which makes them more susceptible to cracking and collapse under the pressures applied in the compound [27, 31]. Incorporating materials, such as GTR (ground tire rubber) and HGMs, into polyethylene reduced its flexibility, resulting in a drop in elongation rates under tensile stress. Additionally, Fig. 11 exhibits favorable compatibility with Fig. 10.

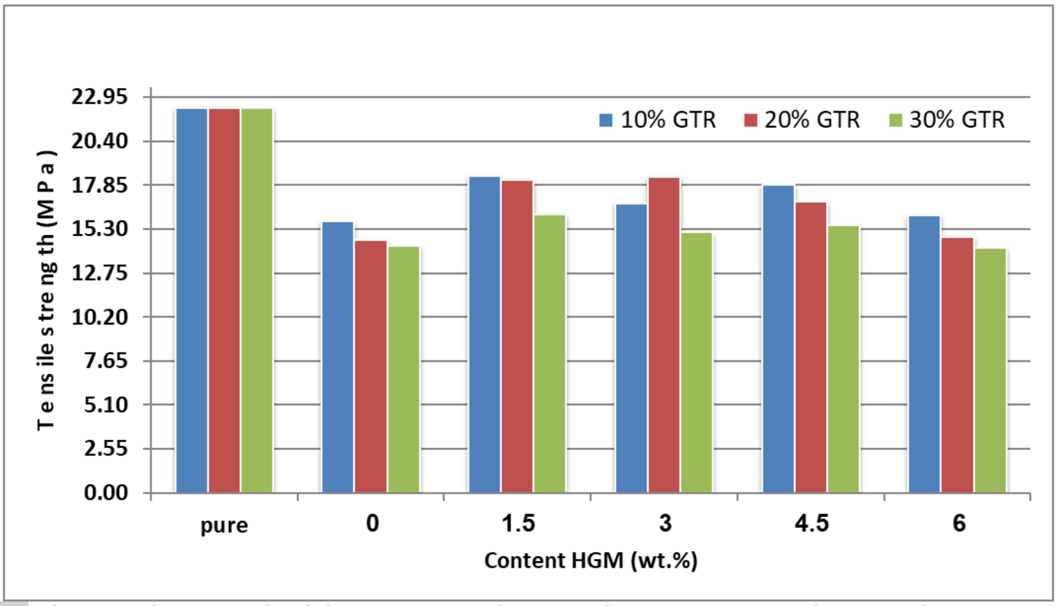


Fig. 10 The Tensile Strength of the Investigated Materials as a Function of GTR and HGMs Content.

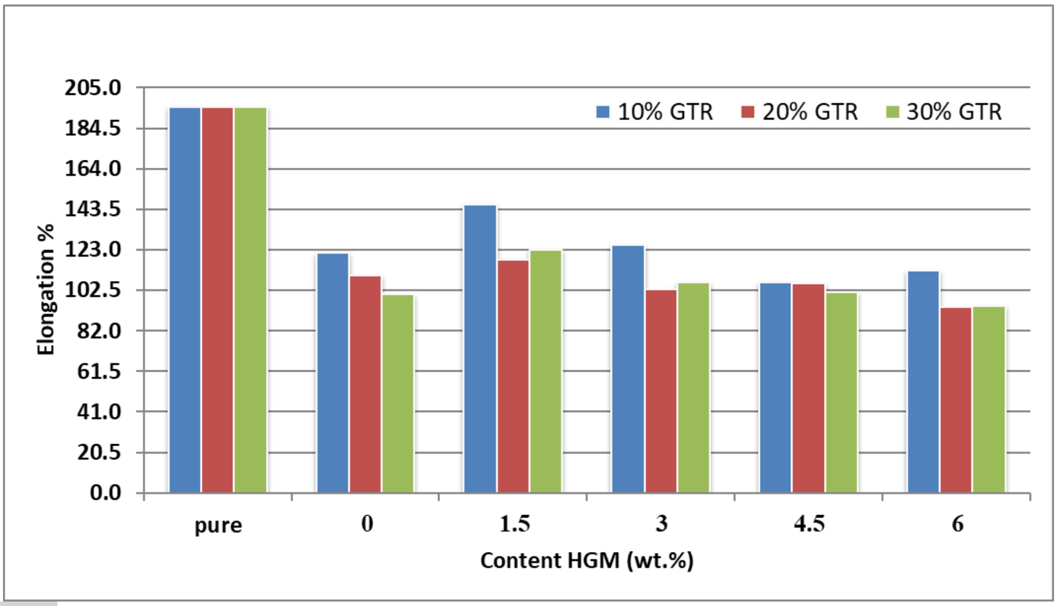


Fig. 11 The Elongation of the Investigated Materials as a Function of GTR and HGMs Content.

3.6.Flexural Strength

Figure 12 illustrates that varying amounts of GTR, combined with the absence of HGMs, decrease the flexural strength of the sample. This phenomenon might be caused by voids or defects in the mixture, as shown in Figs. 5 and 7. The flexural resistance of rubber decreased under applied stress, and the use of rubber materials significantly impacted the rigidity of the structure, resulting in a decrease in overall rigidity. The flexural strength at break cannot be determined due to the absence of a sample fracture under the applied force. Figure 12 also shows that the flexural strength decreased with increasing HGMs content, particularly at 20% and 30% GTR. This reduction was consistent and can be attributed to the mismatch between the surface of the glass spheres and the base material and rubber (GTR). Insufficient interfacial bonding limits the load transfer from the matrix to the hollow glass microspheres (HGMs). However, an increase in flexural strength was observed at 3% HGMs up to 11% compared to GTR /0% HGM, possibly due to the relatively homogeneous distribution during the specimen fabrication [32, 33].

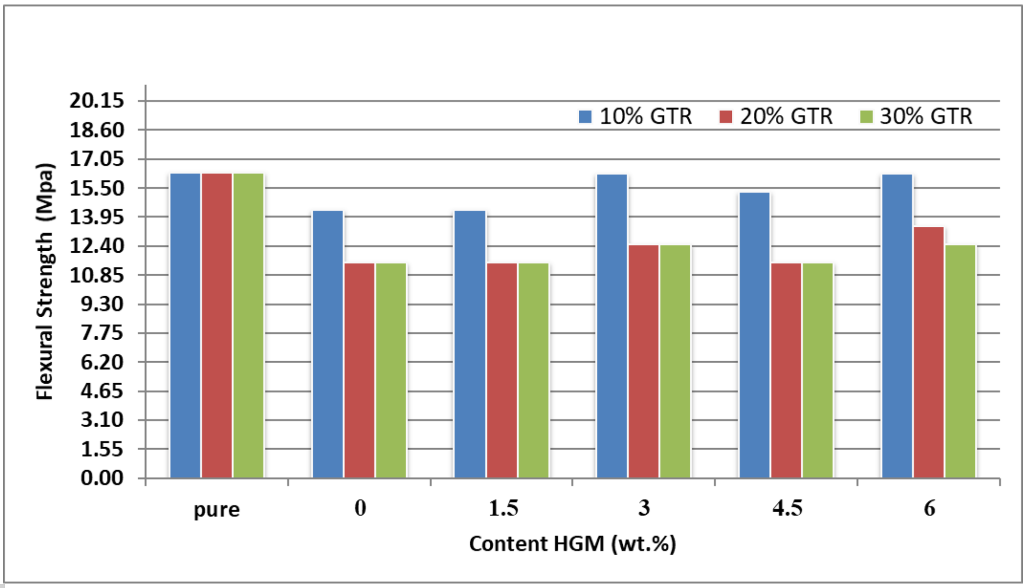


Fig. 12 The Flexural Strength of the Investigated Materials as a Function of GTR and HGMs Content.

3.7.Impact Strength

The addition of GTR enhanced the impact resistance. Within the LDPE/GTR mixture, particularly at the addition ratios of (10% and 20%) GTR, there was a slight reduction in the ratio of (30% GTR), as seen in Fig. 13. The behavior of this product may be attributed to the rubber's capacity to absorb energy due to its cross-linked structure, which is capable of undergoing deformation to increase energy absorption before the initiation of cracking. The glass transition temperature Tg exceeded the ambient temperature, which is why it was adaptable. The drop in the third ratio is due to this addition. The bond strength was somewhat lower than the first and second ratios [12, 27, 34, 35]. Figure 13 shows a relationship between the amount of hollow glass spheres and the impact resistance. The main reason for this phenomenon is the ineffective bonding between the surfaces. However, the impact resistance values improved with increasing HGM ratios and with the ratio (10%GTR), especially when the high glass microspheres (HGM) content reaches 3 wt.%. The impact strength of LDPE/HGM composites exceeds that of all other composites by an increase of 12%. Therefore, the improvement in impact strength does not depend on the improved adhesion of the interface between LDPE and HGM but on creating a comprehensive stress transfer path, which occurs when the HGM content reaches 3 wt.%. This unique and comprehensive stress transfer channel enhances stress transfer and acts similarly to fibers in composites [26].

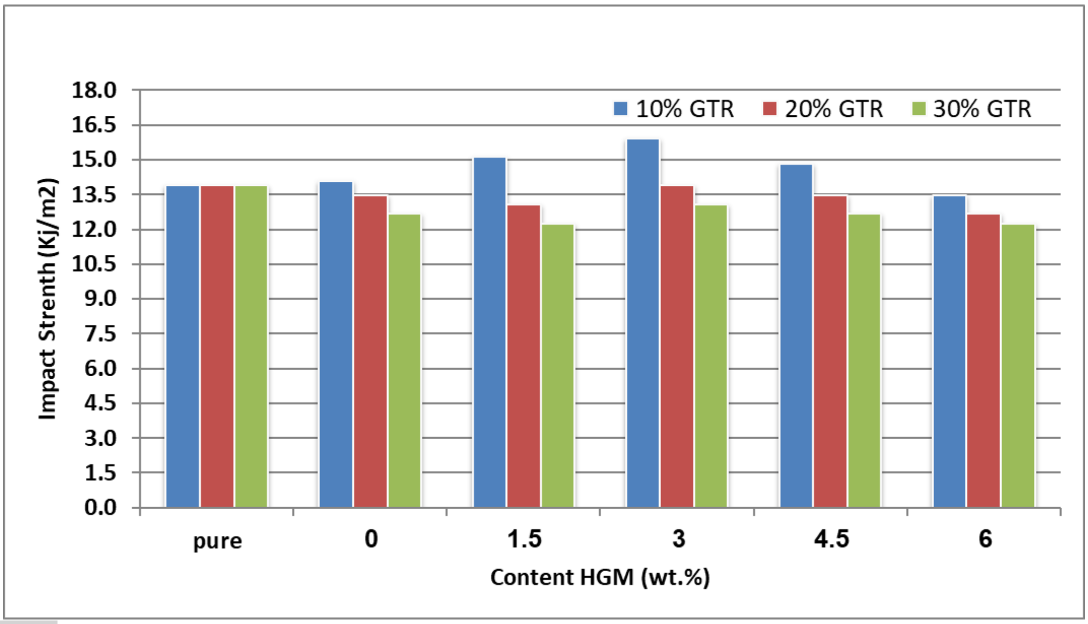


Fig. 13 The Impact Strength (Izod) of the Investigated Materials as a Function of GTR and HGMs Content.

4.CONCLUSIONS

The thermosetting rubber composite was formulated with ground tire rubber (GTR) in three varying ratios (10%, 20%, and 30%) and four ratios of hollow glass microspheres (HGMs) containing a low-density polyethylene (LDPE) core, utilizing a hot-pressure molding apparatus. The characteristics of the mixture were meticulously analyzed. They may be characterized as follows: The TGA examination revealed that varying quantities of GTR marginally influenced the initiation of weight loss, while not impacting the extent of final loss or its stability. In contrast, HGMs elevated the decomposition onset temperature to above 200 °C. A distinct disparity was seen in the quantity of residual material post-weight loss stabilization between the incorporation of HGMs and GTR. The incorporation of GTR and an increase in HGMs content resulted in elevated density values, counterbalanced by a notable reduction in void content and water absorption rates, with optimal outcomes attained at 3% HGMs and varied amounts of GTR. The use of ground tire rubber diminished the composite's stiffness by 6% to 13%. Although the stiffness values were enhanced with HGMs, they ultimately approached the stiffness of the basic material. Augmenting the GTR content markedly diminished the tensile strength and elongation rates; however, this decline was alleviated by HGMs, thereby effectively reinstating these parameters. The incorporation of tire rubber markedly diminished the flexural strength values of polyethylene, particularly at elevated concentrations (20%, 30%). The incorporation of HGMs enhanced the flexural properties, particularly at 3% HGMs and 10% GTR. Ultimately, the introduction of GTR and HGMs to polyethylene resulted in a slight and inconsistent decrease in the impact strength at elevated concentrations (20% and 30% GTR). However, a notable enhancement in impact strength was recorded at 10% GTR, with optimal results at 3% HGMs.

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