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Effect of Hollow Glass Microspheres on Properties of Virgin and Recycled High-Density Polyethylene-Fly Ash Composites

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Abstract:

High-density polyethylene (HDPE) offers an exceptional combination of mechanical properties, chemical resistance, and adaptability. A hybrid composite material was created by reinforcing virgin and recycled HDPE with HGMs and FAs to address current deficiencies. Fly ash from heavy fuel combustion and lightweight HGMs served as eco-friendly reinforcements, enhancing the physical, mechanical, and thermal properties of HDPE composites. Composite samples were fabricated by extrusion and injection molding and evaluated for density, water absorption, void content, tensile strength, flexural strength, impact resistance, and thermal stability. The findings indicated an enhancement in physical attributes, i.e., density, water absorption, and void content, with increased filler content. Fly ash improved the tensile strength by 7.1% in virgin HDPE and 2.3% in recycled HDPE. The findings indicated that the hardness of the fly ash polyethylene composite was inversely affected by the addition of hollow glass beads, with a detrimental impact on the virgin material and a beneficial effect on the recycled material. Nonetheless, HGMs were useful in enhancing thermal stability. The thermogravimetric study validated the enhancement in thermal performance with increasing filler content, underscoring its potential use in temperature-sensitive settings. The present study demonstrates the potential to enhance high-density polyethylene (HDPE) composites with fillers derived from industrial waste, thereby promoting sustainability and expanding their applications in the automotive, packaging, and construction industries.

Keywords:

HDPE; Fly ash; Hybrid; Glass microspheres; Virgin; Recycled.

Highlights:

- Improved environmental sustainability using industrial waste in composites.
- Virgin and recycled HDPE were reinforced with a yellow oil fly ash and glass microspheres.
- Fly ash enhanced tensile strength by 7.1% in virgin HDPE and 2.3% in recycled HDPE.
- Hardness slightly increased with YOFA and HGMs content.
- Thermogravimetric analysis confirmed better thermal performance with filler.

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1.INTRODUCTION

Composite materials have significantly advanced materials science throughout history. A composite material combines properties of two components: a matrix and a reinforcing material. A combination of these components yields materials with unique mechanical, thermal, and physical properties superior to those of the individual components. Plastics are widely used worldwide as matrix materials due to their low cost and desirable properties, such as easy processing [1]. Recently, fiber-reinforced polymer composites based on synthetic fibers, such as Kevlar, carbon, and glass, have made significant progress in several areas to meet the demand of technical applications in various industries, including automobiles, electronics, construction, and aerospace [2]. Industry 4.0 has placed significant emphasis on recycling and the sustainability of plastics and polymers due to serious environmental concerns. Recycling materials, such as plastic, glass, and metal waste, is preferable to landfill disposal. The majority of plastic waste consists of polyethylene and polypropylene (60-70%), with the remainder consisting of polystyrene (10-15%), PVC (15%), and PET (5%) [3]. High-density polyethylene (HDPE) is one of the most widely used polymers in industry due to its high mechanical strength and versatility. The extensive use of HDPE comes with certain limitations that require innovative solutions to improve the value chain and efficiency. Various studies have developed binary HDPE composites to improve mechanical properties by adding fibers, carbon nanotubes, and nanoparticles. Moreover, the extensive use of HDPE presents different environmental and sustainability challenges. HDPE waste is difficult to recycle and sometimes categorized as hazardous [4-5]. Innovative approaches are required to address the sustainability challenges of HDPE. Recycling and repurposing industrial HDPE waste are viable solutions for such challenges. A unique solution to address such challenges includes the use of fly ash and hollow glass microspheres (HGMs). These additions can improve the properties of HDPE, while simultaneously mitigating environmental concerns. Particle-reinforced composites are extensively used, and the addition of reinforcement is known to enhance performance. In HDPE-based composites, improvements in both mechanical and thermal properties have been observed compared to pure HDPE. The use of fly ash as a filler in polymer composites offers significant advantages, including cost reduction, easy availability, and volume-sensitive end uses. This type of use of fly ash waste from the thermal power plants addresses a major environmental problem in the waste-disposal industry [6-8]. Prior research has mostly focused on the impacts of individual fillers, such as HGMs or fly ash, inside an HDPE matrix. Patankar et al. [9] examined the impact of HGMs on enhancing the elasticity modulus of HDPE, which rose by 250%, while the stress at failure decreased by 70%. Furthermore, the yield strength and hardness were improved with the use of just 1% PE-g-MAH. The density and thermal conductivity were decreased. The authors did not investigate the amalgamation of HGMs with alternative fillers. Similarly, GÜMÜŞ [10] investigated montmorillonite (MMT) combined with hybrid glass microspheres (HGMs) in high-density polyethylene (HDPE); however, the study focused solely on the impact of nanoclay, without examining the possible effects of hybrid fillers. Sommerhuber et al. [11] and Sormunen and Karki [12] studied recycled HDPE composites with wood particles and bamboo fibers, respectively; however, neither study used fly ash or HGMs to enhance HDPE properties. These experiments demonstrate the enhancement of HDPE characteristics by the use of fillers. These results may serve as a foundation for using hybrid fillers, including fly ash and HGMs, to enhance the properties and improve the sustainability of these composites. Optimizing the concentration of fillers in HDPE is crucial for attaining optimal characteristics. Kumar et al. [13] demonstrated the incorporation of cenospheres as fillers in HDPE. The brittleness and ultimate tensile strength decreased with increasing filler content. The present study focuses on the formulation of a hybrid composite material comprising HDPE, HGMs, and fly ash. This study seeks to overcome the limitations of single fillers by using hybrid fillers, thereby improving mechanical and physical properties and addressing the existing knowledge gap in this field. The combination of HGMs and fly ash may markedly enhance HDPE performance, due to the lightweight properties of HGMs and the cost-efficiency of fly ash. This work also adds to the overarching objectives of sustainability by using fly ash waste from power plants. This work specifically investigates the combined impact of two fillers, addressing a notable research gap in the use of both reinforcements inside an HDPE-based hybrid composite. To the authors' knowledge, no research has examined the effects of this combination on HDPE. Prior studies examined the impacts of HGMs and fly ash independently on HDPE.

2.MATERIALS AND METHODS

2.1.Materials

High-density polyethylene (HDPE) grade B5429 was supplied by SABIC, Kingdom of Saudi Arabia. Homemade recycled HDPE Granules were used as the matrix material. Hollow glass spheres were procured from

HENAN KEER Metallurgy Material Co., Ltd., a Chinese firm, to serve as fillers, and the particle size (<53μm) was ascertained using sieves. The density of HGMs was determined to be 1.27 g/cm³ using the ASTM D2320-98 standard. Figure 1 shows the microstructure of HGMs examined using a scanning electron microscope (SEM). To determine their chemical composition, HGMs were analyzed using X-ray fluorescence (XRF), as detailed in Table 1. Yellow Flay ash (YOFA) powder was obtained from the Iraq-Qayyarah power plant after being treated with (MgO), grinding, and drying to produce a particle size of 53 ≥ 80 μm. The density (2.18g/cm³) was determined using the ASTM D2320-98 [14] standard. The image was obtained by SEM (Fig. 2) and XRF (Table 2).

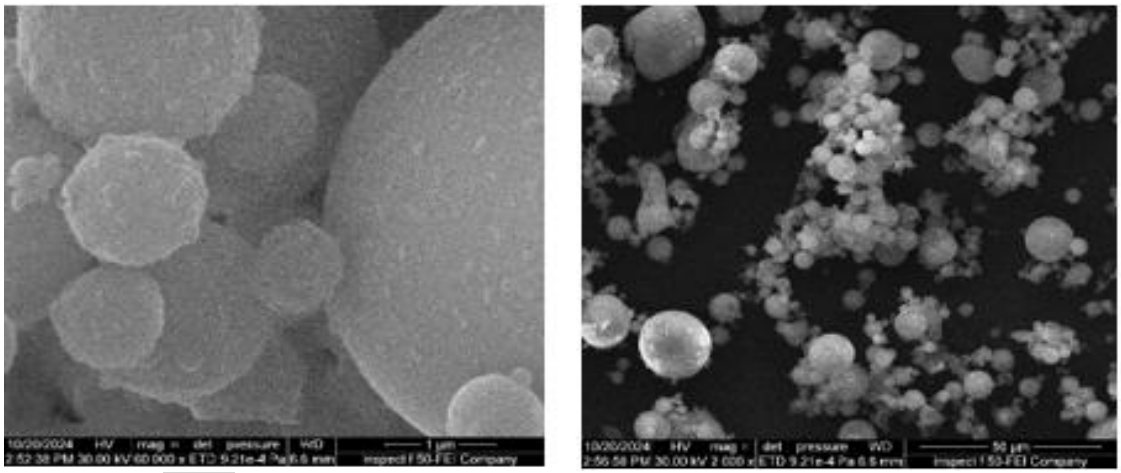


Fig. 1 The Scanning Electron Microscope (SEM) for HGM Particles.

Table 1 Hollow Glass Microspheres Components by (XRF).

Compounds	L.O. I	Na2O	MgO	Al2O3	SiO2	P2O5	SO3	Cl
%	1.26	0.461	0.772	30.108	56.601	0.256	0.648	0.972
Compounds	**K2O**	**Cao**	**Tio2**	**Fe2O3**	**Zn**	**Rb**	**Sr**	**Zr**
%	2.069	2.504	1.068	3.181	0.02	0.008	0.047	0.025

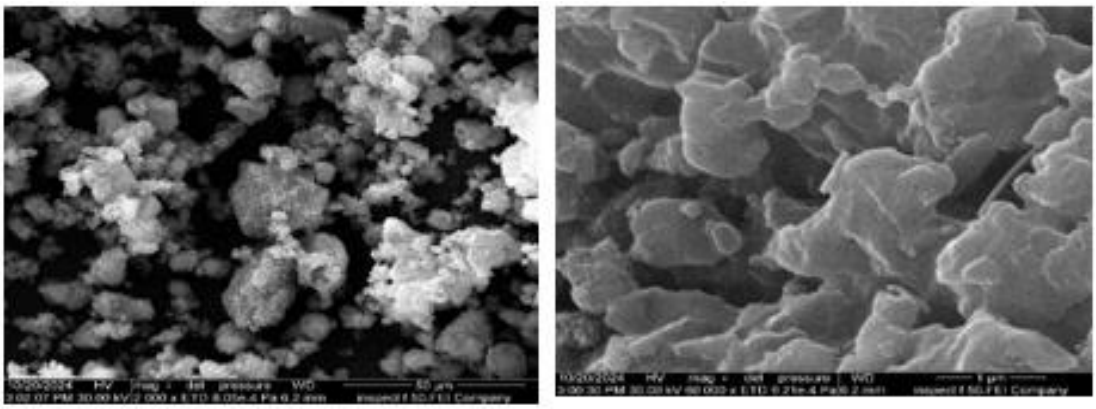


Fig. 2 The Scanning Electron Microscope (SEM) for Yellow Fly Ash Particles.

Table 2 The XRF of YOFA Powder.

Oxide components	Wt.%	components	Wt.%	Elements component	PPm	component	PPm
Al2O3	0.095	MnO	0.044	S	30246	Sr	44
Fe2O3	2.869	P2O5	0.131	Co	588	V	22626
CaO	0.488	SO3	25.5	Cr	3339	Zn	507
MgO	18.761	TOC	7.4673	Cu	25	Zr	46
Na2O	0.074	LOI	8.26657	Mo	56	La	13
TiO2	0.041			Ni	32905	Pb	21

2.2.Composite Preparation

Virgin and recycled HDPE granules were filled with a constant content of (2 wt. %) Yellow fly ash and various contents of hollow glass microsphere particles, i.e., 0, 2, 4, 6, and 8 wt. %. The composite compounds were mixed manually with acetone as a solvent to enhance amalgamation, thereby improving adhesion and interaction among the HDPE particles, HGMs, and yellow fly ash. After conducting a pilot study to produce samples to prepare V/RHDPE/fly ash/HGMs composites, a mixture filament was obtained by melt-blending using a single-screw extruder type SJ25 plastic extruder. The extruder was equipped with a screw of (25 mm) in diameter

and an L/D ratio of 16. The temperature in the first, second, and third zones was maintained at 40°C, 150°C, and 140°C, respectively, from the feeding zone to the mold exit. The screw speed was set between 9 and 11 r.p.m. The granules were then shaped using a vertical plastic injection molding machine, XCX-40G, to create test specimens after a pilot study to attain the standard specifications. All mixed grains of V/RHDPE composites were subjected to drying for 2 hours at 80°C before injection molding to remove any moisture remaining from the extrusion process, as shown in Fig. 3. Table 3 shows the injection molding machine parameters.

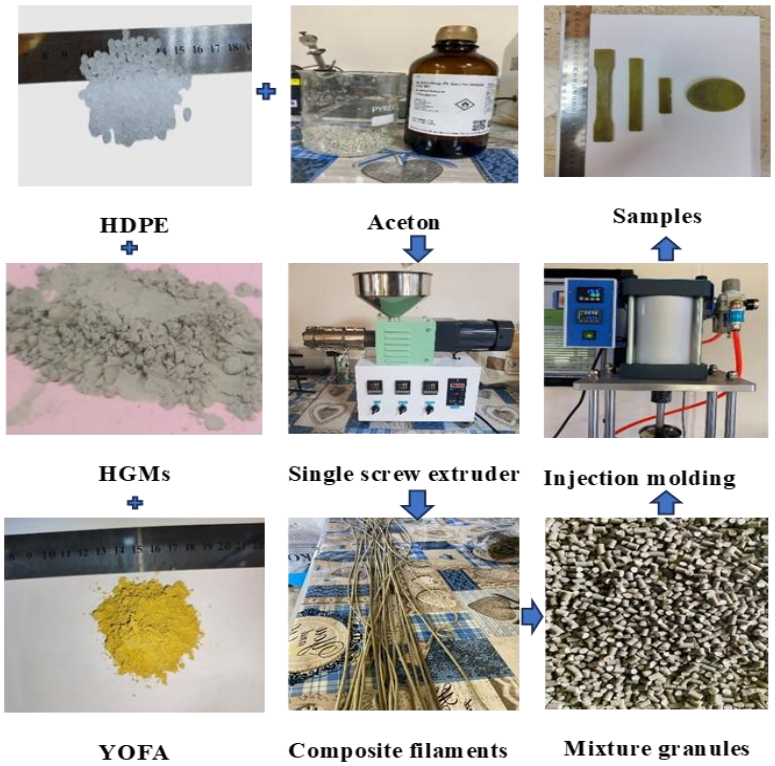


Fig. 3 The Injection Molding Machine Parameters.

Table 3 The Injection Molding Machine Parameters.

Injection molding parameter	Injection temperature	Holding temperature time	Injection pressure	Holding pressure time	Injection time	Mold temperature	Cooling time
	160-180 °C	6-15 min	0.6 MPa	30 s	1 s	23+2 °C	1-2 min

2.3.Physical and Mechanical Properties

2.3.1.Density Measurement

The density of the composite material produced by combining Virgin or Recycled polyethylene, hollow glass, and fly ash was evaluated according to international standards (ASTM D792) [15]. The composite material's void content was tested according to international standards (ASTM D2734) [16], and the water absorption rate was evaluated according to ASTM D570 [17].

2.3.2.Tensile Testing

The ASTM D638 [18] tensile test is a standard method for determining the mechanical properties of plastic materials under tension. In this test, a dog-bone-shaped specimen is stretched at a controlled rate until it breaks, allowing for precise measurement of key properties such as tensile strength, elongation, and modulus of elasticity. The experimental data were obtained using a 50 mm gauge length and a crosshead speed of 50 mm/min on a Universal Testing Machine (UTM) manufactured by LARYEE in China. These properties provide critical insight into a material's behavior under stress, which is essential for quality control, material selection, and design across various engineering applications. ASTM D 638 provides a consistent, reliable framework to assess and compare the performance of plastics in real-world conditions.

2.3.3.Flexural Strength

The ASTM D790 [19] Flexural test measures the bending properties of reinforced and unreinforced plastics. Using a three-point bending system, the specimen is supported at two ends, with a load applied in the middle until it breaks or reaches a specified deflection. The measurements used a gauge length of 80 mm and a crosshead speed of 1.5 mm/min, employing the LARYEE UTM from China. This test is critical for evaluating materials in load-bearing applications.

2.3.4.Impact Strength

The ASTM D256 test [20] for the impact strength of plastics was conducted on samples of Virgin and recycled high-density polyethylene combined with hollow glass beads and fly ash by quantifying the energy absorbed during the fracture of a notched sample under impact. The Izod ASTM pendulum impact resistance of polymers with a 45° angle notch, a 5.5 J hammer, and a 2.54 mm notch depth was evaluated according to a standardized test protocol.

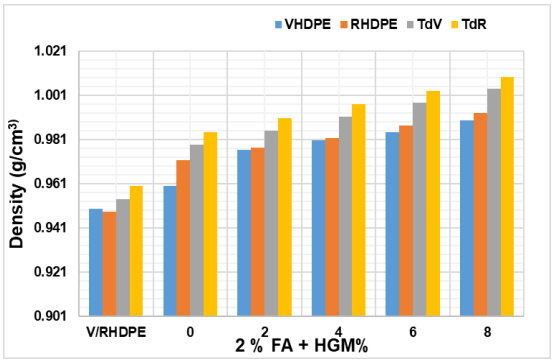
2.3.4.Hardness Test

ASTM D2240 [21] assesses the hardness of the specimens. The Shore D hardness scale employs a tester that delivers a consistent force with a pointed prong to assess a material's resistance to surface deformation. Shore D hardness values apply to thermoplastics and composites.

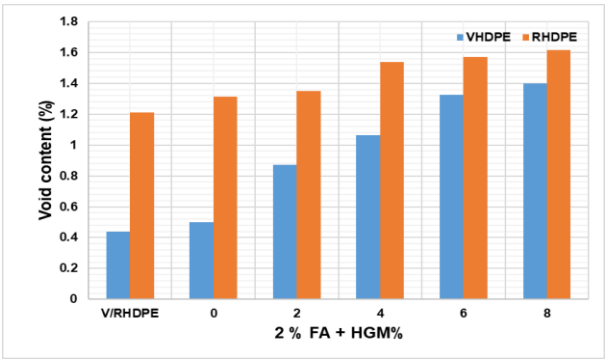
3.RESULTS AND DISCUSSION

3.1.Physical Properties

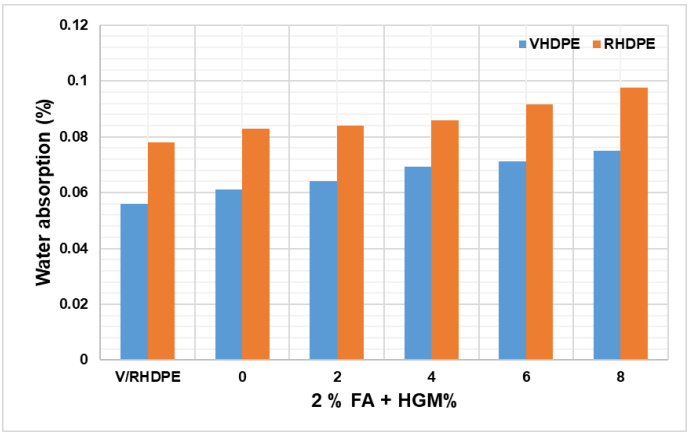
Figure 5 (A) illustrates the correlation between density and HGM concentration in both virgin and recycled HDPE-fly ash composites. The findings demonstrate that the experimental densities of VHDPE closely approximate the theoretical densities, with only a slight discrepancy. In contrast, RHDPE had a higher deviation from the experimental density. This divergence between theoretical and experimental results may stem from several sources. Irregularities, contaminants, or intrinsic structural variations in recycled materials may hinder the composite from attaining ideal packing. This behavior may account for the little reduction in experimental density readings. A further cause of density variation may be the creation of voids during processing or inadequate filler dispersion. These processing difficulties may result in localized density differences, causing a reduction. These observations agree with those of [23-24]. As shown in Fig. 5 (A), the theoretical density of yellow fly ash-filled HDPE (VHDPE/R) composites increased by +1.07% with the experimental density increase, while the theoretical density increased by +2.53%. In contrast, the experimental density of RHDPE with 2 wt.% YOFA increased by +2.44%, while the theoretical density increased by +2.55%. This result is attributed to the higher density of YOFA compared to both VHDPE and RHDPE matrix materials. The result indicates an increase in the composite material's density with increasing HGM concentration. This behavior is due to the density difference between the base and the filler. These findings are in line with those of [24-25].



(a) Density Experimental.



(b) Void Content.



(C) Water absorption

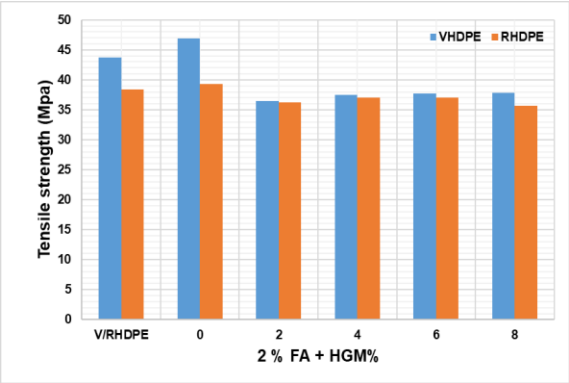
Fig. 5 The Physical Properties of V/RHDPE Composites. (A) Density, (B) Void, and (C) Water Absorption.

Void content is a relative measure of the difference between theoretical and actual densities. Figure 5 (B) shows the void contents of virgin and recycled HDPE composites, showing distinct patterns affected by the addition of varying concentrations of HGMs and 2% yellow fly ash. When 2% by weight of yellow fly ash was added to both virgin and recycled HDPE, the void content increased significantly to 14.5% and 8.5%, respectively. However, as the HGM content increased, the void content of virgin HDPE also increased (0.87188%, 1.0626%, 1.3250%, and 1.4%, respectively). On the other hand, and in the same pattern, the void content of recycled HDPE increased to 1.3510%, 1.5384%, 1.5705%, and 1.6165%, respectively. However, the latter exhibited a lower void content than virgin HDPE, due to impurities that helped fill some of the voids. During manufacturing processing, these bubbles may penetrate the material. Gases are less able to escape during solidification with higher viscosity, increasing the likelihood of gases being trapped in the sample and creating more voids. This behavior persists as the reinforcing particle content increases. On the other hand, Tables 1 and 2 indicate a significant presence of sulfur in the YOFA content, which weakens the physical bond between the V/RHDPE and YOFA molecules, thus increasing the void content [22]. This result is compatible with [23]. Figure 5 (C) shows that water absorption increased slightly from 0.056% to 0.061% and from 0.078% to 0.0829% when 2 wt.% fly ash was added to HDPE/VHDPE without HGMS. The presence of HGMS resulted in a slight increase in water absorption (0.0641%, 0.0693%, 0.0712%, and 0.0750%) for the VHDPE matrix, while the RHDPE matrix showed an increase of 0.0839%, 0.0860%, 0.0915%, and 0.0975%. As expected, virgin and recycled HDPE immersed in water showed very little water absorption. This pattern is fully consistent with the linear upward trend in void content in Fig. 6, indicating that any increase in water uptake is due to the increase in void content. Since both YOFA and HGMs are hydrophilic, increasing the number of voids will increase the potential for water penetration [24-25]. Water absorption was higher for RHDPE. This behavior may be linked to hydrophilic anionic surface-active agents (soaps) in addition to the previously mentioned decisive influences. This result agrees with that of [11, 23].

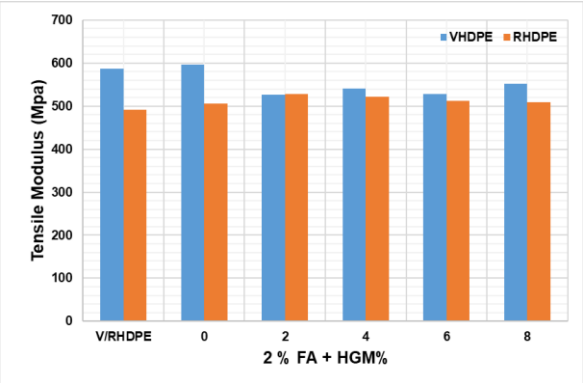
3.2.Mechanical Properties

3.2.1.Tensile Properties

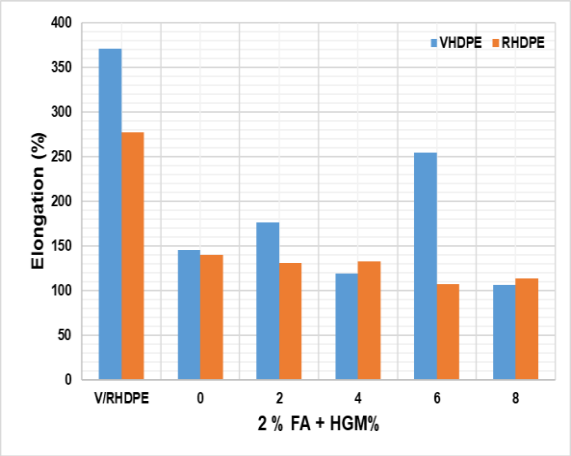
Figure 6 shows how the weight fractions of YOFA and HGM particles affect the tensile strength, tensile modulus, yield strength, and elongation at break of V/RHDPE composites. The tensile strength, modulus, and yield strength of VHDPE were higher than those of RHDPE due to differences in material structure and possible impurities in the recycled material. Adding 2% YOFA improved these properties in both virgin and recycled HDPE, with VHDPE showing greater improvements, i.e., 7%, 2.89%, and 8%, respectively, compared to RHDPE (5.3%, 3.05%, and 1.35%). The increase is due to enhanced stiffness and better stress transfer, with YOFA acting as a nucleating agent. Figure 7 shows that SEM images of the VF0G and RF0G samples exhibit ductile fracture behavior, with fibrous structures and plastic deformation, supporting the improvement in tensile properties. On the other hand, adding 2% HGMs significantly decreased the tensile strength, likely due to poor adhesion between the filler and the matrix. SEM images confirmed weak interfacial bonding. At higher HGM concentrations, tensile strength slightly improved due to better dispersion of HGM particles, which facilitated stress transfer and reduced stress concentration, thereby improving mechanical properties.



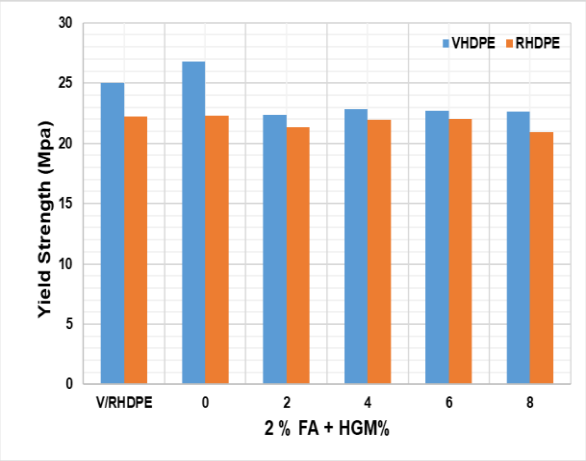
(A) Tensile Strength.



(B) Tensile Modulus.



(c) Yield Strength.



(D) Elongation at Break.

Fig. 6 The Tensile Properties of V/R HDPE Composites.

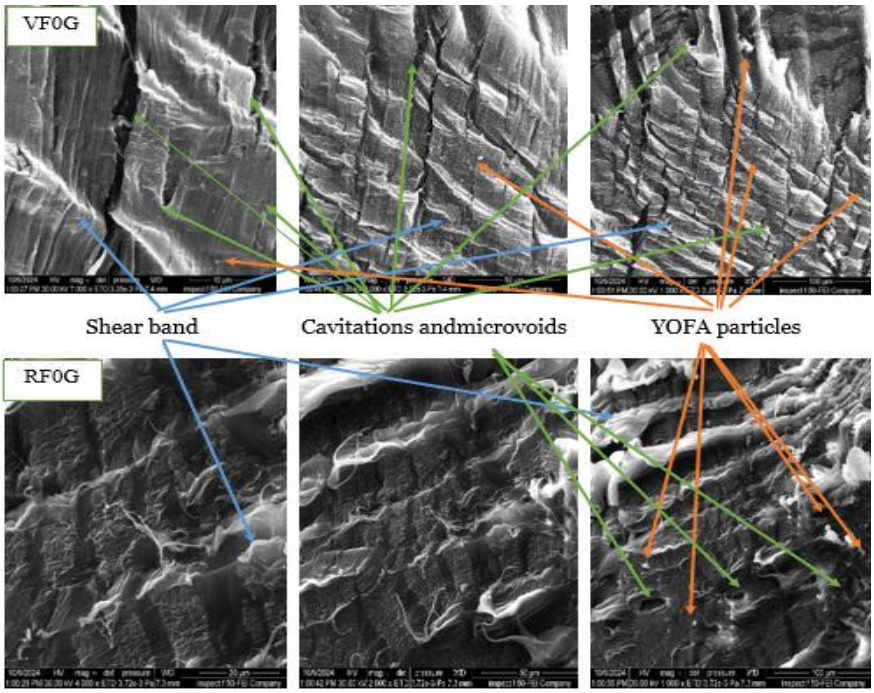


Fig. 7 SEM Image for VF0G and RF0G in Tensile Test.

The best tensile properties were observed with 2 wt.% YOFA reinforcement provided uniform particle dispersion and effective stress transfer. In contrast, 2 wt.% HGMs reinforcement (VF2G and RF2G) resulted in poor tensile properties due to particle agglomeration and weak interface adhesion, leading to reduced bonding with the HDPE matrix. Increasing the hollow glass sphere content from 4 to 8 wt.% resulted in a slight increase in tensile strength, attributed to better particle distribution and improved load transfer. Figure 8 shows that the SEM images of VF8G showed ductile fracture with a fibrous morphology, indicating good load transfer between the particles and HDPE. However, microvoids and dimples on the fracture surface suggested a ductile fracture pattern. Recycled HDPE composites showed a slight improvement in tensile strength at filler contents of 2-6%; however, strength declined at 8 wt.% due to poor particle adhesion and weak bonding, as shown in Fig. 9, the uneven, rough fracture surface of RF2G and RF8G. These weak bonds lead to early failure and low tensile strength at higher filler concentrations. The same behavior was reported by [13, 26]. Figure 6 (B) shows the tensile modulus of virgin and recycled HDPE. Yellow fly ash (YOFA) enhanced the structural properties of both virgin and recycled HDPE, thereby improving the strength modulus. The incorporation of hollow glass spheres (HGM) had mixed effects. In virgin and recycled HDPE, low concentrations of HGM (2%) significantly reduced properties. However, higher concentrations (8%) provided small performance improvements [12]. Res. [34, 35] found the same trend. Figure 6 (c) shows the yield strength of the composites made from virgin and recycled HDPE. The use of 2% fly ash enhances the yield strength of both HDPE/reinforced HDPE by 7.2% and 3.63%,

respectively. However, increasing the HGM concentration reduced the yield strength of both composites. While showing slight fluctuations at high HGM concentrations, recycled HDPE had the lowest decrease for the same reasons mentioned above. This result is consistent with [26]. Figure 6 (D) shows the resulting elongation of V/RHDPE composites. The elongation of V/RHDPE reached its peak at 370.36% and 277.68%. Incorporation of 2 wt.% fly ash reduced the elongation by 60.7% and 49%, respectively. As a solid particle, yellow fly ash acts as a reinforcement that prevents the movement of polymer chains. Increasing the concentration of hollow glass spheres has varying effects on the elongation. This fluctuation behavior is due to improved dispersion, which improves load distribution and components interaction, and to inhomogeneous distribution and stress concentrations. This result agrees with this in [11, 13, 25].

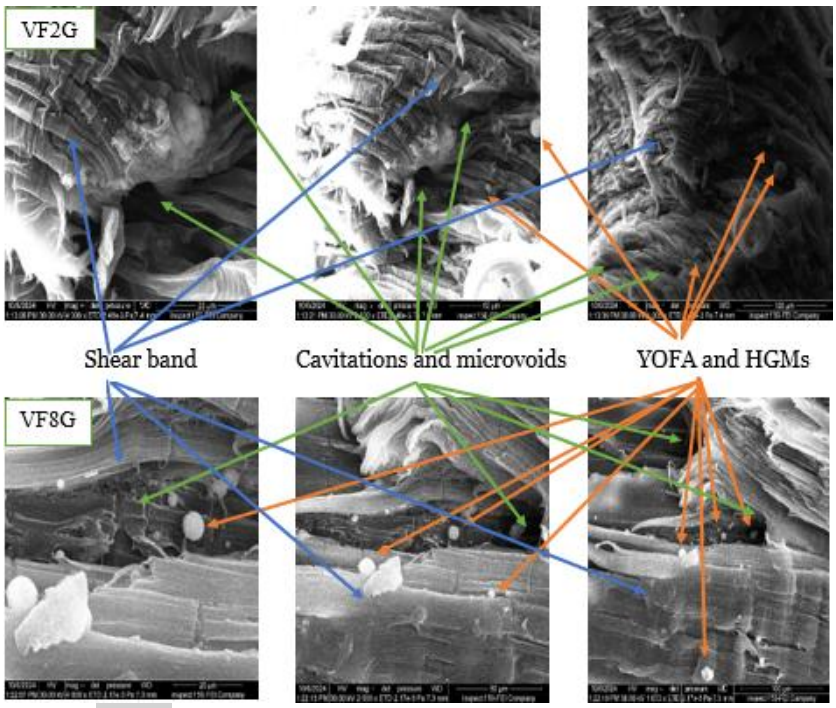


Fig. 8 SEM Images of (VF2G, VF8G) in a Tensile Test.

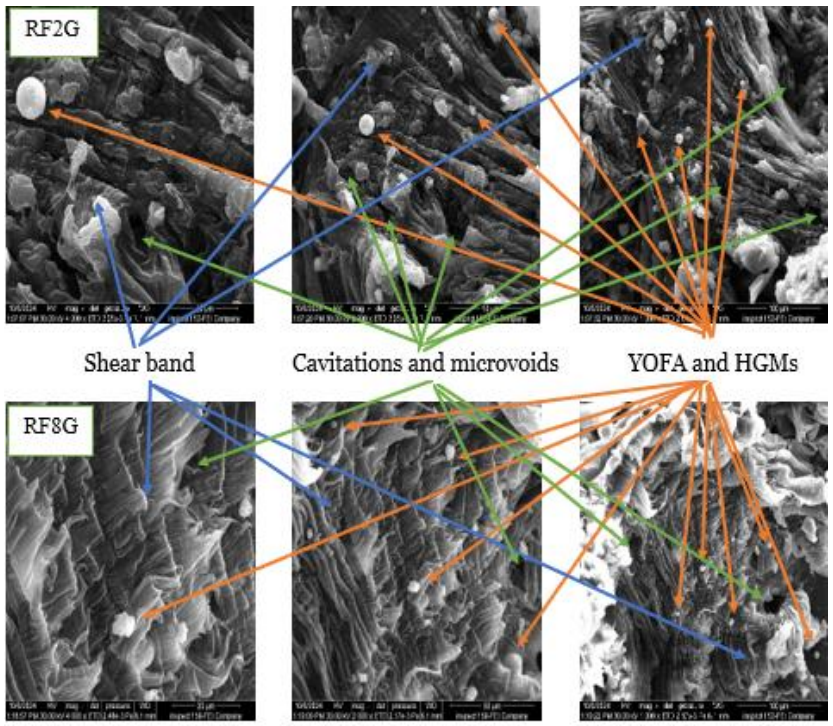


Fig. 9 SEM Images of the (RF2G, RF8G) in a Tensile Test.

3.2.2.Impact Strength

Figure 10 shows the Izod impact strength of virgin and recycled HDPE with 2% fly ash and different HGM contents. It is evident that as the YOFA and HGM content in the V/RHDPE matrix increased, the Izod impact strength decreased linearly. The V/RHDPE core material had the maximum impact strength, while the recycled core material had slightly superior impact strength. Incorporating 2% fly ash reduced the strength by 3.4% and 19.8%. As the HGM concentration increased, the impact strength decreased significantly. With the HGM content, the Izod impact strength decreased by varying percentages for both the virgin (20%, 26.7%, 5.8%, and 14.7%) and the recycled (24%, 30.2%, 11.5%, 9%, and 32.8%). The addition of YOFA and HGM particles to the V/RHDPE matrix results in the formation of stress concentrations. These stress concentrations promote fracture formation and reduce the material's energy-absorption capacity, thereby reducing the impact resistance with hollow glass spheres and YOFA content. The accumulation of fillers also facilitates crack initiation, consistent with similar findings of reduced Izod impact strength reported in [12, 25-28].

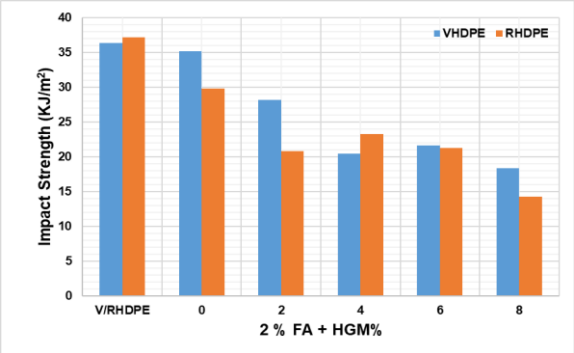


Fig. 10 The Impact Strength for Composites.

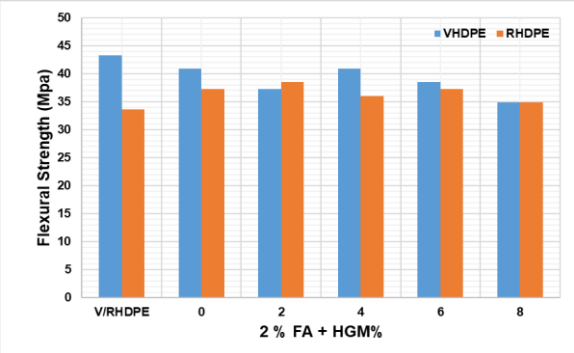


Fig. 11 The Impact Strength for Composites.

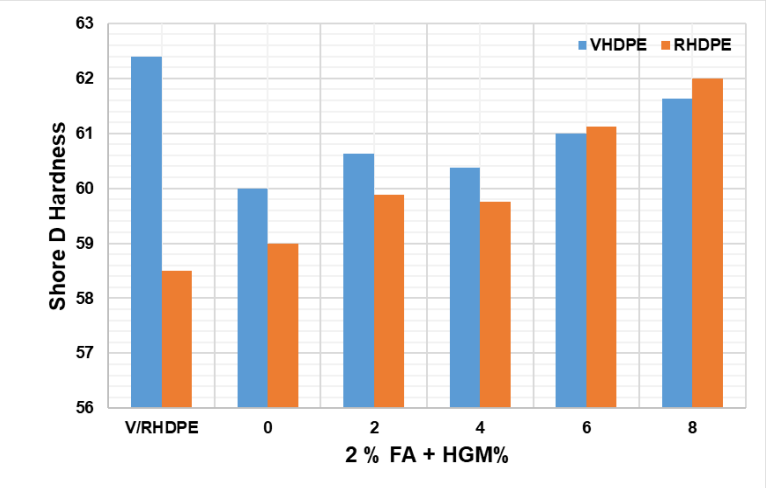


Fig. 12 The Shore D Hardness for Composites.

3.2.3.Flexural Strength

Figure 11 shows that virgin HDPE had the highest flexural strength. Adding 2% fly ash caused a small decrease of 5.55%, while 2% HGM led to a further drop of 8.9%. However, adding 4% HGM partially restored strength, resulting in a 9.7% increase. Increasing HGM to 6% and 8% resulted in strength reductions of 5.8% and 9%, respectively. Recycled HDPE initially showed a 10.73% increase with 2% fly ash and a 3.2% increase with 2% HGM. Increasing HGM to 4% caused a 6.4% decrease; however, it later increased by 3.6% and then decreased by 6.16% at 6-8%. These results highlight the importance of using the appropriate filler ratios, as excessive filler weakens the material, reducing strength and weakening the bond between filler particles and the matrix. High filler levels lead to agglomeration and poor bonding, creating voids and cavities, which negatively affect structural properties, as seen in the SEM images (Fig. 5 (B), Fig. 8, and Fig. 9). This result agrees with [26, 27]. Ref. [29] found the same behavior.

3.2.4.Shore D Hardness

Figure 12 shows that adding 2% fly ash initially decreased hardness by 3.8%, then increased by 1.04%, and then increased further by 6-8%. In contrast, recycled HDPE composites showed a steady increase in hardness, with a slight decrease at 4% HGM and increases at 6% and 8%. This behavior suggests a decrease in polymer matrix continuity or poor bonding. The difference between virgin and recycled HDPE may be due to contamination affecting

the matrix-filler interaction. The decrease in hardness is mainly due to increased void content, as shown in Fig. 5 (B) and in the SEM images (Figs. 8 and 9) of the composites; this impacts mechanical properties and causes uneven stress distribution, reducing stiffness. This behavior highlights the need for proper particle dispersion and matrix interaction in the material. The presence of voids significantly affects the mechanical properties of materials [30]. Localized stress concentrations included by YOFA and HGM particles may lead to an uneven stress distribution, reducing the composite's stiffness. This pattern emphasizes the balance between particle dispersion and polymer-matrix interaction, especially when comparing virgin and recycled HDPE. This result agrees with [12, 26, 31].

3.3.Thermogravimetric analysis (TGA)

Figure 13 presents the TGA results for V/RHDPE, showing the weight loss during degradation. The TGA curves indicate that degradation began between 25 °C and 400 °C, mainly due to moisture evaporation from the samples, with minimal weight loss for HDPE and HDPE/YOFA composites. The main weight loss occurred between 400–500 °C during thermal decomposition, with the largest weight loss observed for VHDPE and VF0G, and the least for VF8G. This weight loss is linked to the pyrolysis of fly ash and hollow glass spheres, though it is incomplete weight loss due to the high thermal stability of the metal particles in the fillers. The TGA data also shows that thermal stability increased with increasing filler content, suggesting stronger bonding between the fillers (YOFA and hollow glass spheres) and the HDPE matrix. This bond reduces polymer mobility near the interface and modifies polymer chain motion, as reflected in the improved mechanical properties observed in earlier sections [6, 32, 33]. The thermal stability of FA and HGM-filled V/RHDPE matrices increased with higher filler content, although the amount of residue decreased with HGM concentrations up to 8 wt.% in the HDPE matrix. The final decomposition stage, between 500 °C and 800 °C, shows the remaining residue at the end of the TGA experiment. Recycled HDPE composites exhibited higher thermal stability than pure HDPE composites, with a lower residual weight, due to the same factors as before, plus the presence of impurities that enhance thermal decomposition. Refs. [34-36] found the same behavior by the TGA Test.

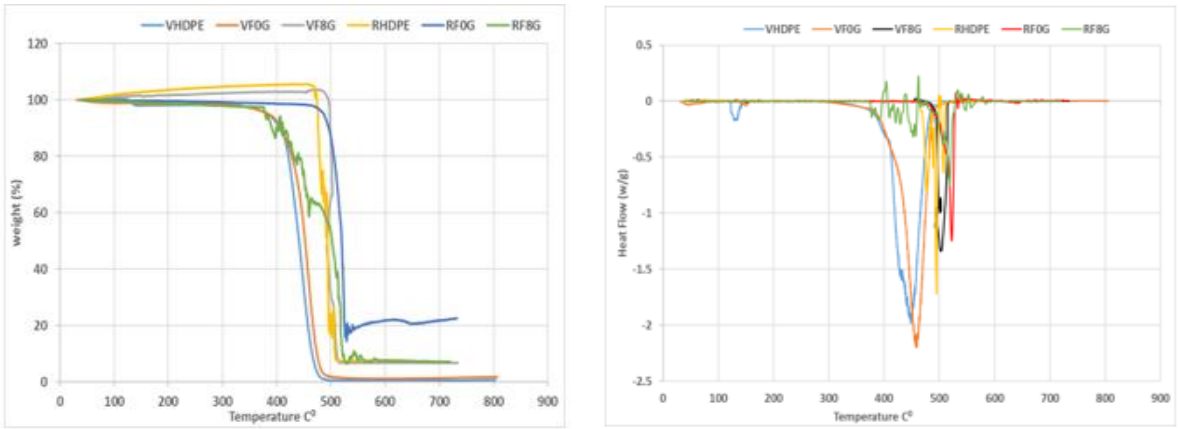


Fig. 13 Thermogravimetric Analyses (TGA) of V/R HDPE Composites.

4.CONCLUSIONS

1- The addition of 2 wt.% YOFA and 2-8 wt.% HGMs improved density. Density measurements closely matched theoretical predictions, with minimal discrepancies due to filler dispersion and processing conditions in HDPE composites.
2- Void and water absorption increased with high filler content.
3- YOFA (2 wt.%) significantly improved tensile strength, tensile modulus, and yield strength of virgin and recycled HDPE (up to 7.1% improvement).
4- HGMs initially reduced tensile properties due to poor filler-matrix interaction; however, recovery occurred at 6-8 wt.% with improved dispersion and load transfer.
5- Flexural and impact strengths decreased with higher HGM content.
6- Thermogravimetric analysis indicated improved thermal stability for composites with YOFA and HGMs, with higher onset and maximum decomposition temperatures compared to pure HDPE.
7- The mechanical and thermal properties of recycled HDPE composites were slightly lower than those of virgin HDPE.
8- The work contributes to solving environmental problems by reusing industrial waste in composite fabrication.
9- Future research should focus on optimizing filler concentrations, investigating long-term durability and environmental impact, and exploring advanced processing techniques to

reduce void content and improve filler-matrix interactions.

LIST OF ABBREVIATIONS

Symbol	Meaning
HDPE	High-density polyethylene
HGMs	Hollow glass microspheres
Yellow fly ash	YOFA
FA	Fly ash
PVC	Polyvinyl chloride
PET	Polyethylene terephthalate
SEM	scanning electron microscope
XRF	X-ray Fluorescence
MgO	Magnesium Oxide
VHDPE	Virgin high-density polyethylene
RHDPE	Recycled high-density polyethylene
VF0G	Virgin high-density polyethylene/2wt.% yellow fly ash/ 0% hollow glass microspheres
VF2G	Virgin high-density polyethylene/2wt.% yellow fly ash/ 2wt.% hollow glass microspheres
VF4G	Virgin high-density polyethylene/2wt.% yellow fly ash/ 4wt.% hollow glass microspheres
VF6G	Virgin high-density polyethylene/2wt.% yellow fly ash/ 6wt.% hollow glass microspheres
VF8G	Virgin high-density polyethylene/2wt.% yellow fly ash/ 8wt.% hollow glass microspheres
RF0G	Recycled high-density polyethylene/2wt.% yellow fly ash/ 0% hollow glass microspheres
RF2G	Recycled high-density polyethylene/2wt.% yellow fly ash/ 2wt.% hollow glass microspheres
RF4G	Recycled high-density polyethylene/2wt.% yellow fly ash/ 4wt.% hollow glass microspheres
RF6G	Recycled high-density polyethylene/2wt.% yellow fly ash/ 6wt.% hollow glass microspheres
RF8G	Recycled high-density polyethylene/2wt.% yellow fly ash/ 8wt.% hollow glass microspheres
TGA	Thermogravimetric analysis

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