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EFFECTS OF ALUMINIUM REINFORCEMENT ON THE MECHANICAL AND MORPHOLOGICAL CHARACTERISTICS OF HIGH-DENSITY POLYETHYLENE COMPOSITES

A. Nayeem FARUQUI[1,*] [0000-0002-6429-834X], Md. Jillur RAHMAN[1] [0009-0005-1283-9131], Md. Mehidi HASAN[1] [0009-0007-1197-7326], Md. Rezaul Karim SHEIKH[1] [0000-0001-7324-4397]

[1]Department of Applied Chemistry and Chemical Engineering, University of Rajshahi, Rajshahi 6205, Bangladesh

Abstract

Polymer matrix composites (PMC) are prominent structural materials that offer a combination of some extra-ordinary properties, including light weight, high strength, high resistance to chemicals, etc. In this research, the influence of aluminium reinforcement content (5–40 wt%) on the morphological, mechanical, and physical properties (impact strength, tensile strength, elastic modulus, and maximum load-bearing capacity) of Al-high-density polyethylene (HDPE) composites has been studied. We used a customized extruder machine to fabricate the composites, followed by injection molding to prepare test specimens. In comparison to virgin HDPE, the impact strength, flexural strength, elastic modulus, and tensile strength of the composites increased at 5 weight percent of aluminium content and declined with increasing reinforcing quantity. The break point is higher for pure HDPE than composites with any weight of aluminium. Using an optical and scanning electron microscope (SEM), a microstructural study of the composites was carried out to assess the cohesion and distribution of the reinforcement and matrix. Based on the particle loading and uniformity, it was observed that composites with a 5 wt% content of aluminium reinforcement exhibited more efficiency for the enhancement of mechanical properties.

Keywords*:* *Polymer matrix composites (PMC), aluminium, morphological analysis, high-density polyethylene (HDPE), mechanical properties.*

Introduction

Composites are materials consisting of two or more different phases separated from one another by a discrete interface, both chemically and physically [1]. The various systems are carefully merged to create a system with superior structural or functional features that could not be obtained from any one of the components by themselves. In general, matrix is less rigid and more ductile. Along with sharing a load, it contains the dispersed phase. The matrix has a discontinuous shape where the dispersed (reinforcing) phase is embedded. This dispersed phase is the second phase. Generally speaking, the dispersed phase is more robust than the matrix phase [2]. These extraordinary materials are becoming a necessary component of modern engineering because of the numerous advantages they offer, including high fatigue strength, low weight, good ease of shaping, economic mass production, electrical and thermal insulation, resistance to corrosion, vibration absorption tendency, attractive optical properties [3], etc. These are frequently made by combining a stiff, powerful, but brittle substance with a ductile one to form a two-phase material that is very stiff, strong, and ductile. The primary objective of combining

*Corresponding author: nayeemfaruqui@ru.ac.bd

elements to create a composite is to capitalise on the synergistic effects of both phases that increase the mechanical properties of the polymer composite [4]. The combined impact of the specific elements, in which the inherent benefits and drawbacks are better balanced, determines the performance of composites [5]. This composites are widely utilized as building materials for everything from space vehicles to homes, electronic packaging to medical devices, and aircraft structures.

Metals give the necessary strength, remarkable ductility, and high stiffness in polymer matrix composites (PMCs) [6]. Aluminium is a lightweight, very durable, easily machined, highly malleable, highly corrosion resistant, and has exceptional thermal and electrical conductivity. Recycling is also rather simple [7]. Aluminium powder is used to increase mechanical qualities such as hardness, dimension accuracy, and thermal conductivity [8-10]. For this reason, aluminium metal is an excellent choice for the reinforcing phase of a composite.

High-density polyethylene (HDPE) is prevalent in use as a matrix because of its high specific strength, high strength-to-density ratio, higher acceptable temperatures, impact resistance, chemical resistance, abrasion resistance, near-zero moisture absorption, low coefficient of friction, low cost, and greater rigidity and hardness than lower-density materials [11]. All things considered, high-density polyethylene-aluminum composites may be inexpensive materials with advantageous mechanical characteristics.

There are numerous techniques available for fabricating HDPE-aluminium hybrid composites, including hand lay-up technique, compression moulding, pultrusion process, extrusion moulding, filament winding process, resin injection technique, hot press method, etc. Among all the techniques, extrusion moulding is most commonly used as it is simple and more economical and can be employed for mass production [12]. In the present investigation, the extrusion technique was used to fabricate high-density polyethylene-aluminium hybrid composites. These composites are tested to quantify their material performance with the Universal Testing Machine (UTM) and Impact Tester. Here, composites were analysed by SEM and OM techniques in order to evaluate the morphological characteristics of composite surfaces, particle distribution, and microstructure. It is expected that Al particle-reinforced HDPE matrix composites would eventually outlast conventional components in a variety of industrial applications due to their durability. This research presents an overall review of the preparation, performance, and application of aluminium powder-reinforced HDPE composite.

Materials and Methods

Materials

In the form of homopolymer pellets, High-density polyethylene (HDPE) was obtained from Chevron Philips Chemical Company LP by Saudi Polymers Company (Al Jubail, Kingdom of Saudi Arabia). Its density ranged from 0.88 to 0.97 g/cm^3, its melting points were between 120 and 180 °C, and its crystallinity was 75%. The powdered aluminium was obtained from Lobe Chemie Pvt. Ltd. in India. Its particle size was 15 µm, its melting point was 660 °C, and its density was 2.7 g/cm^3 [13].

Composite Preparation

For preparing a composite, a definite amount of matrix and reinforcement are needed. In this research, five different kinds of composites were made, in which the matrix and reinforcement ratios were 95:5, 90:10, 80:20, 70:30, and 60:40, respectively. Every time, a 200-gram combination of reinforcement and matrix was utilised to generate one form of composite. For 5 wt% reinforcement, the weight of the matrix was 190 g, and the reinforcement was 10 g. Reinforcements and matrix were chosen appropriately for the remaining composites. Extrusion means squeezing out by applying pressure. In the experiment, it is used to carry out the composite materials through a small opening. An electrically operated, customised extruder is used for this purpose. It consists of a hopper, heating coil, gear controller, rotating shaft, nozzle temperature display board, and motor. The coil temperature is adjusted to the necessary level based on the kind of composite material. To depict present values (PV) and set values (SV), there are actually three display units. The heating coil is immediately turned off when the PV reaches SV. The motor then facilitates the extrusion of composite materials through the nozzle. Aluminium powder and high-density polyethylene (HDPE) were first thoroughly combined before being progressively added to the hopper. The mixture then came into touch with a revolving shaft, where the coils covering the shaft heated and combined the mixture. The first, second, and third heating coils were set to 150 °C, 200 °C, and 250 °C, in that order. The motor helped push out the mixture via the nozzle by maintaining the shaft's speed. Shaft speed was meticulously regulated to provide even and appropriate mixing. Composite materials with different weights of HDPE-Al powder obtained from the extruder machine are shown in Fig. 1.

Fig. 1. Images of (a) 95-5 wt%, (b) 90-10 wt%, (c) 80-20 wt%, (d) 70-30 wt%, and (e) 60-40 wt% HDPE-aluminium

Then the composite was taken to the hot press machine, which consisted of two plates. After that, the composites are cut into small pieces, or chips, for further processing (Fig. 2).

Fig. 2. Composite chips after heat press

Then the composite chips are taken to the hopper within the customised injection moulding machine. The chip material is transferred from the hopper to a barrel that has a heating coil encircling it. The heating coil keeps the temperature of the coil at 65 °C, which heats the barrel. The chips are sufficiently melted at this temperature, so they can be shaped as required by using a mould with a dimension of 80 mm × 10 mm × 3 mm (Fig. 3). The required pressure for injecting the molten chips into the mould was given by rotating hand pressure.

Fig. 3. Prepared sample for tensile and impact tests

Microstructural Analysis

Optical microscopy (OM) (ML-803, Taiwan) and scanning electron microscopy (SEM) (JSM-7600 F) provided by JEOL Company Limited, Japan, have been used to study the interfacial bonding that occurs between reinforcement and HDPE matrix in produced composites. Samples of composite material were coated with gold in order to analyse their morphology under a scanning electron microscope.

Mechanical Testing

The mechanical properties of the produced composite were investigated by performing tensile strength, elastic modulus, flexural, and Charpy impact tests. Five species were evaluated for each combination of mixing ratio, and average outcomes were found. Tensile tests were carried out at a crosshead speed of 10 $mm \cdot min^{-1}$ with a Universal Testing Machine (MSC-5/500, Agawn Seiki Company Limited, Japan) in accordance with ASTM D 638-01. Static flexural tests were conducted using the same testing equipment and crosshead speed as specified in ASTM D 790–00. Furthermore, in accordance with ASTM D 6110–97, notched composite specimens were subjected to dynamic Charpy impact testing.

Result and Discussion

Morphological observation of composites by Optical Microscope (OM)

An optical microscope (OM) was used to examine the microstructure of the manufactured composite samples at various magnifications.

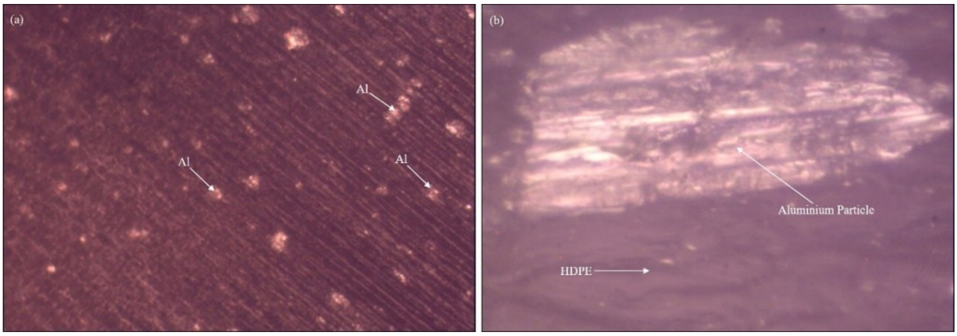

Fig. 4. Optical micrographs of composite surfaces: (a) low magnification and (b) high magnification in 60–40 wt% HDPE-aluminium composites

The HDPE-Al composite from Figs. 4a and b is subjected to optical microstructural observations mainly to investigate the dispersion of the particles of aluminium within the polymer matrix, the existence or absence of particle agglomeration and clusters, voids and inclusions present, as well as the interface frontier's integrity. The composites' optical micrographs display a well-flowing, ductile HDPE matrix encaging near-uniformly distributed aluminium particles. There are no significant voids or reaction products, and the interfaces are sharp with intact integrities [14].

Morphological observation of composites by Scanning Electron Microscope (SEM)

The composites were analysed using SEM to determine the exterior morphology (texture), interfacial adhesion, crystalline structure, and orientation of elements.

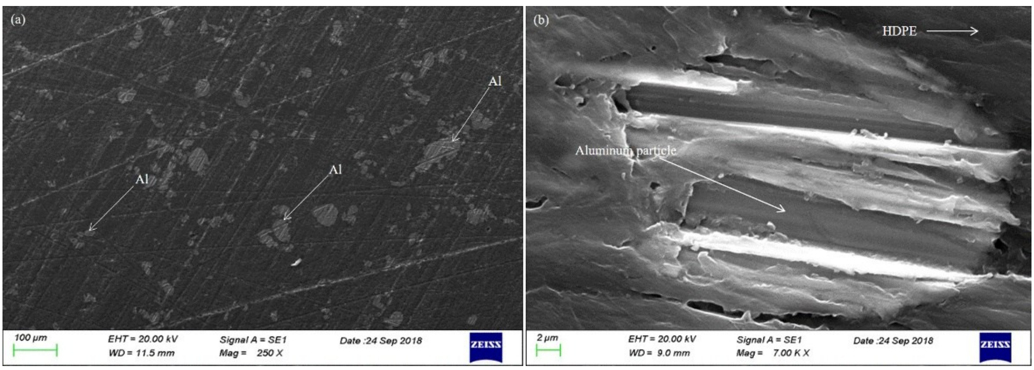

Fig. 5. Scanning electron micrograph (a) distribution of Al particles in 60–40% HDPE–Al composites and (b) particles bonded with matrix in 60–40% HDPE–Al composites (higher magnification)

Fig. 5(a) depicts that the aluminium was incorporated into the matrix with no apparent gaps in the interfacial area, and their surfaces appeared to be covered with HDPE polymer having a uniform distribution of reinforcements. This demonstrated good interface bonding. An improvement in mechanical characteristics confirmed robust attachment at the particle-polymer matrix contact, which was connected to polymer encasement with aluminium. From Fig. 5(b), a close observation of the sample reveals no holes, pores, or voids are present. Appearance of a well-bonded matrix and reinforcement composites are heading towards significantly inherent properties with multifunctional textures. The results show that more effective load transmission and distribution from the matrix to the reinforcement is facilitated by a well-bonded interface [15].

Mechanical Test

Tensile Strength

Fig. 6 summarizes the tensile strength and tensile characteristics of pure HDPE and its composites with varying loading amounts of aluminium reinforcement. It has been noted that when the aluminium content in the composites decreased, their tensile strength and elastic modulus increased. The remarkable rise in mechanical strength may be mainly ascribed to the reinforcing influence that the particles provided, enabling a consistent transfer of stress from the homogeneous polymer matrix to the distributed particle phase [16].

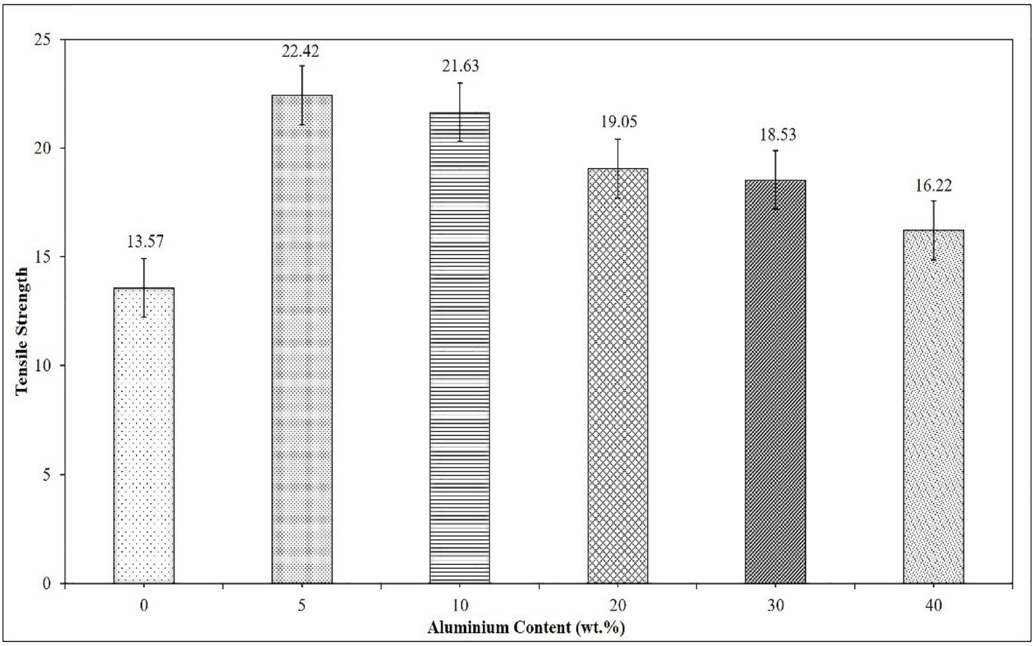

Fig. 6. Tensile strength of HDPE-aluminium composite for different wt% of aluminium reinforcement (three times the experiment was repeated, and error bars are shown around ± 1.43 order of magnitude with the standard error)

At the outset, the tensile strength result is either slightly higher or identical to that of the unfilled resin when the reinforcement content is less than 5 weight percent. After that, tensile strength and elastic modulus started to decrease because excessive particles created a gap between the matrix material, and due to less interfacial adhesion between HDPE and aluminium particles, they could not exert the applied load [17]. The maximum tensile strength is achieved for the 5 wt% reinforcement loading, and the increase in tensile strength is 8.85 MPa, which is better from an application point of view. Tensile strength decreased to 21.63 MPa (a loss of 3.52% with respect to the sample containing 5 wt% reinforcement) when the reinforcement quantity was increased to 10 wt%.

The elastic modulus of the specimens is also impacted by the addition of aluminium powder to HDPE. Fig. 7 shows that when reinforcement is present in the composites up to 5 weight percent, the elastic modulus values increase from 153.6 MPa to 369 MPa, which is almost 140% more than the pure HPDE. This value gradually decreased to 183 MPa when the reinforcement content increased by 30% by weight. This depicted almost 50% degradation when compared with composites containing 5 wt% aluminium reinforcement embedded. The tensile modulus of the composite with 40% aluminium by weight was nearly identical to that of the original polymer. Differences in both of the parameters are directly associated with the composite's structure and the degree of interfacial interactions. The mechanical performance of composite materials is also significantly influenced by the adhesion factor between the polymer matrix and the reinforcement [18].

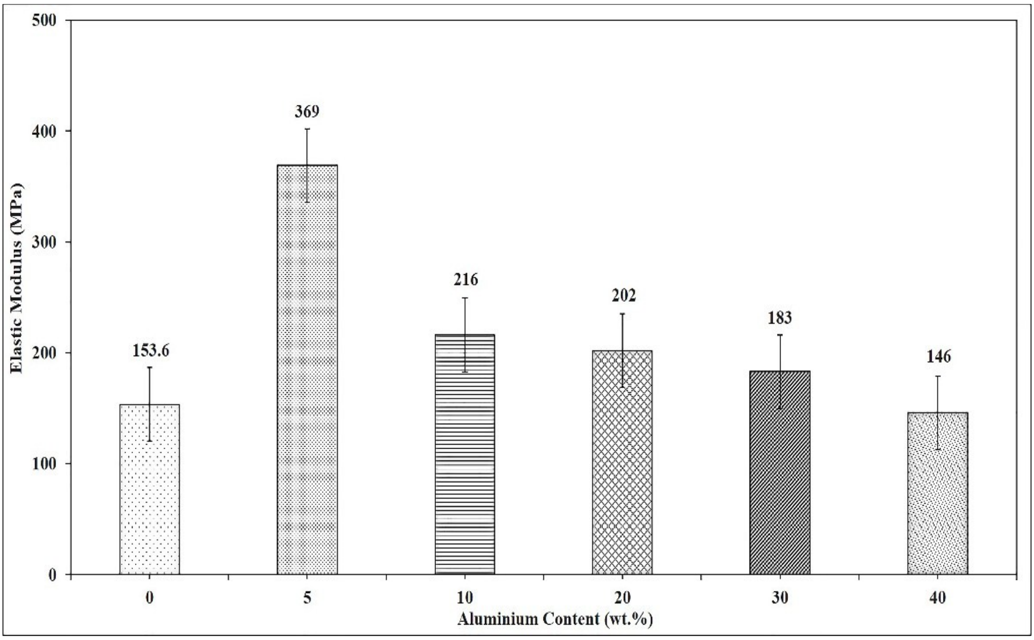

Fig. 7. Elastic modulus of HDPE-aluminium composite for different wt% of aluminium reinforcement (three times the experiment was repeated, and error bars are shown around ± 33 order of magnitude with the standard error)

Impact Strength

Impact strength is a useful metric for calculating the energy-absorbing capacity of materials that are suddenly loaded as well as the temperature at which ductile to brittle behaviour transitions [19].

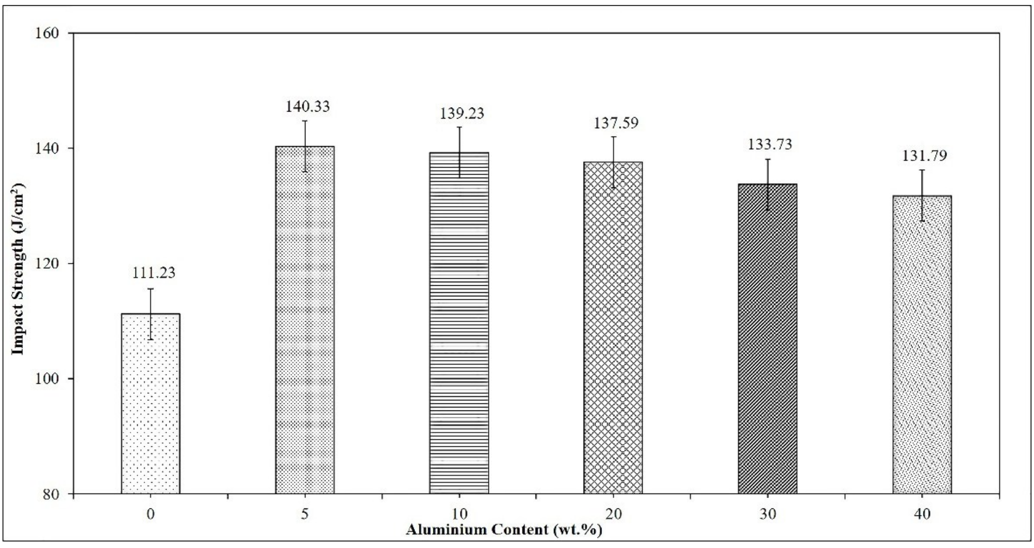

Fig. 8. Impact strength of HDPE-aluminium composite for different weights of aluminium reinforcement (three times the experiment was repeated, and error bars are shown around ± 4.87 order of magnitude with the standard error)

The graph displays the changes in the impact strength of the composite with the volume content of aluminium. It indicates that the impact strength improves as the percentage of aluminium increases. The energy absorbed in the specimen's fracture was found to be the determining factor for the impact toughness of the different weight concentrations of HDPE-Aluminum composite. The energy absorbed is highest for the composite containing 5 wt% of aluminium. The impact energy absorbed by the HDPE-Al composite containing 5 (wt%) of aluminium is almost 1.30 times the energy absorbed by HDPE and gradually decreased with increasing aluminium content (Fig. 8). The aluminium particles' toughening efficiencies varied significantly. The natural flexibility of the matrix, deboning, and an appropriate interparticle spacing are some of the mechanisms that toughen the polymer for the inorganic particles. Reinforcement particle deboning and void formation are the primary consequences of the stress concentration. The inter-particle spacing and the matrix polymer's stress state around the voids are influenced by the particle content [20]. The interparticle distance was large, and the interparticle matrix ligament is in a difficult-to-yield plane strain state. Increases in aluminium content up to 5 wt% result in better impact strength, an appropriate range for the inter-particle distance, and a press condition for the inter-particle matrix ligament that allows for easy plastic yielding. However, an excessively high alumina content caused the interparticle spacing to shrink, resulting in massive [21] agglomerates that served as excellent mediators for brittle behavior. The impact toughness raised with increased particle content up to 5 weight percent, and the reverse phenomena happened when the aluminium concentration was higher, as the gain in energy absorbed was proportionate to the impact toughness.

Load Bearing Capacity and Break Point

The way reinforcement particles form their structure in a polymer medium, how they bond to one another by adsorbing segments of polymer macromolecules on their surface, how they deform, and how unfixed segments from the particle are oriented into the polymer bulk are the factors that dictate the properties of polymer composites with dispersed reinforcements [22, 23]. One of the things that makes mechanical characteristics more complicated is the emergence of an ordered, partially directed boundary layer where stresses release and fracture propagation ceases.

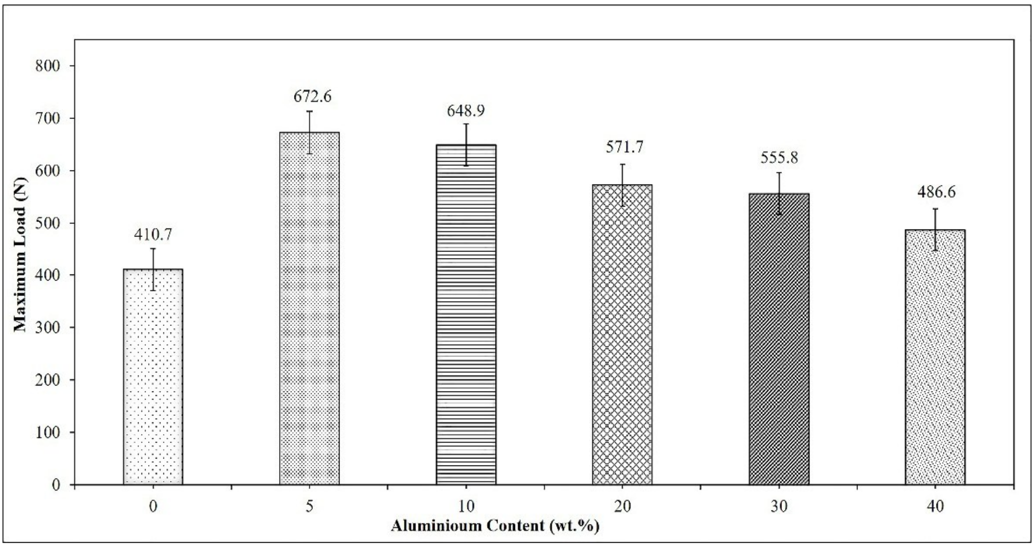

Fig. 9. Maximum load of HDPE-aluminium composite for different wt% of aluminium reinforcement (three times the experiment was repeated, and error bars are shown around ± 39.3 order of magnitude with the standard error)

The reinforcement has a major impact on the load-bearing capacity and break point of composite materials, as does its distribution throughout the material. Fig. 9 revealed that the load-bearing capacity of pure HDPE is 410.7 N, and the capacity is increased to 672.6 N when 5 wt% of aluminium reinforcement is used in composite. A 63.87% increase in load-bearing capacity is noted as a result of the addition of solid reinforcing particles that do not flex under stress, which causes polymer composites to become stiffer and less pliable [24–25].

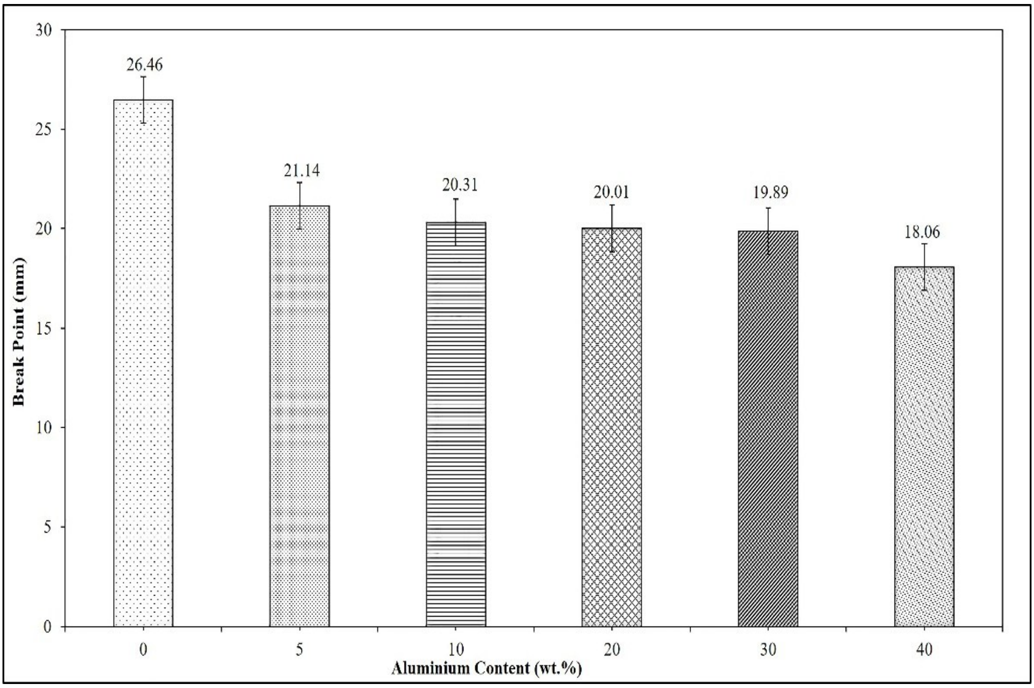

Fig. 10. Break point of HDPE-aluminium composite for different wt% of aluminium reinforcement (three times the experiment was repeated, and error bars are shown around ± 1.46 order of magnitude with the standard error)

The break point of the composite material is also related to its load-bearing capacity. As pure HDPE has less hardness and more flexibility, its break point is higher than that of composites reinforced with aluminium. From Fig. 10, it is shown that the break point of pure HDPE is 26.46 mm and gradually decreased with increasing reinforcement amount. This became 18.06 mm when the reinforcement amount reached 40 wt%. About 31.74% of the breakpoint decreased for composites with 40 wt% aluminium reinforcement compared to pure HDPE.

Density and porosity

The proportional amounts of the matrix and reinforcing components determine a composite's density. Because of voids and pores, there always exists a discrepancy between the theoretical and measured value of density of a composite. Many of the mechanical characteristics and even the effectiveness of composites is greatly impacted by these vacancies. Reduced fatigue resistance and increased vulnerability to weathering and water penetration are often associated with higher void contents [25].

Fig. 11 shows the experimental density of HDPE-Al composites. From Table 1, it is revealed that the theoretical density of HDPE-Al composite is closer to the experimental values, which indicate that the interface between matrix and reinforcement is almost well bonded, formed by the irregular shape of matrix material and reinforced by powders of reinforcement. It is also observed that the measured density values match above 98–99% of the theoretical density values in all the composites. So, due to the high mixing, fully densified HDPE-Al composites were recovered, leading to better mechanical properties of the composite.

However, as the particulate content is increased beyond 5 wt% of Al, a little high porosity is observed in Fig. 12. This is because there is low inter-particle bonding between matrix and reinforcement over 5 wt% reinforcement loading.

The primary function of the reinforcement in a composite is to support the matrix and so boost the composites' strength, whereas the matrix's primary functioning constituents are the intermediate load-bearing constituents. The effective transmission and load distribution between the reinforcement and the matrix is facilitated by a well-bonded interface. On the other hand, a weak connection reduces load transmission, which limits the degree of strengthening. Consequently, the increase in mechanical characteristics can be attributed to a stronger interfacial connection [26].

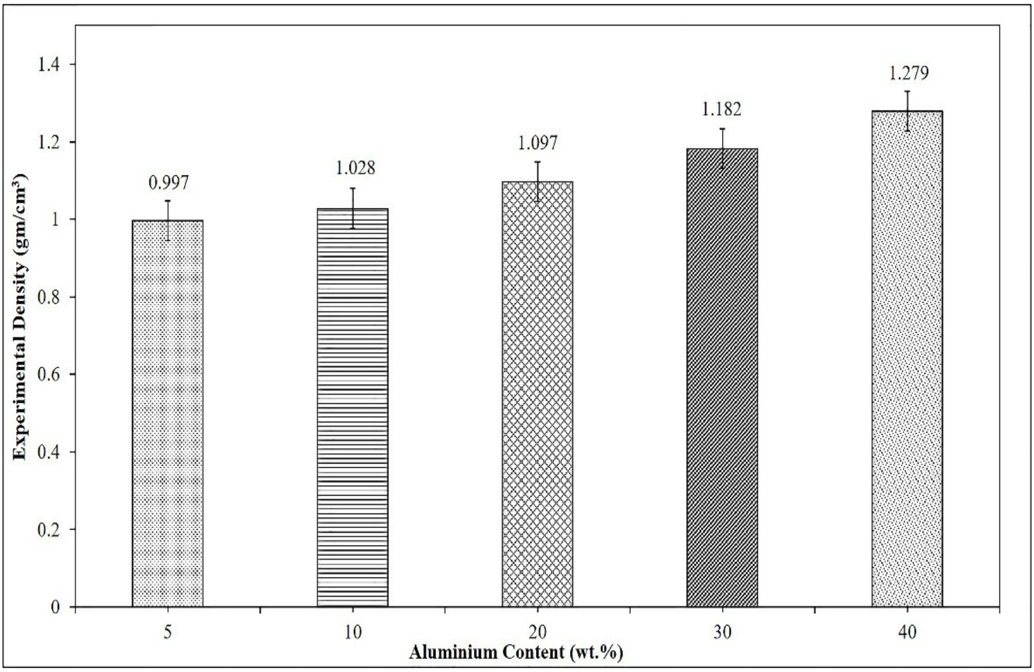

Fig. 11. Experimental density of HDPE-aluminium composite for different wt% of aluminium reinforcement (three times the experiment was repeated, and error bars are shown around ± 0.043 order of magnitude with the standard error)

Table 1. Density of HDPE-Al composites

Mixing condition	Theoretical density (gm/cm^3)	Experimental density (gm/cm^3)	Percentage (%)
95 (wt %) of HDPE- 5 (wt %) of aluminium	1.002	0.997	99.5
90 (wt %) of HDPE-10 (wt %) of aluminium	1.036	1.028	99.2
80(wt %) of HDPE- 20 (wt %) of Aluminium	1.112	1.097	98.6
70 (wt %) of HDPE- 30 (wt %) of Aluminium	1.201	1.182	98.4
60 (wt %) of HDPE- 40 (wt %) of Aluminium	1.304	1.279	98.1

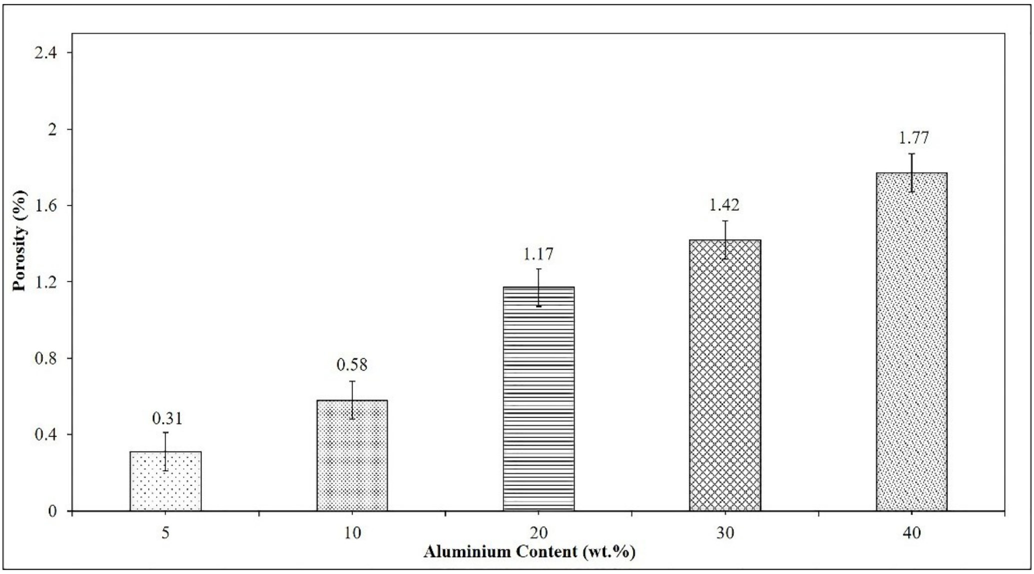

Fig. 12. Porosity of HDPE-aluminium composite for different wt% of aluminium reinforcement (three times the experiment was repeated, and error bars are shown around ± 0.29 order of magnitude with the standard error)

The excellent bonding of HDPE-Al composites, which are the subject of this work, is largely dependent on finely scattered aluminium particles on the polymer matrix. Furthermore, high compactness is attained in part because of the evenly dispersed Al particles produced via injection moulding and extrusion. As shown in Figs. 4(a, b) and 5(a, b), There is high interfacial integrity at the contact between the matrix and the reinforcement. Thus, it can be concluded that extrusion moulding prior to injection moulding has the potential to significantly enhance the characteristics of the HDPE-Al composite.

Conclusion

In this study, the effect of inorganic aluminium reinforcement on the mechanical and morphological characteristics of the HDPE polymer were investigated. The reinforcement was incorporated from 5 to 40 wt% into the polymer matrix via a customised extruder machine and injection moulding machine. The SEM and OM micrographs showed that the reinforcements are finely distributed throughout the HDPE matrix. On the other hand, a direct relationship has been shown with higher weight percentage of aluminium reinforcement and the potential for agglomeration formation. The tensile strength, elastic modulus, impact strength, and maximum load-bearing capacity raised with the incorporation of the aluminium reinforcement with a loading content of 5 wt%. However, the values decreased at high aluminium weight percentages due to less interfacial adhesion between HDPE and aluminium particles and also to the agglomeration tendency of the reinforcement. It has been found that better mechanical properties such as Impact strength, elastic modulus, tensile strength, and load bearing capacity were obtained for 5 wt% aluminium powder-loaded HDPE-Al composites among all other composites. Also, fully densified and less porosity were observed for all the composites. It is also crucial to note that no additional reinforcement was added during the composite fabrication. Overall, the results reported here provide fascinating and useful insights into the engineering and preparation of polymer-metal composites. So, the possible use of HDPE-Al composites could be in automotive construction, aerospace equipment design, and civil construction materials, depending on their desired properties.

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