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Research Article

Experimental Studies on the Performance of Graphene Oxide Based Hybrid Nanopolymers for Bearing Applications

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In this experimental study, graphene oxide-blended glass-filled nylon (GO-GFN) hybrid nanopolymer composites were developed and characterized. Transmission electron microscopic studies were performed to study the dispersion of graphene oxide in glass-filled nylon composites. Dynamic mechanical analysis and thermogravimetric analyses were conducted on the fabricated hybrid nanopolymer composites to analyze the mechanical and thermal stability. Mechanical properties were investigated by tensile test. The test showed improvements in young's modulus and tensile strength. Water absorption test was conducted to study the water absorption resistance of the hybrid nanopolymer composites. Finally, roller bearings with graphene oxide and glass-filled nylon were fabricated and analyzed for wear under varying load and speed conditions in the test rig developed in-house. The tests proved the suitability of deploying hybrid nanopolymer composites for bearing applications.

1. Introduction

In the present ever improving technological scenario, materials are extensively deployed in varying working conditions. Newer materials are invented to face the challenges in varying environmental conditions [1]. Polymer composites with nanofillers are challenging many metallic components with their light weight and improved mechanical, thermal, and elastic properties. Polymers are always light weight which helps in decreasing the overall weight of the components. In spite of being light weight, the major drawback in using polymers or plastics is the low load-bearing capacity. To overcome this, polymers are diffused or blended with nanoreinforcements or additives to improve the various properties. Nanoreinforcements in polymer matrix composites exhibit remarkable attraction due to the presence of excellent mechanical, thermal, optical, and magnetic properties compared to pristine polymeric materials [2, 3]. Polymer nanocomposites consists of extensively two phases in which the inorganic reinforcements of nanoscale ranging between 1 to 100 nm are either diffused or dispersed in polymeric matrix [4]. Due to nanoscale size of these reinforcements, they demonstrate outstanding properties because of their comparatively large surface area per unit volume. The real interest and development in polymer nanocomposites are due to the scientifical fact that the incorporation of very small nanosized reinforcements with the polymer matrix would exhibit a significantly remarkable enhancements in the various properties of polymer. Ever since after 1990, the excellent outcomes of Toyota research centre on polymer nanocomposites, many research were carried to explore the untold properties of these composites. In recent years, there has been an increasing commercial demand in the usage of polymer nanocomposites to obtain hybrid properties which emerge due to the combination of several components, reinforcements, and additives [5]. These nanopolymer composites offer good mechanical, optical, thermal, and electrical properties [6]. The enhancements in these properties are due to the presence of nanoparticles, their state of dispersion with the polymer matrix, and their interaction with the polymers [7]. Many researchers have investigated with several polymers and nanoparticles to explore the optimal usage of these materials in various industrial and engineering applications [8]. Various research works in nanoclays, nanotubes, and nanofibers have revealed the susceptibility of these nanomaterials for industrial applications with some demerits reported such as the cost of these nanoparticles and processing constraints [9–12]. To overcome these demerits and to recommend a suitable nanoparticle for engineering applications, the present research work is focused on reinforcing graphene oxide nanopowder with glass-filled nylon to explore the maximum competency of this hybrid nanopolymer composites for bearing applications. Various characterization tests were conducted on the fabricated graphene oxide-blended glass-filled nylon (GO- GFN) nanopolymer composites. To further explore the efficiency of these materials, bearings were fabricated using nylon and graphene oxide-blended glass-filled nylon, and the wear resistant capabilities of these bearings were studied and analyzed.

2. Experimental Procedure

2.1. Materials. The graphene oxide nanopowder is purchased from United Nanotech Innovations Private Limited, Bangalore, India. Number of layers in graphene oxide varies from 4 to 6, with a thickness of 0.7to2.3 nm. The ultimate carbon purity of the graphene oxide is 99%. Graphene oxide is blended with glass-filled nylon and drawn as wires and cut into pellets and injection molded as plates at Central Institute of Plastics Engineering and Technology, Guindy, Chennai. The technical specifications and elemental analysis of graphene oxide are presented in Tables 1 and 2.

2.2. Synthesis of Graphene Oxide Nanopolymer. Graphene oxide glass fiber reinforced nylon nanopolymers were synthesized by melt blending process. The materials to be blended such as glass-filled nylon pellets and graphene oxide nanopowder were metered into the blend by gravimetric blending process. 0.03 wt. % of graphene oxide nanopowder is added to 1 kg of glass-filled nylon through the feeder on the throat of the processing machine. Initially, the experiment was carried out for 5 compositions such as 0, 0.02, 0.03, 0.04, and 0.05, weight percentages of GO filled with GFN. The results obtained revealed that 0.03 wt. % of GO-filled GFN exhibited comparatively improved properties when compared with other concentrations. Hence, the 0.03 wt. % of GO-GFN is considered for further bearing applications [13]. The blender consists of a mixing section in which all the metered materials were mixed thoroughly to form a homogeneous blend, which is directed to flow into the processor. The processor was operated at a temperature of 300 degree centigrade. At this temperature, the mixture was melted completely. This molten homogeneous mixture was squeezed to flow through the orifice to form a wire. The graphene oxide-blended glass-filled nylon wire squeezing out of the orifice is quenched in a pool of water and subsequently cut into pellets by an automatic cutter fixed to the blending machine. The pellets are collected and injection molded at a temperature of 256°C to form plates for mechanical and characterization testing. The synthetization process is represented in Figure 1.

Table 1: Specifications of graphene oxide.

Parameters	Values
Thickness	105 μm
Porosity	70%
Pore size	0.025 μm

Table 2: Elemental analysis of graphene oxide.

Composition	Weight percentage
Oxygen	41–50%
Hydrogen	0–1%
Nitrogen	0–1%
Sulfur	0–2%
Carbon	49–56%
Oxygen	41–50%
Hydrogen	0–1%

2.3. Characterization Studies. The various characterization tests such as transmission electron microscopic studies, dynamic mechanical analysis, thermogravimetric analysis, water absorption test, and density test were conducted for the fabricated graphene oxide-blended glass-filled nylon nanopolymers.

2.3.1. Transmission Electron Microscopic Studies (TEM). Transmission electron microscopic studies were carried out on the processed nanopolymers. The presence of the nanopowder and the level of dispersion of the nanopowder in the glass-filled nylon matrix were studied from the images obtained at different magnifications.

2.3.2. Dynamic Mechanical Analysis. Dynamic mechanical analysis (DMA) is used to study the viscoelastic nature of the graphene oxide-blended glass-filled nylon nanopolymer. The model of the analyzer is DMS6100, manufactured by SII Nanotechnology, Japan. The analysis is carried out at 2-point bending dual cantilever method. The working temperature is 30°C to 200°C at a dynamic force range of ±10 N. The test is carried out at a heating rate of 2°C/min.

2.3.3. Thermogravimetric Analysis. Thermogravimetric analysis (TGA) is used to study the changes in physical and chemical properties of graphene oxide-blended glass-filled nylon nanopolymers as a function of increasing temperature on time with constant mass. The model of the analyzer is TG/DTA 6200, manufactured by SII Nanotechnology, Japan. The scanning rate of the analyzer is 0.01 to 150°C/

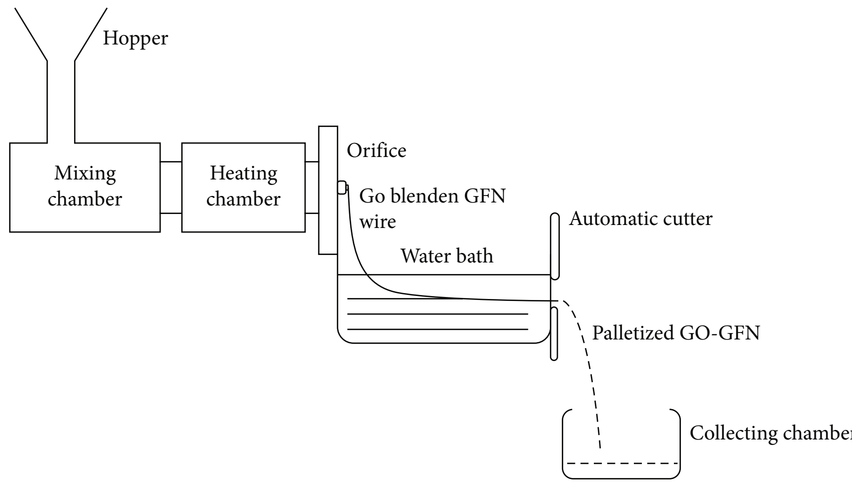


Figure 1: Synthetization process of GO-GFN nanopolymer composites.

min. The working temperature is 30°C–800°C. The test is carried out at a heating rate of 20°C/min.

2.3.4. Water Absorption Test. The hydrophobic or water-resistant properties of the fabricated GO-GFN nanopolymer is studied using water absorption test. Sample specimens of dimensions 60 mm diameter and 3 mm thickness were prepared and dried in an oven. The dried samples were immersed in a distilled water bath at room temperature and weighed periodically till no increase in weight was observed. All the samples were weighed on a weighing balance of 0.1 mg precision. The increase in weight by the nanocomposite is determined by the equation (M_t) [14–17].

$$M_t = \frac{w_w - w_d}{w_w} \times 100\%, \quad (1)$$

where w_d is the weight of the dried material and w_w is the weight of the water absorbed material.

2.3.5. Density Test. Density is a key concept in analyzing the interaction of materials in various domains such as material sciences, engineering, and physics. The density test is carried out in MODSUN EINSTEIN-II TFT ultrasonic flaw detector. The display unit of the detector is shown in Figure 2. The ultrasonic flaw detector is used to find the velocity of sound in the fabricated plates. A standard flat probe of 25 mm diameter is used to sense the velocity of sound at a working temperature of 55°C. From the velocity of sound, the density of the material is found using the following equation:

$$\text{Experimental velocity} = \sqrt{\frac{E}{\rho}}, \quad (2)$$

where E is Young's modulus and ρ is the experimental density. The experimental density found is compared with the theoretical density calculated using the following equation:

$$\text{Density } \rho = \frac{m}{v}, \quad (3)$$

where m is the mass of the object in kg and v is the volume of the object.

2.4. Mechanical Studies. Tensile test was carried out to measure the ultimate tensile strength and elongation at break of graphene oxide-blended glass-filled nylon nanopolymer composites. The specimen is prepared according to ASTM D638 standards under ambient conditions. The test specimens of 10 numbers were cut using press cutter of dumbbell type as shown in Figure 3. The test was conducted at a cross head speed of 50 mm/min and with a load cell of 500 N. In this experimental work, an average speed and load (50 mm/min and 500 N) is chosen for polymer nanocomposites. Ultimate tensile strength was found, and Young's modulus of the hybrid nanopolymer composite was computed from the stress–strain graph. The test was conducted at Micro Labs, Chennai.

3. Bearing Applications: Rolling Contact Wear Test

With reference to the mechanical and characterization tests conducted, experimental study was conducted to study the ability of the hybrid GO-GFN nanopolymer for being used as bearings for industrial applications. The bearing was prepared by injection molding and subsequent machining process. The dimensions of the GO-GFN bearing were presented in Table 3. The fabricated bearing was shown in Figure 4. A wear test rig as shown in Figure 5 was developed in-house [18] to study the wear resistance of the fabricated hybrid GO-GFN nanopolymer bearing. The test rig consists of a mild steel shaft with fixture. A lever arm arrangement is fabricated to apply load radially on the outer rings of the bearing. Varying loads and speeds are applied to the shaft to study the performance of the bearings [19]. The whole setup fitted with the bearings were run for 8 hours. In this performance analysis, the failure of the bearing is taken as the peeling or wrapping of the skin of the inner ring or retainer of the bearing. The variation in wear resistance with

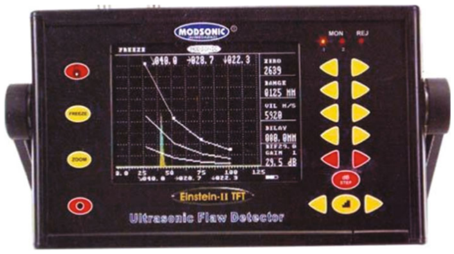


Figure 2: Ultrasonic flaw detector.

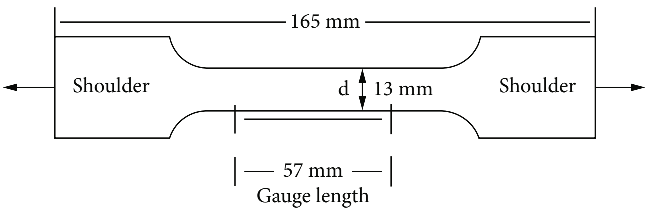


Figure 3: Dumbbell type specimen for tensile test.

Table 3: Dimensions of GO-GFN bearing.

Part	Material	Specification
Outer ring	0.03% of GO with GFN	ED = 52 mm
Inner ring	0.03% of GO with GFN	ID = 16 mm
Retainer	0.03% of GO with GFN	ED = 44 mm, ID = 35 mm
Ball	High carbon, high chrome	Diameter = 8 mm

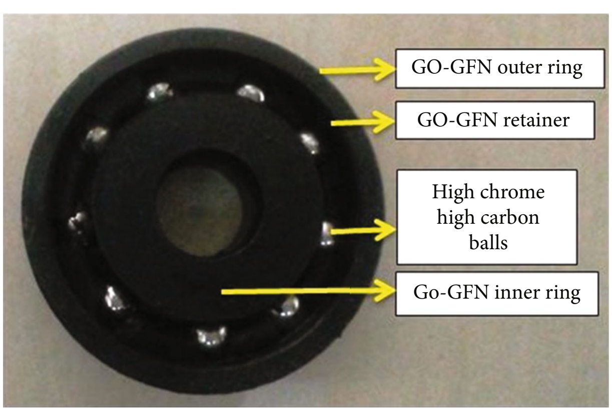


Figure 4: Fabricated hybrid GO-GFN nanopolymer bearing.

respect to temperature and time was studied, and the weight loss was analyzed.

4. Experimental Results and Discussions

4.1. Characterization Tests

4.1.1. Transmission Electron Microscopic Study (TEM). The transmission electron microscopy (TEM) studies were performed on TEM instrument with an accelerating voltage of 200 kV. Graphene oxide is electronically transparent because of its very low atomic number and two-dimensional structures. The TEM image of the fabricated graphene oxide-blended hybrid nanopolymer at various magnifications is represented in Figure 6. Since the graphene sheet is highly stable towards electron beam, it exhibits low background in imaging mode. The TEM image at 500 nm shows multiple folds of graphene oxide sheets on the glass-filled nylon matrix. The 200 nm magnification image shows 2 layers of graphene oxide overlapping with each other. This TEM study confirmed the uniform dispersion of graphene oxide in the glass-filled nylon, and also, it was inferred from the study that the graphene oxide sheets exhibited multiple layered lamellar structure with a thickness of approximately 2 to2.5 nm.

4.1.2. Dynamic Mechanical Analysis. Dynamic mechanical analysis (DMA) is carried out at a temperature range of 50 to 400°C and frequency of 1 Hz. From Figure 7, it was observed that as the temperature increases, the stiffness of the GO-GFN hybrid nanopolymers decreases, which affects the storage modulus of the fabricated hybrid nanopolymer. The graph shows that at a temperature range of 180°C to 220°C, both the rubbery and glassy state of the hybrid polymer occurs. In this region, there is a rapid change in the storage modulus slope. This region represents the glass transition temperature range of the hybrid nanopolymer, and the sharp point of the curve indicates the glass transition temperature (Tg) of the fabricated hybrid nanopolymers. From the graph obtained, the value of Tg is noted as 218°C. The loss modulus takes place at 216.4°C. The tan (δ) value occurs at the peak of 227.9°C. These results confirm that the GO-GFN hybrid nanopolymer has enhanced glass transition temperature which is attributed to the presence and excellent interfacial bonding of graphene oxide with glass-filled nylon.

4.1.3. Thermogravimetric Analysis. Thermogravimetric analysis (TGA) was performed for GO-GFN hybrid nanopolymer to study the changes in physical and chemical properties as a function of increasing temperature on time with constant mass [20]. Figure 8 represents the thermogravimetric analysis of GO-GFN hybrid nanopolymers. The abscissa is taken as temperature, and the ordinate is taken as the weight percentage. The scanning rate of the analyzer is 0.01 to 150°C/min. The working temperature is 30°C–800°C. The peak of the first derivative occurs at 482°C. The curve in this peak denotes the highest rate of weight change for the GO-GFN sample. This peak is called as inflection point. Various peaks are noted at 218°C, 454°C, and 482°C. It was inferred from the result that most of the graphene oxide-containing oxygen functional groups were reduced during the thermogravimetric analysis and hence increases the thermal stability.

4.1.4. Water Absorption Test. The water-resistant property of the hybrid GO-GFN nanopolymer was found using water absorption test. The test was performed in ASTM D570 conditions. To conduct a comparative study, the test was performed for nylon, glass-filled nylon, and graphene

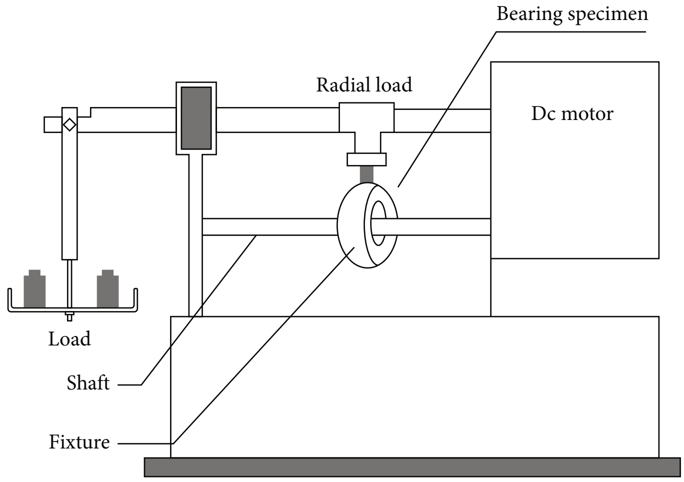


Figure 5: Bearing test rig.

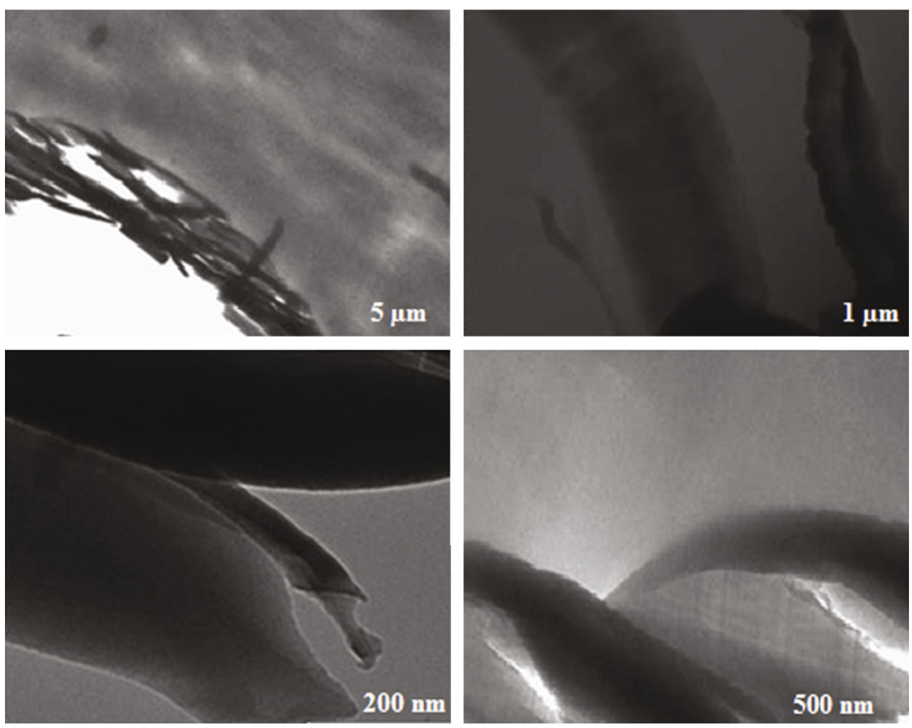


Figure 6: Transmission electron microscopic images of graphene oxide-blended glass-filled nylon at various magnifications.

oxide-blended glass-filled nylon. The test was performed till the weight of the samples achieved constant values under room temperature [21]. Table 4 presents the results of water absorption test.

Figure 9 represents the water absorption of nylon, glass-filled nylon, and graphene oxide-blended glass-filled nylon samples of uniform dimension and weight. The test was conducted for 6 days, out of which no appreciable weight change was observed after the fourth day. It was inferred from the graph that the nanocomposites had absorbed the maximum amount of water within four days. The dimension and mass changes caused by water absorption are studied. It was observed that the higher water absorption resulted in the extraction of water soluble components and causes changes in mechanical properties such as tensile strength, elasticity, and toughness; also, it effects the glass transition temperature and load-bearing capacity of the polymer [22, 23]. By comparing the water absorption capability of nylon, glass-filled nylon, graphene oxide-blended glass-filled nylon samples, the GO-blended glass-filled nylon has better water resistance capabilities. As graphene oxide is an isotope of carbon and carbon is inherently hydrophobic, the water resistance property of GO-blended glass-filled nylon was higher. The GO filler layers in the hybrid nanopolymers

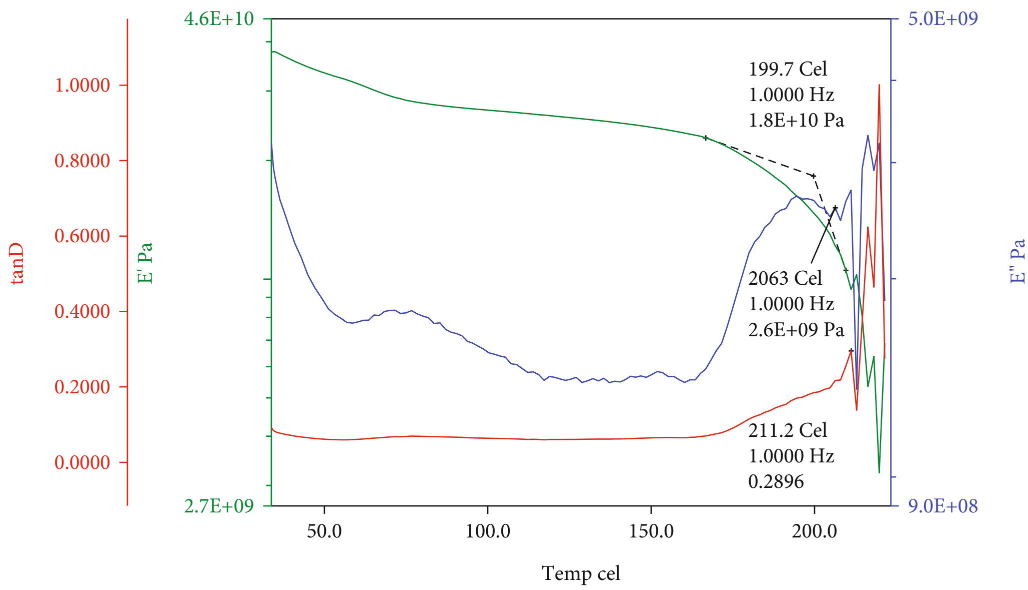


Figure 7: Dynamic mechanical analysis of GO-GFN hybrid nanopolymer.

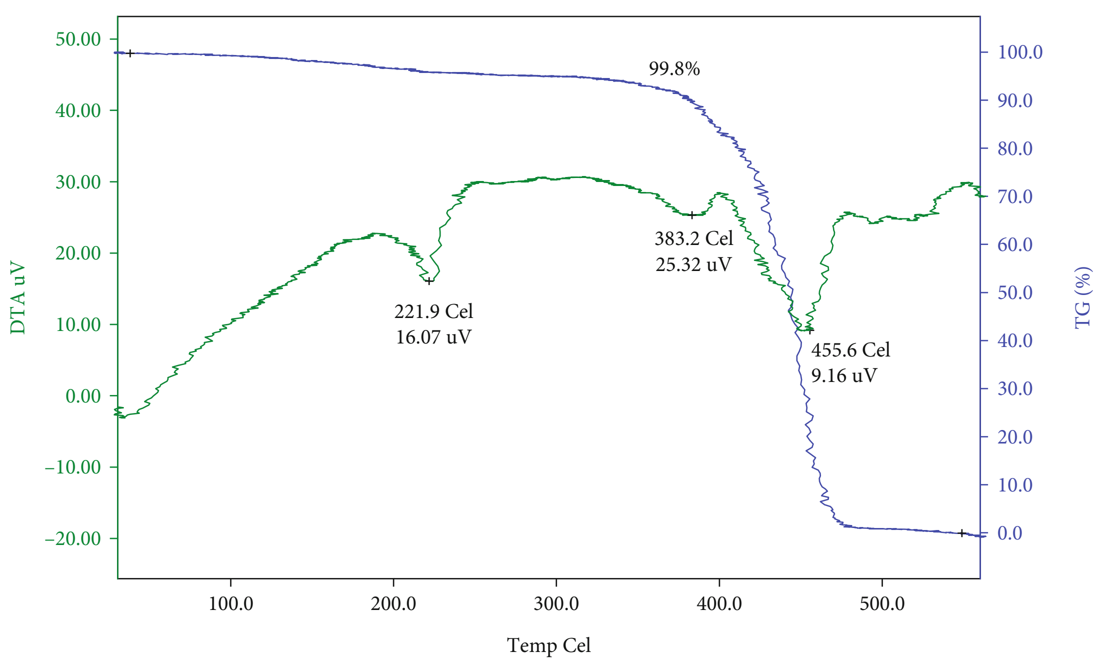


Figure 8: Thermogravimetric analysis of GO-GFN hybrid nanopolymer.

Table 4: Water absorption test.

Day	Average weight of the samples in grams		
	Nylon	GFN	GFN+GO
1	7.020	7.020	7.020
2	7.042	7.030	7.011
3	7.060	7.043	7.027
4	7.089	7.061	7.038
5	7.089	7.061	7.038
6	7.089	7.061	7.038
Fractional increment in weight	0.9829	0.5840	0.2564

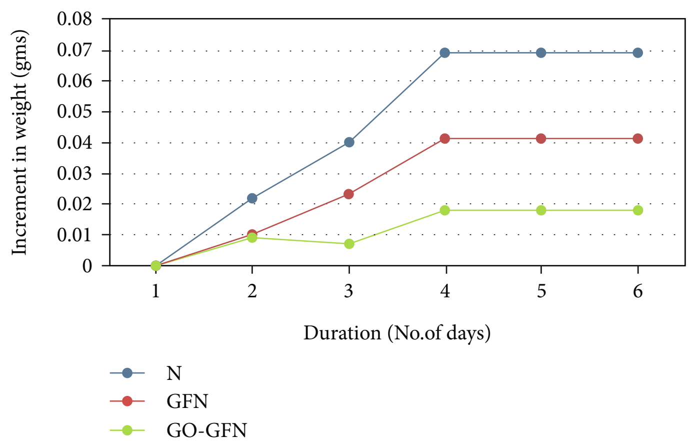


Figure 9: Water absorption of nylon, glass-filled nylon, graphene oxide-blended glass-filled nylon.

have decreased the diffusion path for water to penetrate deeply into the glass-filled nylon polymer. This attributes to the better barrier properties of hybrid graphene oxide-blended glass-filled nylon. The test performed proves that the GO had dispersed well in the glass-filled nylon without any agglomeration.

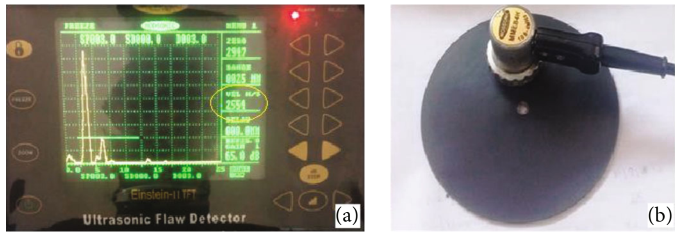
4.1.5. Density Test. The density value for the fabricated hybrid GO-GFN nanopolymer was computed theoretically using mass and volume. The density value was also calculated experimentally and compared with theoretical value. The experiment was conducted using ultrasonic flaw detector to find the experimental velocity which was recorded from the display unit as shown in Figure 10(a). The probe travelling on the specimen to record the velocity is shown in Figure 10(b). The experimental value recorded from the ultrasonic flaw detector and Young's modulus found from stress–strain curve is used for computing the experimental density. Theoretical and experimental value of density for the fabricated graphene oxide-blended glass-filled nylon nanopolymer plate is 2462.34 kg/m^3 and 2454 kg/m^3, respectively. The value of density calculated for the fabricated GO-GFN sample experimentally coincides with the theoretical value.

4.2. Mechanical Tests. The tensile test was carried out in the specimen of dimension D638. The tensile strength was observed for the fabricated hybrid GO-GFN nanopolymer composites. The test procedure was repeated for pristine nylon and glass-filled nylon system. The results obtained were tabulated in Table 5 and compared. From the results, it was inferred that the graphene oxide-reinforced glass-filled nylon has higher tensile strength when compared to nylon and glass-filled nylon [24]. This is due to the presence of graphene oxide which is an isotope of carbon. As carbon imparts higher hardness, the fabricated hybrid nanopolymer possesses higher tensile strength [25]. The excellent interfacial bonding between the graphene oxide nanopowder and glass-filled nylon helps in arresting crack propagation and withstanding the higher load applied, thus enhances tensile strength of the nanopolymer composites.

The stress–strain curve for the glass-filled nylon (GFN) and GO-GFN nanopolymer was plotted as shown in Figure 11. When the GO-GFN plate is subjected to low stress, the material undergoes elastic deformation. This initial slope of the stress–strain curve gives a measure of Young's modulus. For the given load, the hybrid nanopolymer behaves likes a flexible plastic, which elongates and deforms considerably before breaking. At higher loads, the deformation becomes plastic in nature, and the original shape was not regained even after the stress was removed [26]. It was inferred from the curve that the yield point occurrence was well in advance before the ultimate tensile strength and proves that the GO-GFN hybrid nanopolymer was ductile and semicrystalline in nature. The graph also shows the comparative analysis of stress–strain curve of GFN and GO-GFN. For the given load, the GO-GFN nanocomposites are less ductile and possess higher tensile strength and modulus compared with nylon matrix. It was also evident from the curve that the yield point strength of the nanocomposites is also improved by GO infusion in glass-filled nylon matrix.

5. Bearing Application: Go-GFN Hybrid Nanopolymer Bearings

The compatibility of the fabricated hybrid GO-GFN nanopolymer towards bearings for engineering applications was evaluated in the test rig developed in-house. The bearings are mounted in the shaft, and radial loads of 50 N, 150 N, and 300 N were applied. The nylon and hybrid GO-GFN bearing specimens were run at three different speeds 600 rpm, 800 rpm, and 1000 rpm. The temperature is recorded in an infrared thermometer. The bearing test was conducted for eight hours to analyze the wear. In this study, the end of bearing life is taken as the wear in the surface of the inner ring and the deformations that has occurred in the retainer on which the ball rollers slide. The inner ring is also suspected to wear as it bears the sliding race way for the rollers. The spalling and pitting effects are observed in the retainer of the nylon in a larger percentage when compared to GO-reinforced glass-filled nylon bearings retainer



(a) (b)

Figure 10: Ultrasonic flaw detector. (a) Display unit. (b) Probe placed on the GO-GFN plate.

Table 5: Tensile test results.

Test parameters	Observed values Nylon	 Glass-filled nylon	 Graphene oxide-blended glass-filled nylon
Ultimate tensile load (kN)	1.83	2.24	3.80
Ultimate tensile strength (N/mm^2)	40.00	47.00	82.00

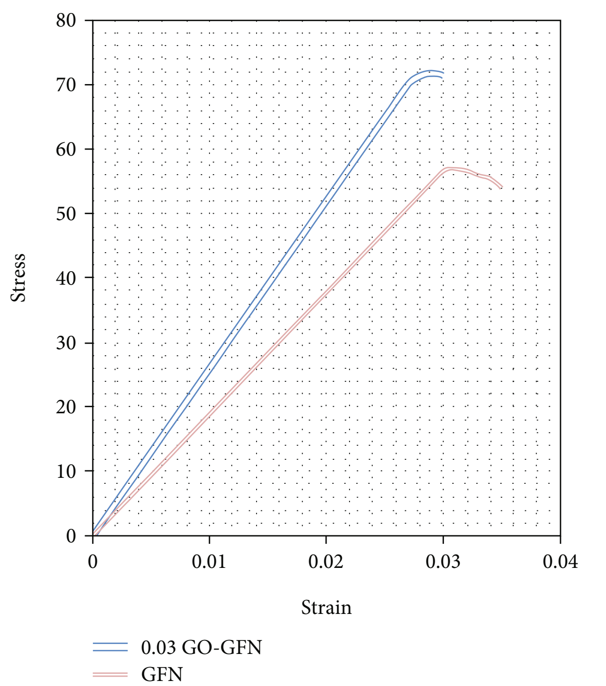
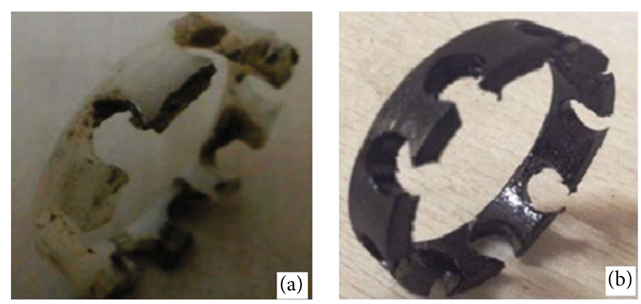


Figure 11: Stress–strain curve for GO-GFN hybrid nanopolymer.

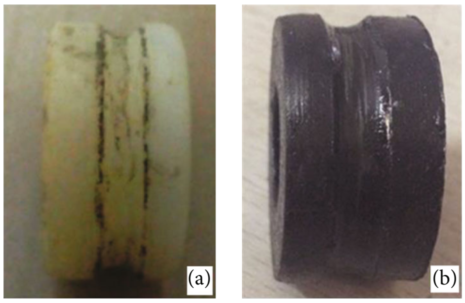


(a) (b)

Figure 12: (a) Retainer of nylon bearing. (b) Retainer of GO-GFN bearing.

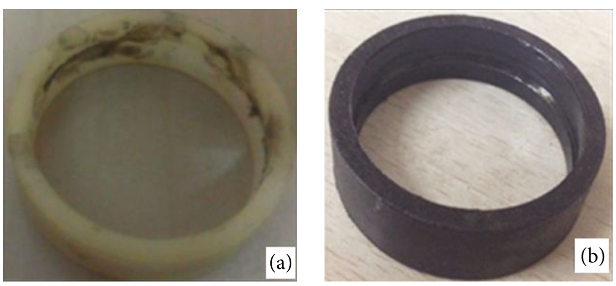
[27–30]. Figure 12 shows the pristine nylon and GO-reinforced glass-filled nylon bearing retainers. Figure 12(a) shows the retainer of nylon in which smearing effect observed is very high when compared to the graphene oxide-blended glass-filled nylon (GOGFN) retainer. Figure 12(b) shows the retainer of graphene oxide-blended glass-filled nylon bearing. When compared with the nylon retainer, the surface of GOGFN retainer is characterized with less distorted skin surface and the tearing of the skin is also very low when compared to the nylon retainer. Figure 13(a) shows the heavy peeling of the skin on the raceway of nylon inner ring which is due to the higher temperature formed by the sliding of the balls. Comparatively, the raceway of the GO-GFN inner ring is characterized by smaller indentions formed by the sliding of the roller balls as shown in Figure 13(b). This is due to the fact that the incorporation of graphene oxide to glass-filled nylon has improved the wear resistance. This is recorded by using infrared thermometer. The outer ring of the nylon bearing was subjected to heavy surface distortions when compared with GO-GFN outer ring as shown in Figures 14(a) and 14(b). Thus, it is inferred from the above results that the graphene oxide-blended glass-filled nylon bearing has significantly improved wear resistance which is due to the reinforcement of graphene oxide nanoparticles.

Figure 15 shows the effect of temperature and speed on the wear of the inner rings of the nylon bearings when the shaft is rotated at 600 rpm, 800 rpm, and 1000 rpm. The maximum temperature attained on the inner ways of the nylon bearing is higher when compared to the temperature



(a) (b)

Figure 13: (a) Inner ring of nylon bearing. (b) Inner ring of GO-GFN bearing.



(a) (b)

Figure 14: (a) Outer ring of nylon bearing. (b) Outer ring of GO-GFN bearing.

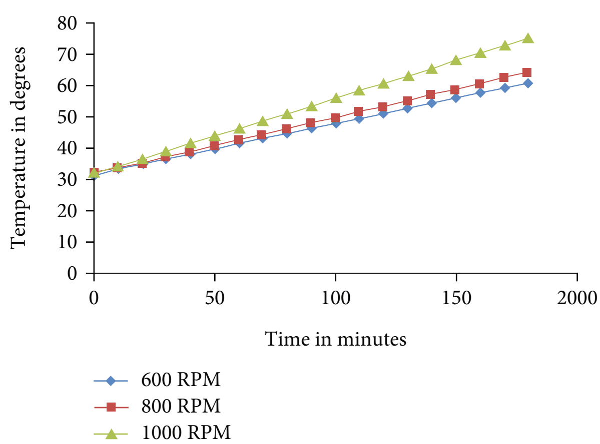


Figure 15: Time–temperature graph of nylon bearings.

built upon the inner ways of graphene oxide-blended glass-filled nylon bearings. The effect of temperature over time, when the shaft is rotated at a speed of 600 rpm, 800 rpm, and1000rpm for graphene oxide-blended glass-filled nylon bearings, is shown in Figure 16. From the above two figures, it was inferred that, when the speed increases, the temperature also increases, which leads to localized plastic deformation at some points of inner ring which is indirect contact with the shaft. Low temperature distribution in graphene oxide-blended glass-filled nylon is attributed to the presence of graphene oxide nanoparticles which possess high thermal

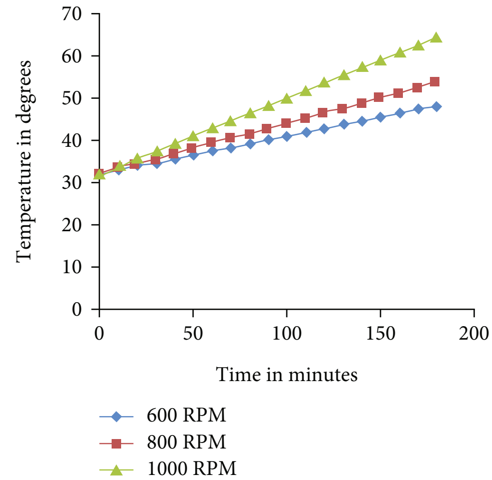


Figure 16: Time–temperature graph of GO-GFN bearing.

conductivity and improve the heat resisting properties of polymers [31–39]. The results obtained from the bearing test proved that the GO-GFN hybrid nanopolymers possesses all the desirable properties for being used as bearings such as low temperature distribution, less distortion, higher resistance, and improved life cycle performance when compared with pristine nylon bearings.

6. Conclusion

From the experimental work presented, the following conclusions were observed. Hybrid graphene oxide glass-filled nylon nanopolymer was synthesized and processed to study its suitability and compatibility for engineering applications. The graphene oxide nanopowder blended with glass-filled nylon with a very low weight percentage influences greatly the mechanical and physical properties of the hybrid nanopolymer which was confirmed by the various characterization tests conducted. The density and water resistance capability of the fabricated hybrid nanopolymer were investigated. The results proved that the hybrid nanopolymer exhibits excellent density and water resistance properties which eventually helps in improving various properties such as tensile strength (68%), toughness (57%), and elasticity (52%) when compared with pristine glass-filled nylon. Finally, the hybrid nanopolymers compatibility for engineering applications were investigated by fabricating roller bearings. Wear rates due to plasticization and softening of the polymer was reduced significantly by the incorporation of graphene oxide. Wear rate due to surface crack was lower in hybrid nanopolymer when compared to nylon polymer. The reduced specific wear rate of these polymer nanocomposites bearings were attributed to the superior properties of graphene oxide such as high specific surface area, good adhesion properties, and enhanced glass transition temperatures. The graphene oxide nanocomposite bearings seem to be a potential alternative against conventional bearings for engineering applications. It can be used as alternate with improved life wherever polymeric gears are currently being used. The investigation confirmed the suitability of the graphene oxide-blended glass-filled nylon for engineering applications.

Data Availability

The data used to support the findings of this study are included within the article.

Disclosure

This study was performed as a part of the Employment of Jimma Institute of Technology, Jimma, Ethiopia.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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