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ENHANCED THERMAL AND MECHANICAL PROPERTIES OF POLYCARBONATE COMPOSITES REINFORCED WITH AL_2O_3, GRAPHITE, AND HEXAGONAL BORON NITRIDE

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Abstract— In this work, thermal conductivity and mechanical properties of polycarbonate (PC) composites reinforced with aluminium oxide (Al_2O_3) graphite, and hexagonal boron nitride (BN), were investigated at different filler loadings. Composites were prepared via melt mixing using a co-rotating twin screw extruder, with polydimethylsiloxane and amino-functional silane employed to improve filler dispersion. Through-plane thermal conductivity of PC/Al_2O_3 (30%) and PC/Graphite (30%) composites reached 0.6 and 3.01 W/mK, respectively, compared to 0.27 W/mK for PC. PC/Al_2O_3 remained electrically insulating, whereas PC/Graphite was conductive. PC/BN composites, particularly at 10–15 wt%, achieved thermal conductivity up to 1.05 W/mK while maintaining electrical insulation, with minimal impact on composite density. Mechanical properties were also influenced by filler type and loading. PC showed tensile stress at yield of ~73 MPa and elongation of ~5%. While Al_2O_3 and graphite reduced elongation, PC/BN composites maintained tensile stress at yield of 60–70 MPa and moderate elongation (2–3.5%) with elastic modulus, without significantly increasing density. These results highlight that BN is an effective reinforcing filler, providing an optimal combination of thermal conductivity, electrical insulation, mechanical performance, and lightweight characteristics. PC/BN composites at 10–15 wt% are promising for thermal management applications in electronics, energy storage, and automotive components.

Keywords— Aluminium Oxide / Graphite / Hexagonal Boron Nitride, Mechanical Properties, Polycarbonate (PC), Thermal Conductivity

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I.INTRODUCTION

Polymers have become commonly used in modern industry and everyday applications because of their combination of stability, mechanical flexibility, and low density [1]. As electronic devices are undergoing rapid miniaturization and power density is increasing, effective thermal management has become an important challenge to ensure device reliability and performance [2]. Polymers have inherently low thermal conductivity, but despite this limitation they offer certain advantages such as relatively low cost, straightforward large-scale processing, and adjustable structural properties that will continue to position polymers as potential candidates for thermal management [3,4].

Previous studies show that the thermal conductivity of polymers can be improved by adding conductive fillers [5,6]. Conventional low-aspect-ratio fillers are limited in effectiveness even at high loadings [7]. In contrast, BN-based materials are particularly appealing due to their high thermal conductivity, thermal stability, wide band gap, and electrical insulation [8]. Nevertheless, high interfacial thermal resistance between polymer and filler can restrict overall performance, resulting in lower conductivity compared to metals and ceramics [9,10].

Current research focuses on strategies such as surface modification of fillers, hybrid filler systems, and hierarchical composite architectures to reduce interfacial resistance and enhance heat transport [11, 12, 13]. The table of thermal conductivities of polymers is presented in Table 1, showing that polymers generally have very low thermal conductivities (0.1–0.5 W/m·K). Compared to metals and inorganic materials, these values are very low, limiting their direct use in applications requiring efficient heat transfer [14]. Therefore, developing polymer composites with highly conductive fillers is a promising approach [13].

Ceramic fillers, such as aluminium oxide (Al_2O_3) [15], silisium dioxide (SiO_2) [16], zinc oxide (ZnO) [17], magnesium oxide (MgO) [18], beryllium oxide (BeO) [19], nickel oxide (NiO) [20], calcium oxide (CaO) [21], aluminium nitride (AlN) [22], boron nitride (BN) [23], silicon nitride (Si_3N_4) [24], silicon carbide (SiC) [25], and boron carbide (BC) [26], are preferred due to high intrinsic thermal conductivity, electrical insulation, and chemical stability. Particle size, morphology, dispersion, and interfacial compatibility with the polymer matrix are critical for forming effective thermally conductive pathways [27]. Optimizing these factors enhances thermal transport while maintaining mechanical and processing properties [28].

Additional studies emphasize filler orientation, hybrid filler combinations, and surface functionalization for improved thermal conductivity. Proper dispersion and alignment of high-conductivity fillers can significantly enhance performance even at low loadings [29]. Interfacial engineering, using coupling agents or polymer grafting, reduces thermal boundary resistance [30]. Filler loading, particle size distribution, and matrix viscosity also affect thermal transport. Strategies like 3D filler networks, anisotropic alignment, and hierarchical structuring maximize heat transfer efficiency [31]. Comparative studies show that polymer/ceramic composites maintain electrical insulation while achieving reasonable thermal performance [32]. Surface modification of BN and AlN improves filler dispersion and network formation. Processing methods such as melt blending, solution casting, and hot pressing influence the final microstructure and thermal conductivity. Advanced composites are being explored for electronics [33], energy storage [34], electrical vehicles [35], combining mechanical flexibility [36], electrical insulation [37], and thermal efficiency [38]. Well-designed filler architectures enable thermal conductivities approaching or exceeding 10 W/m·K, while hierarchical designs integrating nano-, micro-, and macro-scale fillers offer scalable and reliable solutions [39]. Understanding filler morphology, dispersion, interfacial adhesion, and processing is key to optimizing performance [40]. Therefore, rational design principles and comprehensive characterization of polymer/ceramic composites are essential for developing materials with tailored thermal, mechanical, and electrical properties [41, 42].

In this study, polycarbonate (PC) was chosen as the polymer matrix because of its mechanical strength, thermal stability, and inherent electrical insulation, making it suitable for demanding engineering applications such as electric vehicle connector components. The research focuses on the development and characterization of thermally conductive PC-based composites reinforced with aluminium oxide, graphite, and boron nitride, with the aim of achieving materials that combine enhanced thermal conductivity with maintained electrical insulation, while also evaluating their mechanical performance for advanced thermal management applications.

II. EXPERIMENTAL

A. Materials

In this study, polycarbonate (PC) with a melt flow rate of 7 g/10 min (300°C/1.2 kg) and a density of 1.20 g/cm³ was used. The filler materials used were Al_2O_3 with grain sizes of D_{50}: 40–90 µm and D_{97}: 80–140 µm, graphite, known for its high thermal and electrical conductivity, and boron nitride (h-BN), which is electrically insulating but offers high thermal conductivity. Phenolic and phosphide antioxidants were used for stabilization, and two external and one internal lubricant were used for ease of processing.

B. Polymer Composites Preparation

As seen in Table 1 with sample codes and rates, the experimental work was carried out in three main groups. In the first group (PC series), polycarbonate-based composites containing 30 wt% alumina or 30 wt% graphite were prepared, alongside polycarbonate. In the second group (PH series), polycarbonate-based hybrid composites were produced with combined filler loadings of 25 wt% alumina + 5 wt% graphite, 20 wt% alumina + 10 wt% graphite, and 15 wt% alumina + 15 wt% graphite. In the third group (PB series), polycarbonate composites were prepared with boron nitride at loadings of 5 wt%, 10 wt%, and 15 wt%. Thermal conductive fillers and polycarbonate raw materials were dried at 120°C for 3 hours before the process. The compounding process was carried out in a prototype co-rotating twin-screw extruder (L/D ratio of 46 and a screw diameter of 30 mm) at a temperature profile of 250–280°C and a screw speed of 250 rpm, with a throughput capacity of 30-35 kg/h. The extrudates were pelletized to obtain PC compound granules, which were subsequently injection-molded into test specimens. All formulations from these groups were subsequently compared to evaluate their overall thermal, mechanical, including measurements of thermal conductivity, melt flow properties, density, and surface resistivity.

TABLE 1 PC COMPOSITE FORMULATIONS WITH FILLER TYPES AND CONTENTS.

Sample Code	**PC**	**Al_2O_3**	**Graphite**	**BN**	**Lubricant**	**Antioxidants**
PC1	99,5	-	-	-	0,25	0,25
PC2	69,5	30	-	-	0,25	0,25
PC3	69,5	-	30	-	0,25	0,25
PH1	69,5	25	5	-	0,25	0,25
PH2	69,5	20	10	-	0,25	0,25
PH3	69,5	15	15	-	0,25	0,25
PB1	94,5	-	-	5	0,25	0,25
PB2	89,5	-	-	10	0,25	0,25
PB3	84,5	-	-	15	0,25	0,25

All values are expressed as weight percent (wt%).

C. Determination of Physical Properties

Density of the samples was determined in accordance with ISO 1183 using the immersion method. The melt flow properties were evaluated with a ZwickRoell Cflow device following ISO 1133, where the tests were performed at 300°C under a 1.2 kg load, and the resulting MFR values were used to assess the processability of the material. In addition, electrical conductivity values were determined as surface and volumetric resistance using an electrical conductivity measuring device in accordance with the IEC 60093 standard.

D. Determination of Mechanical Properties

Tensile properties were evaluated according to ISO 527-1 and ISO 527-2 using a universal testing machine equipped with a ZwickRoell Longstroke extensometer. Test specimens with standard dimensions of 170 mm × 10 mm × 4 mm were mounted in the grips of the machine. Impact resistance was determined following ISO 180 with a ZwickRoell HIT5.5P pendulum impact tester. Samples with dimensions of 80 mm × 10 mm × 4 mm were conditioned at room temperature prior to testing. For the notched configuration, a V-shaped notch (45° angle, 2 mm depth, 0.25 mm root radius) was introduced, after which the specimens were positioned vertically in an Izod-type fixture and fractured by releasing a pendulum of 5 J nominal energy from a defined height.

E. Determination of Thermal Properties

The thermal conductivity (κ) of the polymer samples was measured in accordance with ISO 8302 using a Discovery Xenon Flash 200+ Thermal Conductivity Instrument. Tests were conducted under controlled conditions, and the thermal conductivity values were expressed in W/m·K, providing quantitative information on the material's heat transfer performance.

III.RESULTS AND DISCUSSION

A. Mechanical Properties of PC Composites with Different Fillers

In this section, mechanical properties such as tensile strength, elongation, elastic modulus, and impact resistance of polycarbonate matrix composites were evaluated depending on different filler types and ratios, including: polycarbonate (PC1), polycarbonate + 30% alumina (PC2), polycarbonate + 30% graphite (PC3), polycarbonate + 25% alumina + 5% graphite (PH1), polycarbonate + 20% alumina + 10% graphite (PH2), polycarbonate + 15% alumina + 15% graphite (PH3), polycarbonate + 5% boron nitride (PB1), polycarbonate + 10% boron nitride (PB2), and polycarbonate + 15% boron nitride (PB3).

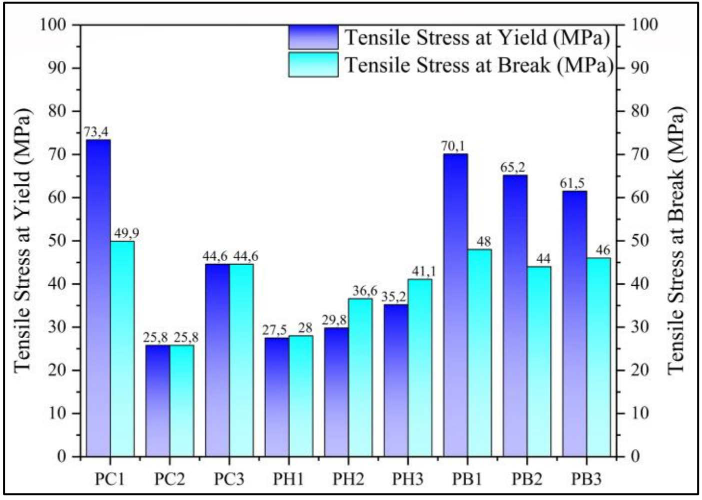

Fig. 1. Tensile Stress at Yield and Break Comparison of PC Composites with Various Fillers.

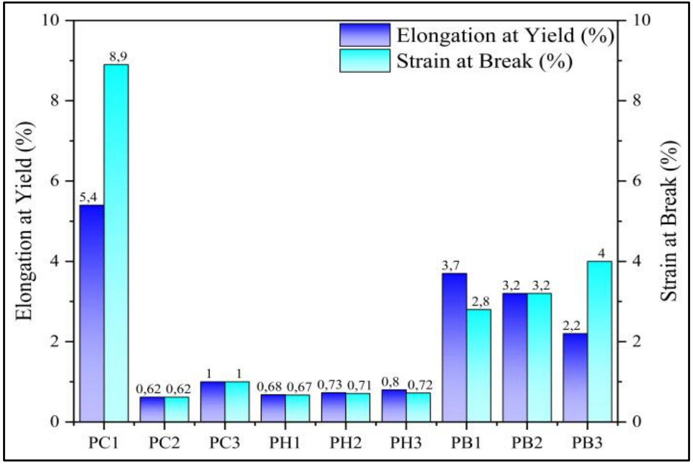

Fig. 2. Elongation at Yield and Strain at Break Comparison of PC Composites with Various Fillers.

Tensile stress and elongation of PC composites at yield and break are shown in Figures 1 and 2. High alumina content reduced the ductility of the polycarbonate matrix, leading to more brittle behaviour. The addition of graphite, while slightly reducing elongation at high concentrations, facilitated load transfer and limited crack propagation, improving overall fracture performance. In hybrid filler systems, increasing graphite content partially offset the embrittling effect of alumina, enhancing toughness. Boron nitride remained compatible at low concentrations, maintaining ductility, while higher concentrations gradually reduced both elongation and strength.

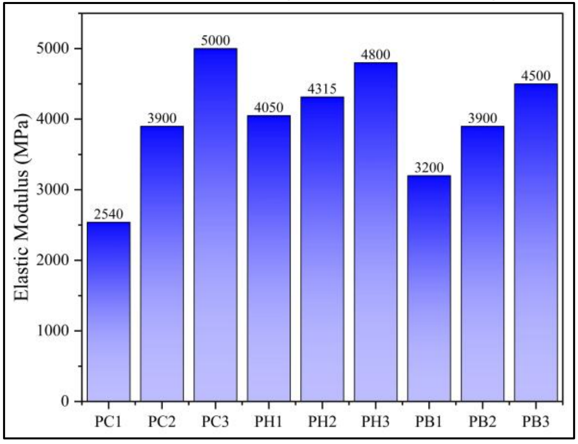

Fig. 3. Elastic Modulus Break Comparison of PC Composites with Various Fillers.

The elastic modulus of PC composites is shown in Figure 3. While polycarbonate has a relatively low elastic modulus, the addition of alumina and graphite fillers increased the material's stiffness. Increasing the graphite content in hybrid filler systems further increased the elastic modulus, improving the mechanical performance of the filler combinations. Boron nitride filler, on the other hand, was compatible with the matrix at low ratios and provided a significant increase in elastic modulus at higher ratios.

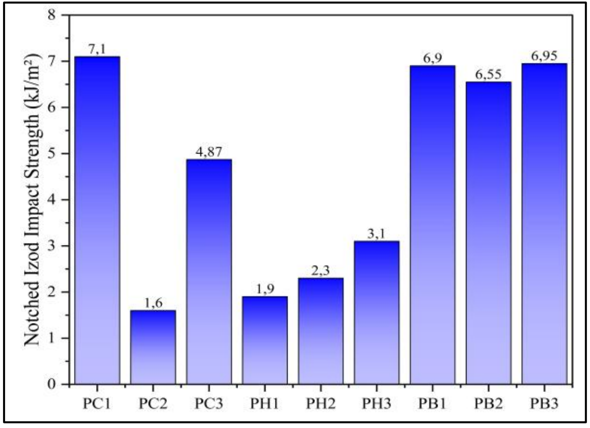

Fig. 4. Notched Izod Impact Strength Comparison of PC Composites with Various Fillers.

The impact strength of PC composites is presented in Figure 4. While polycarbonate exhibited high impact strength, the addition of a high percentage of alumina filler reduced strength by making the material brittle. Graphite addition partially increased impact strength, and in hybrid systems, increasing the graphite content offset the negative effects of alumina, improving performance. Boron nitride filler-maintained strength at low and medium concentrations, with a limited decrease at higher concentrations.

B. Physical and Thermal Properties of PC Composites with Different Fillers

The physical and thermal properties of the polycarbonate composites, including density, melt flow rate (MFI), and thermal conductivity, were examined to assess the effects of different fillers.

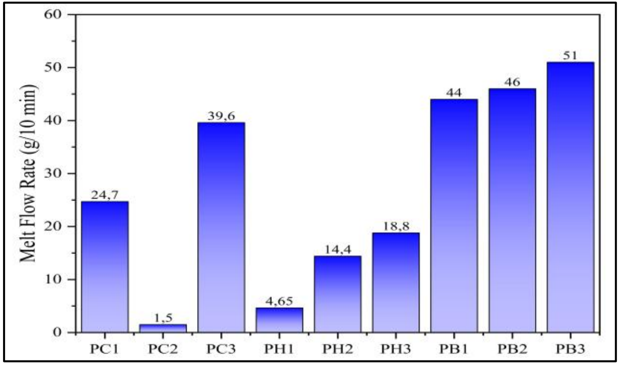

Fig. 5. Melt Flow Rate Comparison of PC Composites with Various Fillers.

As shown in Figure 5, Alumina significantly reduced MFI, indicating decreased processability, while graphite increased MFI moderately in hybrid systems. Boron nitride slightly enhanced MFI at low and medium loadings, providing a balanced improvement in flow behaviour.

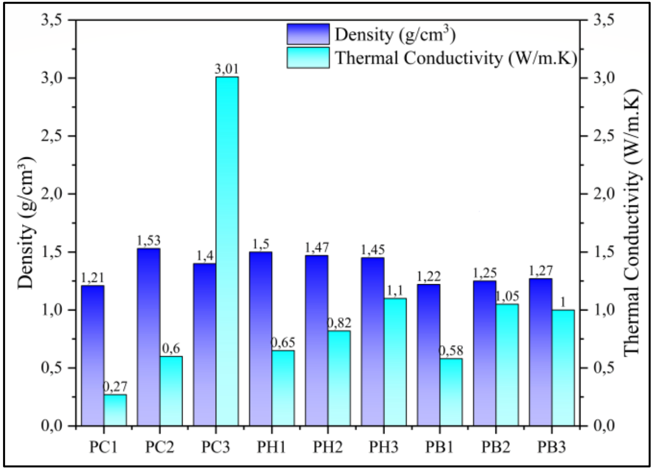

Fig. 6. Density and Thermal Conductivity Comparison of PC Composites with Various Fillers.

As shown in Figures 6, the fillers increased both the density and thermal conductivity of the polycarbonate composites. Alumina addition significantly increased the density while moderately enhancing thermal conductivity, whereas graphite provided high thermal conductivity with a limited density increase. In hybrid systems, increasing the graphite content gradually improved thermal conductivity, while boron nitride at low and medium loadings slightly increased density and enhanced thermal conductivity in a balanced manner.

C. CONCLUSIONS

Polycarbonate (PC) composites reinforced with Al_2O_3, graphite, and BN differed in density, mechanical, and thermal properties. PC thermal conductivity has been found ~0.27 W/mK. Reinforcing PC with 30 wt% Al_2O_3, increased thermal conductivity to 0.6 W/mK, while 30 wt% reinforced graphite-PC based composites showed 3.01 W/mK but caused a high electrical conductivity limiting electronics applications. Hybrid systems also improved thermal conductivity of composites consist of Al_2O_3 and graphite fillers. The highest thermal conductivity of the composite structure reinforced with Al_2O_3 and graphite up to 30% was obtained in the study where blending was done at 15-15%, and it was found that the material exhibited electrical insulating properties with 15% graphite level and showed 1.1 W/mK thermal conductivity.

Beside this, BN composites were particularly effective; 10 wt% BN raised conductivity to 1.05 W/mK while preserving electrical insulation, offering an optimal balance for electronics.

The mechanical performance results of the materials used as fillers also differed from each other. PC exhibited 73 MPa tensile strength and 5% elongation. Al_2O_3 and graphite composites were brittle, with elongation below 1%. Al_2O_3 and graphite hybrid composites showed moderate performance (27–35 MPa strength, 0.7–0.8% elongation). BN composites achieved 60–70 MPa tensile strength, 2–3.5% elongation, and moderate modulus improvement. These results confirm that filler choice is crucial to thermomechanical behaviour.

In summary, the investigation affirmed that loading and filler selectivity are very important considerations into thermomechanical performance in PC composites. While graphite has high thermal conductivity, its limitations are caused by concerns of conductivity. Al_2O_3 possesses structure strength properties that may be enough to reinforce composites. On the other hand Al_2O_3 has positive electrical insulating properties but its thermal conductivity has been found to be lower than BN and graphite. Also, it has been determined that hybrid samples, which combine the electrical insulating properties of Al_2O_3 and the high thermal conductive properties of graphite, provide optimum performance. By the way, BN has the best overall thermal, mechanical, and electrical performance in a composite. Notably, 10–15 wt% BN/PC composites showed suitable performance for laboratory and real-world applications, including in electronic devices, energy storage sources, and automotive parts.

These findings suggest that reinforcing BN or Al_2O_3-graphite blends with PC and by design principles with optimum filler compositions, effective thermal management materials can be produced from polymers. Future work should explore hybrid fillers and nanoscale modifications alongside BN loading, as these could offer further performance gains, valuable academic insights, industrial advancements, and improved end-user products.

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