Iranian Polymer Journal
https://doi.org/10.1007/s13726-026-01628-w

ORIGINAL RESEARCH

Graphene and zinc borate reinforced nanocomposites of recycled polypropylene: mechanical, tribological and dynamic mechanical properties

Beril Eker[1] · Okan Bakbak[2] · Besim Emre Birkan[2] · Münir Taşdemir[3]

Received: 28 May 2025 / Accepted: 6 January 2026
© Iran Polymer and Petrochemical Institute 2026, modified publication 2026

Abstract
Recycled polypropylene (RPP)-based nanocomposites reinforced with graphene (GNP) and/or zinc borate (ZB) were prepared with two different weight fractions (0.5 and 1). This study focused on RPP-based hybrid nanocomposites containing both GNP and ZB reinforcements, investigating their mechanical, thermal, and tribological properties. The hybrid nanocomposites were produced via twin-screw extrusion and injection moulding. Mechanical properties were evaluated through tensile, hardness, and Izod impact tests, while dynamic mechanical analysis (DMA) was performed to examine the storage modulus. Abrasion and friction tests were also conducted to assess tribological behaviour. Incorporation of ZB into RPP improved the elastic modulus by up to 62%, while yield strength increased by 10% compared to pure RPP. Slight enhancements in hardness and impact strength were also observed. Hybrid RPP-GNP-ZB nanocomposites exhibited higher stiffness and improved post-yielding behaviour than single-reinforced and pure RPP samples. DMA results indicated that GNP has a more pronounced effect on the storage modulus than ZB, and hybrid nanocomposites maintained improved thermo-mechanical performance up to 120 °C. Tribological tests demonstrated that higher reinforcement contents were associated with increased wear rates. Static and dynamic friction coefficients increased slightly with ZB and more notably with GNP. According to these findings, GNP and ZB reinforcements in recycled polypropylene measurably enhance mechanical and dynamic mechanical properties, highlighting the potential for high-performance polymer applications.

Keywords Recycled polypropylene · Graphene · Zinc borate · Mechanical properties · Tribological properties · Dynamic mechanical properties

Introduction

Recently, polymer nanocomposites have attracted considerable attention due to their advantages, including cost-effective manufacturing technologies, lightweight properties, ease of transportation, and the ability to meet diverse industrial requirements. From an energy consumption perspective, lightweight polymer composites provide lower transportation costs, vehicle fuel savings, and improved ergonomics in design. Primarily, PP-based materials are utilised in automotive components to achieve weight reduction and cost savings, with applications including bumper fascias, instrument panels, door trims, door panels, and pillars [1, 2]. Reducing resource consumption and waste not only preserves natural resources but also contributes to maintaining the world's ecological balance. Consequently, the use of recycled materials is crucial, and in this study, recycled polypropylene is employed as a matrix material to evaluate waste within the scope of sustainability. Utilising recycled materials conserves resources and supports the principles of a circular economy, thereby achieving long-term ecological and economic goals.

✉ Beril Eker
beker@yildiz.edu.tr

[1] Yıldız Technical University, Science and Technology Application and Research Center, 34200 Davutpaşa, Esenler, Istanbul, Turkey

[2] Department of Mechanical Engineering, Yıldız Technical University, 34349 Barbaros Bulvarı, Yıldız-Beşiktaş, Istanbul, Turkey

[3] Department of Metallurgical and Materials Engineering, Marmara University Faculty of Technology, 34722 Goztepe, Istanbul, Turkey

Published online: 02 March 2026

Beyond sustainability considerations, the performance of polymer composites can be further enhanced by incorporating various reinforcements, which enable the tailoring of mechanical, thermal, and functional properties according to specific application requirements [3, 4]. These reinforcements help overcome inherent limitations, such as brittleness, low thermal conductivity, and limited environmental resistance, and play a crucial role in designing multifunctional materials suitable for modern engineering applications, including those in the aerospace, automotive, and electronic industries.

Building upon these general concepts, specific nanofillers such as graphene and zinc borate can be employed to further enhance composite properties. Graphene has attracted considerable interest due to its exceptional mechanical, thermal, and electrical performance [5]. With its two-dimensional hexagonal lattice structure, graphene exhibits remarkable strength, including a Young's modulus of about 1 TPa and tensile strength around 130 GPa [6]. Based on its reliability and durability, it is an attractive subject of study in various research and application areas. According to the literature survey, the incorporation of graphene into the polymer matrix at low proportions enhances both the mechanical and thermal properties of the material. Moreover, a uniform dispersion of graphene within the polymer matrix leads to significant improvements in electrical performance [7], barrier and corrosion resistance [8], as well as rheological and mechanical behavior [9, 10] and time- and temperature-dependent viscoelastic responses such as creep and stress relaxation [11] in graphene-reinforced polymer composites. Its high surface area and two-dimensional layered structure enable effective load transfer and interfacial bonding, improving hardness and tensile strength even at low filler contents [12]. Graphene also enhances thermal conductivity and provides solid lubrication, resulting in reduced friction and improved tribological performance in both polymer and metal matrices [13]. Studies indicate that the optimum graphene content for hybrid composites typically lies between 1 and 3 wt%, beyond which agglomeration may reduce the reinforcement efficiency [14]. Zinc borate (ZB), with chemical formula $2ZnO{\cdot}3B_2O_3{\cdot}3.5H_2O$, is a commercially available white crystalline nanomaterial that is non-toxic, has anti-corrosive properties, low density, and is compatible with various polymers [15]. ZB is widely used as a flame retardant and smoke suppressant in polymeric materials, and it can enhance the thermal stability, mechanical strength, and toughness of epoxy composites. For example, incorporating 5 wt% ZB into epoxy has been shown to increase strength by 50% and raise the glass transition temperature from 52 to 71 °C [15]. In this study, graphene and ZB were employed as hybrid fillers to synergistically integrate the superior mechanical and thermal properties of graphene with the flame-retardant functionality of zinc borate.

The literature includes numerous studies on graphene-reinforced thermoplastic matrices. D.G. Papageorgiou et al. provided a comprehensive review of these publications [16]. These studies indicate that the addition of graphene fillers can significantly improve the tensile modulus and Young's modulus of polymer composites [17]. P. Song et al. prepared polypropylene nanocomposites by coating graphene sheets with PP latex followed by melt blending, achieving a well-dispersed graphene phase. Graphene loadings of 0.1, 0.5, 1, 2, and 5 wt% were tested, with 1 wt% providing the most significant improvements: the yield strength and Young's modulus of PP increased by approximately 75% and 74%, respectively, due to efficient load transfer. The incorporation of graphene also slightly increased the glass transition temperature and improved thermal oxidative stability, demonstrating that small amounts of well-dispersed graphene can effectively reinforce thermoplastic matrices [18]. MM Shokrieh and VA Joneidi produced polypropylene nanocomposites with graphene at 0.1, 0.5, and 2 wt%. Their tensile test results showed that the 0.5 wt% graphene specimens exhibited the highest yield strength and Young's modulus. Charpy impact tests also indicated that the impact strength was maximized at 0.5 wt% graphene. In addition to the experimental results, computational simulations based on a strain rate–dependent micromechanics model closely matched the observed mechanical behaviour. These findings demonstrate that even low graphene loadings can significantly enhance the tensile, modulus, and impact properties of polypropylene, and that computational models can reliably complement experimental results [1].

ZB is incorporated into polymer matrices primarily to modify physical properties, particularly due to its flame-retardant characteristics. According to the literature, zinc borate not only provides excellent flame retardancy but also enhances the mechanical properties of polymers [19–21]. N. S. Suharty et al. incorporated 20 wt% bentonite and 5 wt% zinc borate into recycled polypropylene (rPP). They reported a 62% increase in tensile strength and a 676% rise in Young's modulus compared to neat rPP. Additionally, flammability tests demonstrated a 703% improvement in time to ignition (TTI) and a 62% reduction in burning rate (BR). These enhancements were mainly associated with the exfoliation of bentonite within the rPP matrix and the flame-retardant contribution of zinc borate, which together improved the mechanical and fire-resistance properties of the composites [22]. F. You et al. investigated the effect of 0.6 wt% graphene nanosheets functionalized with polypropylene-graft-maleic anhydride (MAPP) and tryptophan on polypropylene. They observed a 20.8% improvement in tensile strength and a 44.6% increase in flexural modulus,

Table 1 Physical and mechanical properties of starting materials

Material	Density (g/cm^3)	MFR (g/10 min)	Melting point (°C)	Yield strength (MPa)	Hardness (MPa)	Particle size/thickness	Surface area (m^2/g)
RPP	0.965	5.5	147	28	69	–	–
ZB	0.4–0.6	–	–	–	–	3.2 µm	–
GNP	2.27	–	–	–	–	5 nm (thickness) 7 µm (diameter)	135

Table 2 Compositions of the RPP-based nanocomposites

Designation	RPP (wt%)	ZB (wt%)	GNP (wt%)
RPP	100	–	–
Z0.5	99.5	0.5	–
Z1	99	1	–
G0.5	99.5	–	0.5
G1	99	–	1
H0.5	99	0.5	0.5
H1	98	1	1

which was attributed to the effective dispersion of graphene within the polypropylene matrix and strong adsorption between graphene and functionalized PP chains. Utilising the interaction between graphene and functionalized PP is thus a facile method to enhance graphene dispersion in the PP matrix [23].

Additional studies on hybrid and natural fibre-reinforced polymer composites provide insights relevant to the reinforcement mechanisms, although conducted in different polymer matrices. For example, Shankarganesh et al. demonstrated that epoxy-based hybrid composites using Neem and Indian almond fibres improved tensile, flexural, and impact properties due to the strategic placement of high-strength fibres [24]. Manikanda Raja et al. demonstrated that the incorporation of graphene oxide (GO) and carbon nanotubes (CNTs) into polypropylene/epoxy hybrid composites improved their mechanical performance, wear resistance, and hardness through a one-step silane functionalization process [25]. Venkatesan et al. investigated natural fibre/epoxy composites with aluminium nitride, showing that microstructural optimisation via deep-dip coating improved both mechanical and tribological behaviour [26]. Padmavathy et al. reported that inorganic-organic nanocomposites incorporating Indian almond fiber, TiO_2, ZrO_2, and CNTs exhibited improved tensile, flexural, impact, and dynamic mechanical properties using silane dip-coating [27]. Finally, Kumar et al. found that rice husk fillers enhanced mechanical and tribological properties in hybrid fibre-reinforced epoxy composites, demonstrating the positive effect of agro-waste fillers on composite performance [28].

Despite the extensive use of polymer nanocomposites, RPP reinforced with GNP and ZB has not been systematically investigated to date. While GNP is well known for enhancing mechanical performance and ZB for providing flame retardancy, their combined effect within an RPP matrix remains unexplored. Overall, the literature indicates that although graphene and zinc borate individually improve mechanical and thermal properties in various polymer systems, no comprehensive study has examined their synergistic influence in recycled polypropylene. The present study therefore aims to develop lightweight and sustainable polymer nanocomposites with enhanced mechanical, dynamic-mechanical, and tribological performance. The novelty of this work lies in (i) introducing a hybrid reinforcement strategy by incorporating both GNP and ZB into recycled polypropylene and (ii) providing a comprehensive evaluation of the combined effect of these additives on the overall performance of RPP-based nanocomposites.

Experimental

Materials

In this study, recycled polypropylene (RPP, Moplen EP548P) was used as the matrix material, supplied by LyondellBasell Industries N.V. Zinc borate (ZB-4013, ZnO≥37%, B_2O_3≥45%) and graphene nanoplatelets (GNP) were used as reinforcements, supplied by Melos Kaucuk VE Plastik and Nanografi Nano Teknoloji, respectively. The main physical and mechanical properties of these starting materials are summarised in Table 1.

Sample preparation

Seven different polymer composites were prepared. Table 2 presents the compositions of polymer composites. The procedure for sample preparation is given below.

Initially, all materials were homogenised in an LB-5601 liquid–solids blender (The Patterson-Kelley Co., USA) for 15 min. The premixed powders were subsequently melt-compounded in a Mikrosan co-rotating twin-screw extruder (Microsan Instrument Inc., Turkey) under processing conditions of 30–40 bar pressure, a screw rotation speed of 50 rpm, and a barrel temperature profile of 200–230 °C. The obtained extrudates were oven-dried at 105 °C for 24 h and subsequently processed into test specimens using an

injection moulding machine at an injection temperature of 200–230 °C, an injection pressure of 110–120 bar, and a screw speed of 30 rpm.

Test procedure

All experiments, including tensile, hardness, impact, DMA, and tribological tests, were performed at least in triplicate for each sample, and the reported values correspond to the average of these measurements. This approach ensures the repeatability of the conducted experiments, as the observed trends were consistent across repeated tests. Although measurements were performed within the same laboratory and under controlled conditions, the experimental procedures followed standard protocols commonly reported in the literature, supporting the reproducibility of the results. Therefore, the presented data can be considered reliable and representative of the material behaviour.

Tensile test (ASTM D638)

Tensile tests were carried out in accordance with ASTM D638 specifications using an Instron universal testing machine (Instron, USA) with a load cell capacity of 100 kN.

Hardness test (ASTM D2240)

Hardness tests were carried out in accordance with ASTM D2240 using a Zwick hardness tester (Zwick/Roell, Germany).

Izod impact test (notched)

Notched Izod impact tests were performed at room temperature according to ASTM D256 using a Zwick B5113 impact testing device (Zwick, Ulm, Germany).

Dynamic mechanical analysis (DMA)

DMA was carried out to determine the storage modulus (E') and viscoelastic behaviour of the nanocomposites. Experiments were performed using a Perkin Elmer DMA-8000 dynamic mechanical thermal analyser over a temperature range of 20–160 °C. Test specimens measured 10.4 mm in length, 10 mm in width, and 4 mm in thickness. Single cantilever bending deformation was applied at a frequency of 1 Hz, with a heating rate of 5 °C/min and an oscillation stress of 0.05 MPa, thereby allowing the assessment of frequency- and temperature-dependent molecular rearrangements within the polymer matrix.

Static and dynamic coefficient of friction

Static and dynamic frictional properties of the nanocomposites were evaluated in accordance with ISO 8295 using Devotrans friction coefficient measurement equipment. Test specimens measured 80 × 200 × 4 mm, and sled specimens measured 63 × 63 × 4 mm. Friction tests were conducted at a speed of 100 mm/min under applied loads of 1.96, 2.94, 3.92, and 6.86 N. Each sample was tested twice to determine the static (μ_s) and dynamic (μ_D) friction coefficients, which were calculated using Eqs. 1 and 2, respectively.

$$\mu_s = \frac{F_s}{F_p} \tag{1}$$

$$\mu_D = \frac{F_D}{F_P} \tag{2}$$

Here μ_s represents the static coefficient of friction, F_s is the static frictional force (N), F_P denotes the normal force (N), μ_D corresponds to the dynamic coefficient of friction, and F_D is the dynamic frictional force.

Wear rate

The wear tests were performed in accordance with the DIN 53 516 standard using a Devotrans DA5 abrasion test device (Devotrans, Turkey). A 500-grit sandpaper, wrapped around a rotating cylinder, was employed as the abrasive element. During the test, the sandpaper abraded the polymer specimens at a constant rotational speed that did not cause heating, while compressed air was applied to remove adhered debris from the sandpaper surface. The test specimens were fabricated with a thickness of 7.0 mm and a diameter of 15.5 mm. The normal load (F_N) was set to 10 N (corresponding to 1 kg), and the cylinder rotational speed was maintained at 40 rpm. The total sliding distances (L) were 20, 40, 60, and 80 m. The friction coefficients and wear rates reported in this study represent the averages of three independent measurements. After the wear tests, the specific wear rate (Ws) was calculated using the following equation:

$$W_S = \frac{\Delta m}{\rho F_N L} \tag{3}$$

here Δm represents the mass loss, ρ denotes the material density, F_N is the applied normal load, and L corresponds to the total sliding distance.

Results and discussion

Mechanical properties

Stress–strain behaviours and mechanical properties of pure RPP and RPP-based nanocomposites containing ZB and graphene (GNP) at 0.5 and 1 wt% were obtained from tensile tests. For pure RPP, the notation RPP is used; for RPP-composites containing 0.5 and 1 wt% ZB, the notations Z0.5 and Z1 are employed, respectively; for RPP-nanocomposites containing 0.5 and 1 wt% GNP, the notations G0.5 and G1 are used; and for RPP-hybrid nanocomposites containing 0.5 and 1 wt% GNP and ZB, the notations H0.5 and H1 are adopted. Figure 1 presents the tensile true stress–strain behaviours of all composites, showing the effects of adding 0.5 and 1 wt% ZB and GNP, as well as their hybrid combinations, to pure RPP.

Figure 1a compares the results for 0.5 wt% reinforcement, while Fig. 1b compares the results for 1 wt% reinforcement.

As shown in Fig. 1, the overall material behaviour observed in RPP is approximately maintained in the Z0.5 and Z1 composites. Initially, the stress–strain response was nearly linear up to the onset of yielding. Beyond this point, a non-linear trend was detected, indicating post-yield behaviour. In RPP, a slight softening was observed after yielding, followed by strain hardening until fracture. Similar behaviour was noted in RPP-based nanocomposites; however, the softening behaviour was more pronounced, followed by a distinct strain hardening region. Furthermore, Fig. 1 illustrates that the incorporation of ZB and GNP at different weight fractions (wt%) enhances the tensile properties of the composites. In this study, the tensile behaviour of RPP-hybrid nanocomposites containing both ZB and GNP was systematically investigated. As illustrated in Fig. 1, H0.5 and H1 hybrid nanocomposites containing both ZB and GNP exhibited stress–strain behaviour similar to that of RPP. Compared to RPP, these hybrid nanocomposites exhibited noticeable improvements in both the elastic region and post-yield behaviour, including distinct strain softening and strain hardening zones, which reflect enhanced mechanical properties. H0.5 and H1 hybrid nanocomposites exhibited higher elastic modulus than pure RPP and G0.5, though Z0.5 showed the highest modulus. In terms of yield strength, H1 was the highest overall, while H0.5 exceeded RPP and G0.5 and was comparable to Z0.5. To further clarify the effects of reinforcement, Fig. 1 also compares the stress–strain responses of RPP-nanocomposites and RPP-hybrid nanocomposites with equivalent reinforcement weight fractions to the control RPP.

As depicted in Fig. 1, Z0.5–Z1 composites exhibited superior tensile performance compared to RPP and G0.5–G1 nanocomposites. In particular, the Z0.5 composite demonstrated enhanced mechanical properties across the elastic region (elastic modulus), yield region (yield strength), and strain hardening region. Moreover, RPP-hybrid nanocomposites outperformed RPP-GNP nanocomposites at both reinforcement weight fractions. These results indicate that the incorporation of ZB and GNP effectively improved the tensile characteristics of RPP.

The elasticity modulus, presented in Fig. 2, was determined from the slope of the initial linear portion of the stress–strain curve, while the yield strength, shown in Fig. 3, corresponds to the maximum stress prior to plastic deformation. Both parameters were extracted from the acquired stress–strain data.

The elasticity modulus of RPP was 967 MPa. The addition of reinforcements increased the elasticity modulus for all the composites and nanocomposites. The maximum modulus was obtained by adding 0.5 wt% ZB to pure RPP, resulting in a 62% improvement. It is evident that the stiffness of RPP also increases with GNP and hybrid (ZB + GNP) reinforcement. Although the elasticity modulus of G0.5 nanocomposites is higher than that of RPP, it remains lower than that of H0.5-H1 hybrid nanocomposites; however, this difference is still moderate. This may be attributed to the better structural compatibility of ZB with the RPP

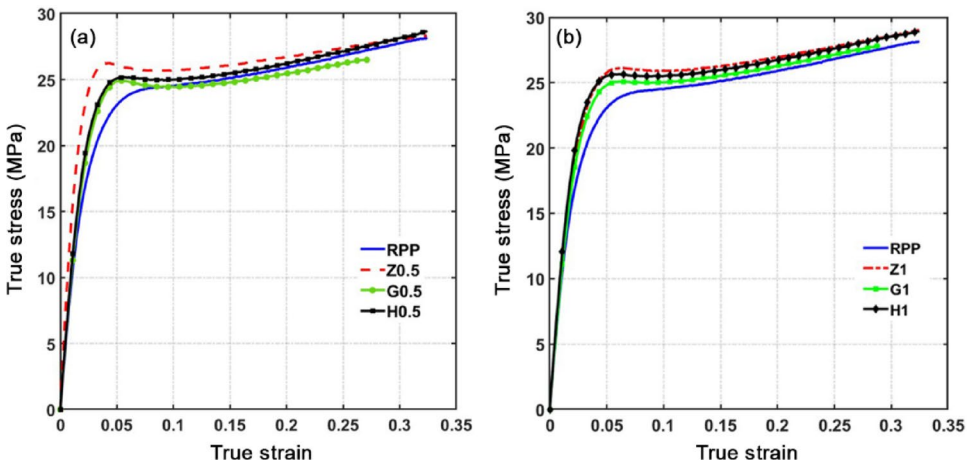


Fig. 1 The true stress-strain behaviours of RPP nanocomposites and RPP-hybrid nanocomposites with the same weight fraction of reinforcements were compared to that of pure RPP: (**a**) 0.5 wt% reinforcements, and (**b**) 1 wt% reinforcements

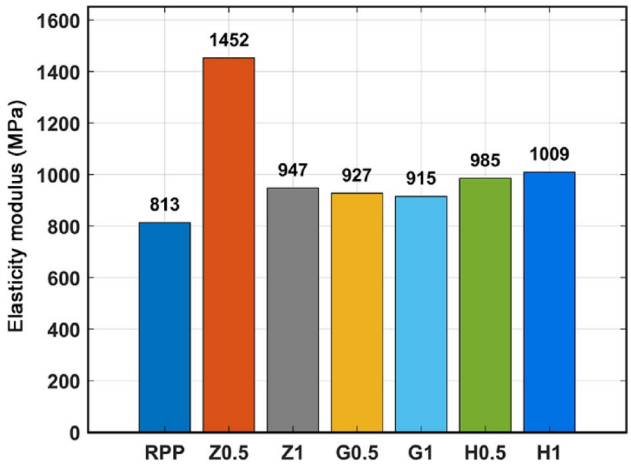


Fig. 2 The elasticity modulus obtained from the tensile test for RPP and the produced composites and nanocomposites

matrix and the enhanced load transfer mechanism resulting from increased interfacial interaction [29]. In general, the reinforcement elements added to RPP created cross-linking points, which acted as a barrier by restricting molecular chain mobility and contributed to the improvement in modulus [30].

Figure 3 presents the variations in mechanical properties, including yield strength, tensile strength, and elongation-at-break, as derived from the stress–strain data obtained during the tensile tests.

The yield strength of RPP, initially 17.87 MPa, increased by approximately 10.4% and 10.6% with the addition of ZB at 0.5 and 1 wt%, respectively. For GNP-reinforced nanocomposites, the corresponding increases were 8.11% and 6.93% at 0.5 and 1 wt%. Although the tensile strength of RPP-based nanocomposites generally increased, the enhancements were relatively modest compared to RPP. While the tensile strength of neat RPP was 28.16 MPa, the highest value of 29.39 MPa was observed in RPP-ZB composites containing 1 wt% ZB, representing a 4.36% improvement. These slight increases in strength can be attributed to the relatively strong interfacial bonding between ZB and GNP with the RPP matrix [31].

The improvement in tensile strength was less pronounced than that of the elastic modulus, which can be attributed to stronger interactions between RPP and the reinforcement elements in the linear elastic region, as well as to the adverse effects of interfacial interactions at higher stress levels [21]. Although reinforcement generally enhanced all mechanical properties, the smallest improvements were observed in G0.5–G1 nanocomposites. A slight deterioration in material behaviour with increasing GNP content may be attributed to the tendency of graphene to agglomerate due to inherent Van der Waals interactions [5]. Higher GNP loadings can lead to clustering and reduced reinforcement efficiency, potentially weakening the interfacial interactions between GNP and the RPP matrix. The presence of ZB in H0.1–H0.5 hybrid nanocomposites compensated for this effect, resulting in improved mechanical behaviour compared to G0.5–G1 nanocomposites. Furthermore, increasing the GNP content reduced the elongation-at-break of RPP, indicating that the

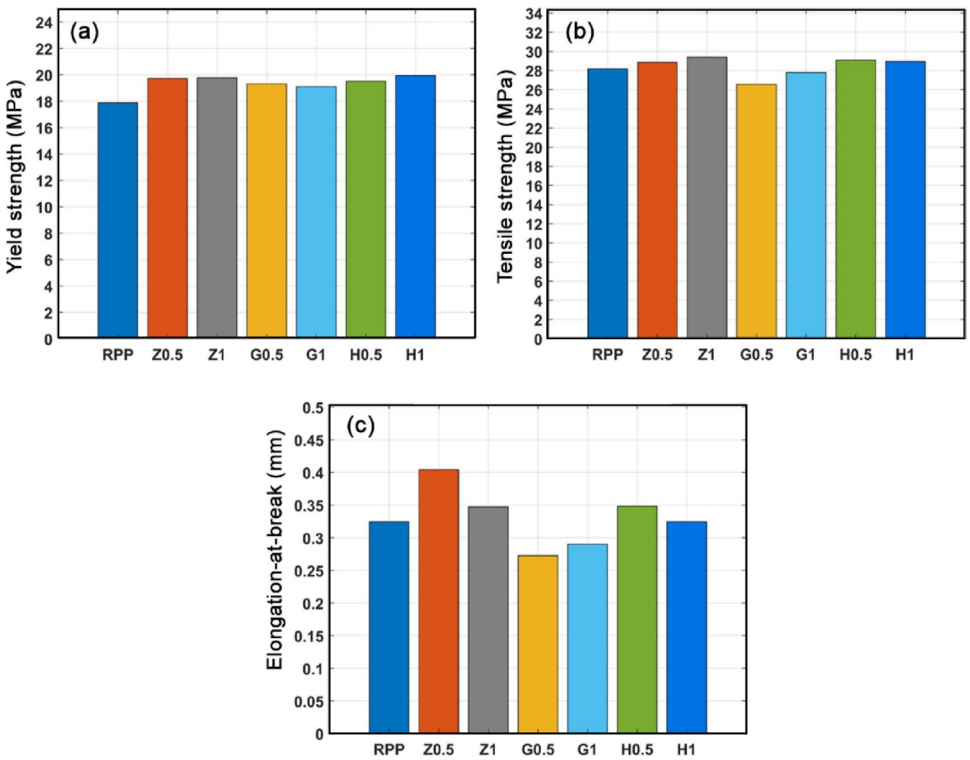


Fig. 3 Mechanical properties (yield strength, tensile strength and elongation-at-break) obtained from the tensile test for RPP and the RPP nanocomposites

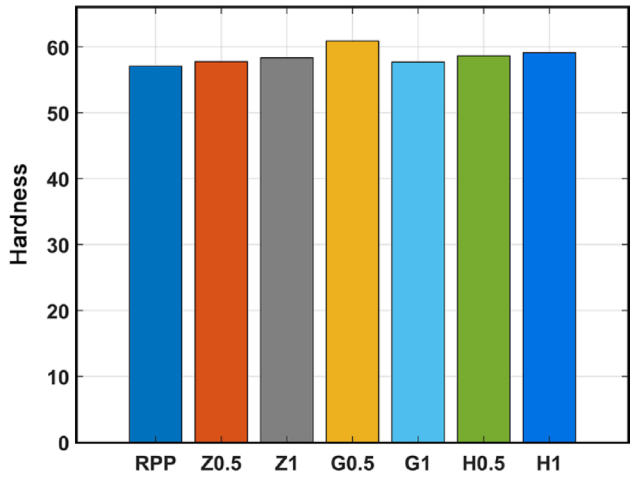


Fig. 4 Hardness values for all specimens

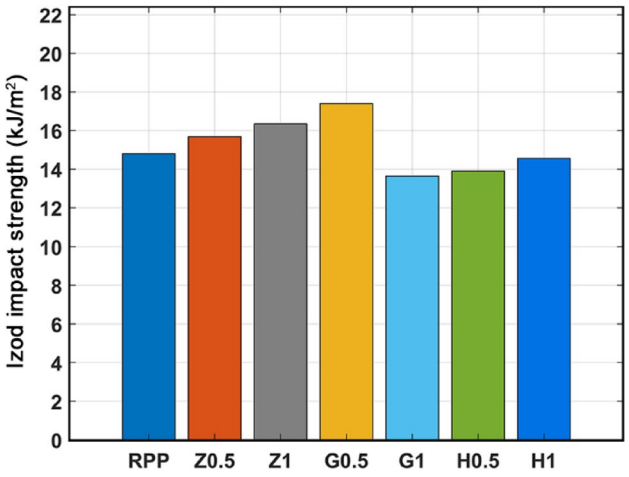


Fig. 5 Impact strength values for all the groups

addition of GNP rendered G0.5–G1 nanocomposites more brittle than other nanocomposites and neat RPP [32]. Overall, the results demonstrate that the combined incorporation of ZB and GNP enhances the tensile properties of RPP, and that both the production method and reinforcement content are critical factors influencing performance.

Hardness

The hardness values of composite samples produced with different amounts of reinforcement and pure RPP are presented in Fig. 4. The hardness of pure RPP was 57.08, whereas for Z0.5, Z1, G0.5 and G1, the hardness values were measured as 57.75, 58.35, 60.9, and 57.7, respectively. Additionally, for H0.5 and H1, the hardness values were measured as 58.65 and 59.1. Although adding the reinforcements enhances the hardness values, the G0.5 nanocomposite has the highest improvement.

The addition of ZB led to only a slight increase in hardness, which can be considered negligible. This limited improvement may be attributed to the partial precipitation of ZB particles within the polymer matrix, causing a minor densification effect. Similar observations were reported by Badritala et al. [33]. Researchers found that ZB treatment had no significant impact on the hardness of wood flour/PP composites, with minor changes attributed to the deposition of zinc borate salts in the cell walls and voids. On the other hand, the incorporation of GNPs resulted in a more pronounced improvement in hardness. This enhancement is consistent with the findings of Ulutas and Tasdemir [34], who reported that GNP positively affects the hardness of polymer matrices, and also with the study by Mindivan [35], who attributed the improvement to the high strength and rigidity of GNP. Moreover, the nucleation sites introduced by GNP facilitate polymer crystallisation, induce changes in the crystalline structure, and ultimately lead to an increase in hardness [36, 37]. As a result, the highest improvement was observed in the composite reinforced with 0.5 wt% GNP.

Impact

Figure 5 presents the impact test results of pure RPP and RPP-based nanocomposites with different reinforcement contents. The impact strength of pure RPP was 14.8 kJ/m^2, while for the composites Z0.5, Z1, G0.5, G1, H0.5, and H1, the values were 15.68 (6% rise), 16.34 (10.4% increase), 17.4 (17.6% enhancement), 13.64 (7.8% reduction), 13.9 (6.1% decrease), and 14.56 kJ/m^2 (1.6% decrease), respectively.

The incorporation of ZB reinforcement led to an improvement in the impact strength of RPP. This enhancement can be attributed to the ability of ZB particles to act as micro-reinforcements within the matrix, which may promote better energy absorption during crack initiation and propagation. A similar trend was reported by Mapossa et al. [38], who observed that the addition of ZB to polypropylene-based composites helped maintain or slightly improve notched impact strength, even when significant amounts of flame retardants were incorporated. In the case of GNP reinforcement, the incorporation of 0.5 wt% GNP resulted in an improvement in impact strength compared to pure RPP. This enhancement can be attributed to the high mechanical strength and low density of GNP, which enables it to act as an efficient reinforcing element within the polymer matrix [39]. However, when the GNP content was increased to 1 wt%, a decrease in impact strength was observed. As highlighted by Ulutas and Tasdemir [34], this reduction can be attributed to the tendency of GNP to agglomerate at higher concentrations, resulting in the formation of crack-initiating regions within the polymer matrix.

Dynamic mechanical analysis (DMA)

The storage modulus of RPP and RPP-based nanocomposites containing 0.5 and 1 wt% of ZB and GNP was determined using DMA. In polymeric materials, the storage modulus reflects the elastic response and represents the material's ability to store energy. The temperature-dependent variation of the storage modulus for RPP, Z0.5–Z1 composites, and G0.5–G1 nanocomposites is presented comparatively in Fig. 6a and b. Additionally, the changes in storage modulus for H0.5–H1 hybrid nanocomposites containing ZB and GNP at the same weight fractions, relative to RPP, are illustrated in Fig. 6c.

When the results in Fig. 6 are examined, it is observed that both RPP and RPP nanocomposites exhibit a similar trend in the temperature-dependent storage modulus behaviour, with the storage modulus decreasing as the temperature increases. Depending on the elevated temperature, the increase in polymer chain mobility has a negative effect on the properties [11]. Increasing temperature enhances the viscosity and flexibility of the polymer, resulting in reduced viscoelastic properties. Thermal motion of polymer chains may further disrupt molecular arrangements, leading to a decrease in storage modulus. Consequently, the storage modulus of polymers and polymer composites generally declines with increasing temperature [40].

At 26 °C (close to room temperature), the storage modulus of neat RPP was measured as 527 MPa. The addition of 0.5 wt% GNP or ZB did not produce a significant change, whereas a slight increase was observed for 1 wt% GNP, while ZB supplementation had minimal effect. Storage modulus also increased for the H0.5 hybrid nanocomposite up to 120 °C; at 26 °C, it reached 545 MPa. This modest enhancement can be attributed to the stiffening effect of GNP, which restricts the mobility of polymer chains and improves the overall rigidity of the nanocomposite. GNP, being one of the hardest known materials, acts as a barrier to the mobility of RPP molecular chains, thereby enhancing stiffness. Although 0.5 wt% ZB initially increased the storage modulus, its decline with rising temperature was greater than that of neat RPP, likely due to weaker interfacial interactions between ZB and the RPP matrix. Strong interfacial bonding, as provided by GNP, facilitates effective load transfer and positively influences the enhancement of material properties [40, 41]. The reduction in storage modulus observed with increasing ZB content was not evident in GNP-reinforced nanocomposites. Higher GNP loadings resulted in increased storage modulus across the temperature range (Fig. 6d).

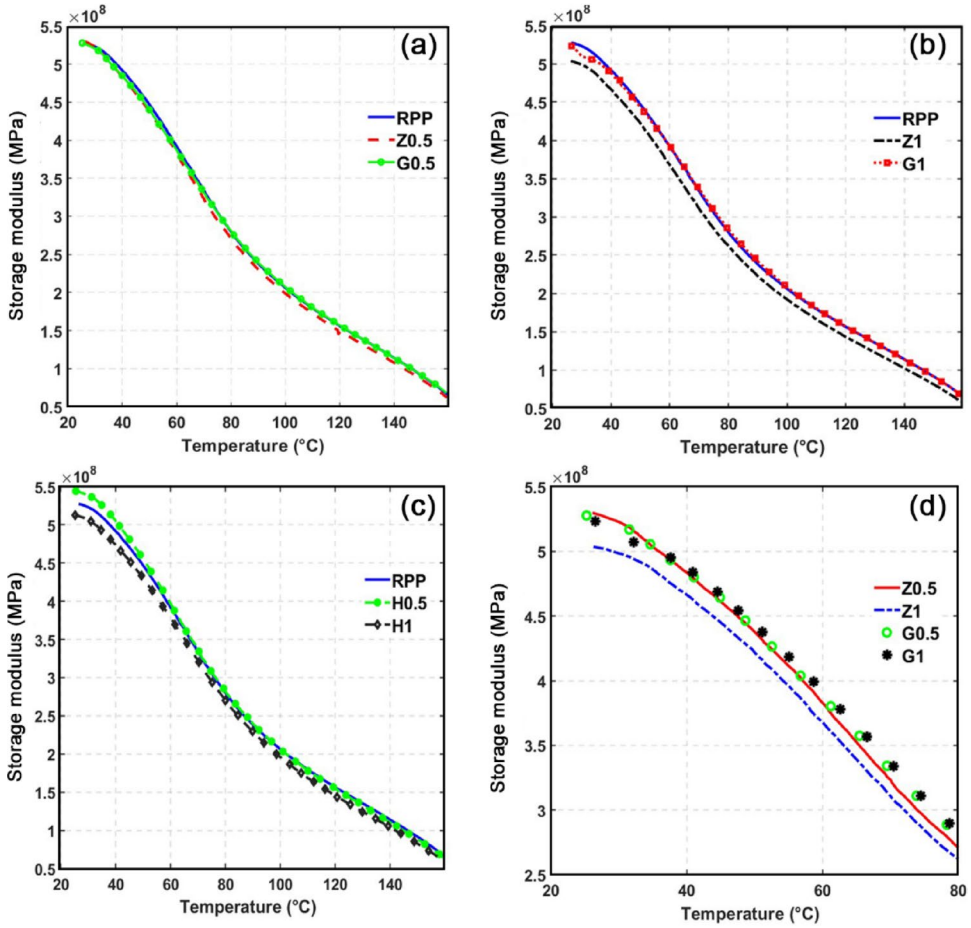


Fig. 6 Temperature-dependent changes of storage modulus of RPP and G0.5-G1 and Z0.5-Z1

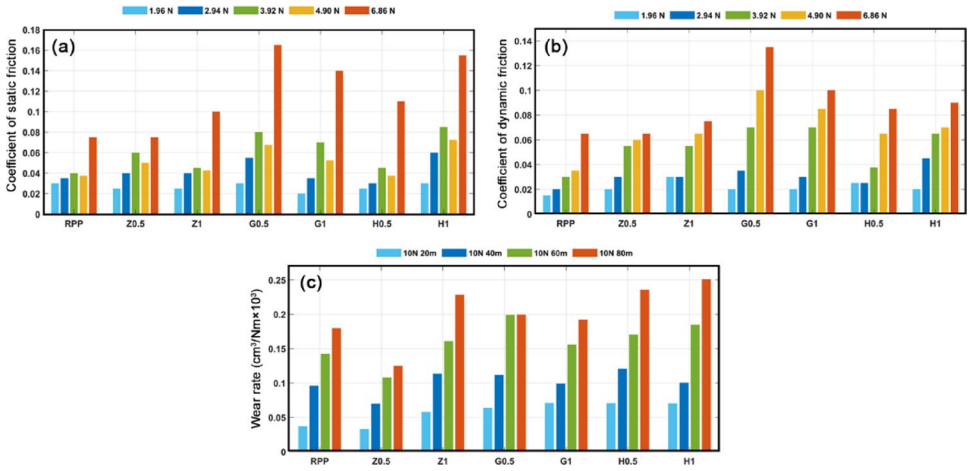


Fig. 7 (**a**) Static friction coefficients of RPP nanocomposites as a function of applied load, (**b**) dynamic friction coefficients of RPP nanocomposites as a function of applied load, and (**c**) wear rates of RPP nanocomposites with respect to sliding distance and applied load

For instance, at 60 °C, nanocomposites containing 0.5 and 1 wt% GNP exhibited storage modulus values of 386 and 392 MPa, respectively, whereas the corresponding values for ZB-reinforced nanocomposites were 380 and 368 MPa. The results indicate that GNP supplementation has a more pronounced effect on the thermo-mechanical properties than ZB, consistently enhancing the storage modulus across the entire temperature range. Although the improvements from additive incorporation are modest, they are promising. Functionalization of the additives could further strengthen interfacial bonding between the RPP matrix and reinforcement elements, potentially yielding greater enhancements [11]. The promising performance of the H0.5 hybrid nanocomposite, even with unmodified additives, suggests that the storage modulus of neat RPP can be effectively enhanced by maintaining a low ZB content and a higher GNP content, thereby improving interfacial interactions. This finding further highlights the potential for achieving significant improvements in storage modulus.

Friction coefficients of the nanocomposites

The coefficient of friction is a dimensionless scalar quantity and can be defined as the ratio of the frictional force between two surfaces to the normal force applied. Figure 7a and b present the static and dynamic friction coefficients for various specimens under sliding load. The results indicate that the applied load has a significant effect on both static and dynamic friction coefficients, with higher loads generally leading to increased values. However, the observed differences in tribological behaviour are not solely attributed to the applied load; the interfacial bonding between the RPP matrix and the fillers, which varies with filler content, also plays a critical role.

The incorporation of ZB into RPP slightly increases both static and dynamic friction coefficients, likely due to changes in surface roughness, filler–matrix interactions, and microstructural effects.

GNP, renowned for its exceptional hardness and unique surface properties, further enhances these coefficients by increasing surface roughness and energy absorption of the matrix. The highest static and dynamic friction coefficients were observed for RPP containing 0.5 wt% GNP; however, increasing the GNP content to 1 wt% resulted in a decrease in both coefficients relative to the 0.5 wt% level.

Wear properties of the nanocomposites

Wear rates of the nanocomposites were evaluated at sliding distances of 20, 40, 60, and 80 m under a 10 N load. As the sliding distance increased, the wear rate also increased. As shown in Fig. 7c, H1 hybrid nanocomposites exhibited the highest wear rates, while the lowest values were observed for Z0.5 composites. These results indicate that the incorporation of 0.5 wt% ZB improves the wear resistance of RPP. In contrast, higher concentrations of ZB and GNP led to increased wear rates, which may be attributed to the weakening of interfacial bonding between the reinforcements and the RPP matrix. Specifically, excessive reinforcement content can adversely affect the filler–matrix interactions, thereby reducing wear resistance.

Conclusion

This study evaluates the mechanical, dynamic-mechanical (DMA), and tribological properties of RPP reinforced with ZB, GNP, and a ZB-GNP hybrid. The key findings are:

Both ZB and GNP improved the tensile properties, including tensile modulus, yield strength, and tensile strength. ZB exhibited a greater enhancement than GNP. It provided greater stiffness and yield by transferring load effectively to the RPP matrix. For Z0.5, the elastic modulus increased

by 62% and the yield strength improved by 10% compared with pure RPP. Z1 had the highest tensile strength at 29.39 MPa, which is a 4.4% increase. In contrast, RPP-GNP nanocomposites exhibited lower elongation-at-break. Hardness increased slightly with the addition of filler, consistent with the trend of tensile stiffening. Compared to the hardness value of RPP, it was found that this value increased by 6.7% and peaked at G0.5. This peak is attributed to the 0.5 wt% GNP, providing effective nucleation and added rigidity. Impact strength peaked at G0.5, reaching approximately 17.4 kJ/m^2, which is about 17.6% higher than pure RPP at 14.8 kJ/m^2. This behaviour is consistent with a low, well-dispersed GNP content, which promotes crack deflection and greater energy absorption. Storage modulus increased in filled composites, peaking at H0.5 hybrids, indicating enhanced interfacial interaction and more effective load transfer across a wide temperature range. Increasing filler content raises asperity interactions (ploughing/adhesion), thereby increasing the wear rate. Static and dynamic friction coefficients rose slightly with ZB and more notably with GNP, peaking at G0.5. Furthermore, the incorporation of limited amounts of GNP and ZB did not significantly impact the overall material costs.

Acknowledgements This work has been supported by Yıldız Technical University Scientific Research Projects Coordination Unit (BAP) under Project number FBA-2021-4551. The authors gratefully thank YTU BAP for providing financial support in preparing this research.

Author contributions All authors accept responsibility for the complete content of this manuscript and have confirmed their approval for its submission. Beril Eker: Writing-review & editing, Writing-original draft, Project administration, Visualisation, Methodology, Investigation, Supervision, Conceptualisation; Okan Bakbak: Writing-review & editing, Writing-original draft, Visualisation, Methodology, Investigation, Conceptualisation; Besim Emre Birkan: Writing-review & editing, Writing-original draft, Visualisation, Methodology, Investigation, Conceptualisation; Münir Taşdemir: Writing-review & editing, Writing-original draft, Methodology, Visualisation, Investigation, Supervision, Conceptualisation.

Data availability All raw data obtained from the testing devices in the study are included in the article. For any additional inquiries, please contact the corresponding author.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work presented in this paper. The research was conducted independently, and all findings are presented in accordance with high academic and ethical standards.

References

1. Shokrieh M, Joneidi V (2015) Characterization and simulation of impact behavior of graphene/polypropylene nanocomposites using a novel strain rate–dependent micromechanics model. J Compos Mater 49:2317–2328. https://doi.org/10.1177/0021998314545191
2. Moritomi S, Watanabe T, Kanzaki S (2010) Polypropylene compounds for automotive applications. Sumitomo Kagaku 1:1–6
3. Akçay SB, Kocaman M, Çelebi M (2024) Surface modification for improving interfacial, mechanical and thermal performance characteristics in epoxy composites: Electroless nickel enhancement of dendritic copper particle-reinforced epoxy. Surf Coat Technol 478:130417. https://doi.org/10.1016/j.surfcoat.2024.130417
4. Keleş A, Karabudak F, Acar V (2025) Corrosion and structural properties of lightweight magnesium and aluminum alloy cores based sandwich composites. Polym Compos 2025:29889. https://doi.org/10.1002/pc.29889
5. Colak OU, Birkan B, Bakbak O (2023) Functionalized graphene–epoxy nanocomposites: experimental investigation of viscoelastic and viscoplastic behaviors. Mech Time-Depend Mater 27:185–205. https://doi.org/10.1007/s11043-021-09530-z
6. Çelebi M, Çanakçı A, Özkaya S (2025) Effect of mechanical milling time on powder characteristic, microstructure, and mechanical properties of AA2024/B4C/GNPs hybrid nanocomposites. Powder Technol 449:120439. https://doi.org/10.1016/j.powtec.2024.120439
7. Eda G, Chhowalla M (2009) Graphene-based composite thin films for electronics. Nano Lett 9:814–818. https://doi.org/10.1021/nl8035367
8. Chang CH, Huang TC, Peng CW (2012) Novel anticorrosion coatings prepared from polyaniline/graphene composites. Carbon 50:5044–5051. https://doi.org/10.1016/j.carbon.2012.06.043
9. Bafana AP, Yan X, Wei X (2017) Polypropylene nanocomposites reinforced with low weight% graphene nanoplatelets. Compos Part B 109:101–107. https://doi.org/10.1016/j.compositesb.2016.10.048
10. Quiles-Díaz S, Enrique-Jimenez P, Papageorgiou DG (2017) Influence of the chemical functionalization of graphene on the properties of polypropylene-based nanocomposites. Compos Part A 100:31–39. https://doi.org/10.1016/j.compositesa.2017.04.019
11. Birkan BE, Bakbak O, Colak O, Acar A (2023) Time-dependent thermo-mechanical behavior of graphene epoxy nanocomposites: creep, relaxation, compression. J Compos Mater 57:3449–3462. https://doi.org/10.1177/00219983231186462
12. Çelebi M, Çanakçı A, Özkaya S (2025) Comparative study of powder characteristics and mechanical properties of Al2024 nanocomposites reinforced with carbon-based additives. Adv Powder Technol 36:104835. https://doi.org/10.1016/j.apt.2025.104835
13. Çelebi M, Çanakçi A, Güler O (2023) Study on effect of milling time on the mechanical and wear properties of the ZA40-B4C-graphene hybrid nanocomposites fabricated by vacuum hot-pressing. JOM 75:3935–3950. https://doi.org/10.1007/s11837-023-06007-x
14. Çanakçı A, Çelebi M (2024) Determination of nano-graphene content for improved mechanical and tribological performance of Zn-based alloy matrix hybrid nanocomposites. J Alloys Compd 1001:175152. https://doi.org/10.1016/j.jallcom.2024.175152
15. Kabakçı G, Caner S, Yıldırım C (2025) A detailed investigation into the curing kinetics of zinc borate-epoxy composites. Solid State Sci 165:107926. https://doi.org/10.1016/j.solidstatesciences.2025.107926

16. Kausar A, Rafique I, Muhammad B (2017) Aerospace application of polymer nanocomposite with carbon nanotube, graphite, graphene oxide, and nanoclay. Polym-Plast Technol Eng 56:1438–1456. https://doi.org/10.1080/03602559.2016.1276594
17. Papageorgiou DG, Kinloch IA, Young RJ (2017) Mechanical properties of graphene and graphene-based nanocomposites. Prog Mater Sci 90:75–127. https://doi.org/10.1016/j.pmatsci.2017.07.004
18. Song P, Cao Z, Cai Y et al (2011) Fabrication of exfoliated graphene-based polypropylene nanocomposites with enhanced mechanical and thermal properties. Polymer 52:4001–4010. https://doi.org/10.1016/j.polymer.2011.06.045
19. Fang Y, Wang Q, Guo C et al (2013) Effect of zinc borate and wood flour on thermal degradation and fire retardancy of Polyvinyl chloride (PVC) composites. J Anal Appl Pyrolsis 100:230–236. https://doi.org/10.1016/j.jaap.2012.12.028
20. Güldaş A, Çankaya A, Güllü A, Gürü M (2014) ÇİNko borat katkili polİpropİlen'İn reolojİk özellİklerİnİn belİrlenmesİ. Gazi Üniversitesi Mühendislik-Mimarlık. Fakültesi Dergisi 29:24326. https://doi.org/10.17341/gummfd.24326
21. Feng C, Zhang Y, Liang D (2015) Influence of zinc borate on the flame retardancy and thermal stability of intumescent flame retardant polypropylene composites. J Anal Appl Pyrolsis 115:224–232. https://doi.org/10.1016/j.jaap.2015.07.019
22. Suharty NS, Ismail H, Wibowo FR (2015) Effect of bentonite and zinc borate (zb) addition on recycled polypropylene composites against tensile and burning rate properties. Adv Mater Res 1105:56–61. https://doi.org/10.4028/www.scientific.net/AMR.1105.56
23. You F, Wang D, Li X (2014) Interfacial engineering of polypropylene/graphene nanocomposites: improvement of graphene dispersion by using tryptophan as a stabilizer. RSC Adv 4:8799–8807. https://doi.org/10.1039/C3RA47112H
24. Shankarganesh PSP, Muralikannan R, Selvabharathi R, Karuppasamy R (2019) Investigation of tensile, flexural and impact properties of Neem-Indian almond hybrid fiber based epoxy composites. Mater Res Express 6:085322. https://doi.org/10.1088/2053-1591/ab20f7
25. Raja GM, Vasanthanathan A, Selvabharathi R (2023) Effect of one-step dipping coating process on microstructure and tribology of polypropylene/graphene oxide/carbon nanotube nanocomposites. Iran Polym J 32:739–748. https://doi.org/10.1007/s13726-023-01161-0
26. Venkatesan G, Selvabharathi R, Kulathuraan K, Vivek V (2024) Influence of microstructure and tribology properties on deep-dipping coating method of sappanwood (SW)/ polyvinyl alcohol (PVA)/ Polyethylene (PE)/ Aluminium nitride (AlN) natural fiber nanocomposite materials. J Polym Res 31:299. https://doi.org/10.1007/s10965-024-04151-9
27. Padmavathy S, Ramya G, Selvabharathi R (2024) Effect on one-type dipping coating method of microstructure and physical properties of Indian almond fiber (IAF)/titanium oxide (TiO_2)/zirconium oxide (Zr_2O_3)/carbon nanotube (CNT) inorganic-organic nanocomposite materials. Biomass Conv Bioref 14:31561–31573. https://doi.org/10.1007/s13399-023-04983-3
28. Kumar S, Mer KKS, Gangil B, Patel VK (2019) Synergy of rice-husk filler on physico-mechanical and tribological properties of hybrid Bauhinia-vahlii/sisal fiber reinforced epoxy composites. J Mater Res Technol 8:2070–2082. https://doi.org/10.1016/j.jmrt.2018.12.021
29. Wang J, Song F, Ding Y, Shao M (2020) The incorporation of graphene to enhance mechanical properties of polypropylene self-reinforced polymer composites. Mater Des 195:109073. https://doi.org/10.1016/j.matdes.2020.109073
30. Ahmad SR, Xue C, Young RJ (2017) The mechanisms of reinforcement of polypropylene by graphene nanoplatelets. Mater Sci Eng B 216:2–9. https://doi.org/10.1016/j.mseb.2016.10.003
31. Papageorgiou DG, Kinloch IA, Young RJ (2016) Hybrid multifunctional graphene/glass-fibre polypropylene composites. Compos Sci Technol 137:44–51. https://doi.org/10.1016/j.compscitech.2016.10.018
32. Liang JZ, Du Q, Tsui GCP, Tang CY (2016) Tensile properties of graphene nano-platelets reinforced polypropylene composites. Compos Part B 95:166–171. https://doi.org/10.1016/j.compositesb.2016.04.011
33. Badritala A, Hosseini Hashemi SK, Kord B (2013) Morphology and mechanical properties of zinc borate-pretreated poplar wood flour/plastic composite. BioResources 8:913–922. https://doi.org/10.15376/biores.8.1.913-922
34. Ulutas E, Tasdemir M (2024) Engineering the microstructure: unveiling the synergistic effects of GnP and blowing agents on PA6 composite foams. Mater Today Commun 41:110995. https://doi.org/10.1016/j.mtcomm.2024.110995
35. Mindivan F (2017) Effect of graphene nanoplatelets (GNPs) on tribological and mechanical behaviors of polyamide 6 (PA6). Tribol Ind 39:277–282. https://doi.org/10.24874/ti.2017.39.03.01
36. Chatterjee S, Nüesch FA, Chu BTT (2013) Crystalline and tensile properties of carbon nanotube and graphene reinforced polyamide 12 fibers. Chem Phys Lett 557:92–96. https://doi.org/10.1016/j.cplett.2012.11.091
37. Shin MK, Lee B, Kim SH (2012) Synergistic toughening of composite fibres by self-alignment of reduced graphene oxide and carbon nanotubes. Nat Commun 3:650. https://doi.org/10.1038/ncomms1661
38. Mapossa AB, Dos Anjos EGR, Sundararaj U (2024) Boosting flame retardancy of polypropylene/calcium carbonate composites with ınorganic flame retardants. Materials 17:4553. https://doi.org/10.3390/ma17184553
39. Sutar H, Mishra B, Senapati P (2021) Mechanical, thermal, and morphological properties of graphene nanoplatelet-reinforced polypropylene nanocomposites: effects of nanofiller thickness. J Compos Sci 5:24. https://doi.org/10.3390/jcs5010024
40. Bakbak O, Colak O (2024) Experimental investigation of the effect of functionalized graphene on the creep behavior of epoxy. J Reinf Plast Compos 43:1133–1150. https://doi.org/10.1177/07316844231201281
41. Feng QP, Shen XJ, Yang JP (2011) Synthesis of epoxy composites with high carbon nanotube loading and effects of tubular and wavy morphology on composite strength and modulus. Polymer 52:6037–6045. https://doi.org/10.1016/j.polymer.2011.10.049

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.