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The effect of waste tire granules on the properties of polyethylene terephthalate thermoplastic

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Abstract. The utilization of waste tire granules (WTG) as a reinforcing agent in polyethylene terephthalate (PET) offers a sustainable approach to enhancing thermoplastic composites. PET is known for its recyclability, while WTG provides a solution for waste tire management. This study examines the effect of WTG content and particle size on PET/WTG composites. Scanning Electron Microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR) were used to analyze the composites' morphology and chemical composition. Mechanical tests evaluated elongation and impact performance with WTG incorporation. SEM showed a compatible morphology between the PET matrix and WTG. FTIR spectra displayed characteristic vibrations of polyisoprene from WTG and PET-specific functional groups. The inclusion of WTG significantly improved mechanical properties that leads to enhanced elongation at break (EB) and increased ductility. Impact strength also improved notably at 10% WTG. These findings demonstrate the potential of WTG as a filler to enhance PET mechanical properties and contribute to sustainable waste management as well as the development of value-added products from recycled materials.

1 Introduction

The growing concern for environmental sustainability has led to increased interest in recycling and reusing materials that would otherwise contribute to waste. Polyethylene Terephthalate (PET), commonly used in plastic bottles and packaging is one such material known for its recyclability and durability. PET can be reused making it a key player in the development of eco-friendly materials. As global plastic consumption rises, so does the need for effective recycling methods to mitigate environmental pollution and conserve resources.

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PET thermoplastic properties allow it to be melted down and reformed multiple times without significant degradation making it an ideal candidate for sustainable material innovations [1]. However, another significant environmental challenge is the disposal of waste tires. Millions of tires are discarded each year, creating severe environmental problems due to their non-biodegradable nature. Tires are composed of complex materials designed for durability which makes them resistant to natural decomposition processes [2]. This durability, while beneficial for their intended use, poses a substantial disposal problem. Waste tires often end up in landfills or are incinerated both of which have negative environmental impacts. Finding innovative ways to recycle waste tires is crucial for reducing their environmental footprint and transforming a waste problem into a resource opportunity.

One promising solution is to use waste tire granules (WTG) as a reinforcing agent in PET thermoplastics. By incorporating WTG into PET, it is possible to create a composite material that not only recycles waste tires but also enhances the properties of PET. This approach addresses two major environmental issues by reducing plastic waste and finding a sustainable use for discarded tires. WTG derived from the shredding and granulating of used tires can be mixed with PET to form a composite with improved mechanical properties. This method not only diverts tires from landfills but also adds value to recycled PET products by enhancing their performance, thus creating a win-win situation for both waste management and material engineering [3].

Research has shown that adding fillers to polymers can improve their mechanical properties. WTGs, which are rich in polyisoprene, have the potential to enhance the strength and durability of PET composites. Polyisoprene, a major component of rubber, provides elasticity and toughness, which can be beneficial when integrated into PET matrices. Previous studies have explored various fillers such as glass fibers, carbon black, and natural fibers but the use of WTG in PET composites is a relatively new area of research with promising results [4]. The unique properties of rubber such as its flexibility and resilience can impart desirable characteristics to the composite material. This approach will lead to applications in areas where enhanced mechanical performance is crucial [5].

This study aims to investigate how the addition of WTG affects the properties of PET by analyzing different concentrations and particle sizes of WTG. Characterization techniques such as Scanning Electron Microscopy (SEM), Fourier Transform Infrared Spectroscopy (FTIR) and mechanical testing are used to examine the structure, chemical composition and mechcanical properties of the composites. This research contributes to sustainable waste management practices by providing a valuable use for waste tires and enhancing the mechanical properties of PET thermoplastics. These composites can be excellent candidates for applications in automotive components, construction materials, and consumer goods where enhanced mechanical properties and environmental sustainability are vital.

2 Method

2.1 Materials

Waste tire granules (WTG) with particle sizes exceeding 2 mm were sourced from a local tire recycling facility. The polyethylene terephthalate (PET) was provided by HICOM-Teck See Manufacturing Malaysia Sdn Bhd (HTS), a local automotive manufacturing company.

2.2 Preparation of waste tire granule

Initially, the waste tire granules (WTG) were thoroughly cleaned with water to eliminate dirt and contaminants. The cleaned samples were then dried at 50°C for 6 hours. Once dried, the

WTG was ground using a grinder and then sieved to ensure uniformity. The processed WTG was categorized into different particle size ranges, specifically from 250 μm to 1 mm, to be used as filler material.

2.3 Composite making

To fabricate the specimens, various sizes and compositions of WTG were mechanically mixed with PET. Initially, the PET and WTG were dry-blended to achieve a preliminary mixture and ensuring that the WTG particles were evenly distributed throughout the PET matrix before any thermal processing. The dry-blended mixture was then subjected to high-intensity mechanical mixing using a high-shear mixer set at a speed of 3000 rpm for 10 minutes at room temperature. This process was crucial in overcoming the challenge of limited affinity and achieving a more uniform dispersion of WTG particles within the PET matrix.

The mechanical energy applied during this process helped to break down any agglomerates and distribute the WTG particles more evenly. The PET/WTG mixtures were then processed through injection moulding. The mixtures were preheated for 6 minutes and subsequently subjected to a 4-minute compression moulding process at 160°C. After moulding, the composites were cooled under pressure for two minutes at room temperature. The specimens were then stored in plastic bags for further characterization.

2.4 Characterization of composite

The morphological surface of the PET/WTG composites was analyzed using scanning electron microscopy (SEM) with a ZEISS EVO 50 instrument from Germany. Prior to SEM analysis, the samples were coated with platinum using a sputter coater to enhance their conductivity and imaging quality.

Fourier Transform Infrared Spectroscopy (FTIR) was employed to investigate the interaction and presence of organic compounds within the PET/WTG composites. The analysis was conducted over a wavenumber range of 4000 to 500 cm^{-1}, with each sample spectrum plotted accordingly.

The mechanical properties of the composites were evaluated through elongation at break (EB) and impact tests. EB, which signifies the material's stretchability before fracture was determined following ASTM D638 standards using an Instron machine. The tests were conducted at a controlled crosshead speed of 20 mm/min at ambient temperature. Five specimens were tested for each condition and the average EB value was recorded using INSTRON software. Additionally, the impact resistance of the PET/WTG composites was assessed using the Charpy impact test in accordance with ASTM D6110 standards. Before testing, samples were notched using a Dynisco notcher model. The impact tests were performed using a Tinius Olsen Impact 104 model, which subjected the samples to a standardized impact force. To ensure reliability, ten samples were tested for each WTG concentration and size. The average impact value, indicating the energy absorbed by the samples upon impact was determined. The standard deviations for the impact tests were consistently below 10%, ensuring the reliability of the obtained data.

3 Results

3.1 SEM morphology of composite

The surface morphology of the pure PET and PET/WTG composites was analyzed using Scanning Electron Microscopy (SEM) at 100× magnification as shown in Figure 1. Figure 1

(a) depicts pure PET characterized by a smooth and homogeneous surface, indicating a well-defined and uniform structure without significant inclusions or irregularities. Meanwhile, Figure1 (b) shows the PET mixed with waste tire granules (WTG) revealing a rougher texture with visible particulate inclusions dispersed throughout the surface. These inclusions are the WTG particles embedded within the PET matrix. The rougher texture and embedded granules suggest successful dispersion and integration of WTG, enhancing the interfacial bonding between PET and WTG. This morphological change indicates that the addition of WTG disrupts the smooth PET surface.

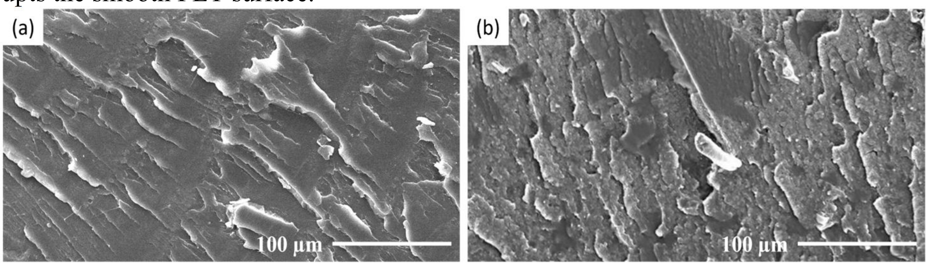

Fig. 1. (a) SEM image of PET at 100× magnification; **(b)** SEM image of PET/WTG at 100× magnification.

3.2 FTIR analysis of composite

FTIR analysis was performed to gain insights into the chemical structure of the components investigated in this study. The FTIR spectrum of polyethylene terephthalate (PET) shown in Figure 2 (a) revealed characteristic bands related to ester groups and benzene rings. These included the stretching vibration of the ester carbonyl group (C=O) at 1715 cm^{-1}, C–H stretching modes at 2962 and 2870 cm^{-1}, and C–O stretching vibrations at 1240 cm^{-1}. Additionally, strong bands corresponding to the aromatic ring stretching appeared at 1410 cm-1 and 870 cm^{-1} [6-8]. The presence of these bands indicates the typical chemical structure of PET which confirms the integrity of the material used in the study.

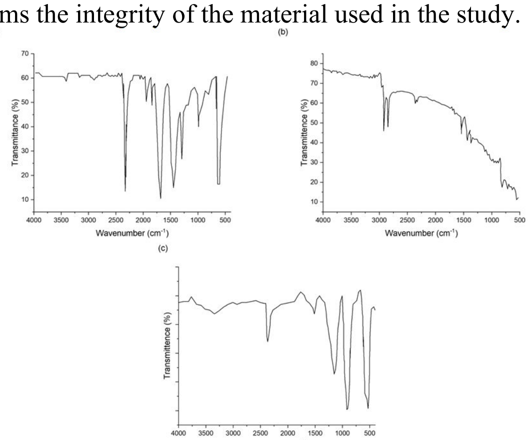

Fig. 2. (a) FTIR of neat PET; **(b)** FTIR of WTG; **(c)** FTIR of PET/WTG.

On the other hand, the FTIR spectrum of waste tire granules (WTG) depicted in Figure 2 (b) exhibited bands associated with polyisoprene vibrations. These bands corresponded to CH symmetrical stretching (2915 cm^{-1}), CH2 symmetrical stretching (2848 cm^{-1}), C=C-H stretching (3037 cm^{-1}), out-of-plane bending (818 cm^{-1}), stretching of unsaturated double bond C=C (1536 cm^{-1}), and deformation vibrations of CH2 and CH3 (1432 and 1371 cm^{-1}). These vibrational modes confirm the presence of polyisoprene which is a major component of tire rubber in the WTG samples [9]. Furthermore, the FTIR spectrum of the PET blend with WTG is illustrated in Figure 2 (c).

The IR spectrum of the PET/WTG composite depicted similar characteristic bands of PET such as the ester carbonyl stretching at 1715 cm^{-1} and aromatic ring stretching at 1410 cm^{-1}. Notably, blending PET with WTG resulted in shifts and modifications in the FTIR peaks, reflecting the formation of new chemical entities. Specifically, new bands appeared in the region 465–520 cm^{-1}, attributed to –C–S and S–S groups [10]. The band at 850–920 cm^{-1}, corresponding to the C–H bending vibration of–C=C butadiene and aromatic benzene, exhibited increased intensity with the augmentation of WTG. These modifications suggest chemical interactions between PET and WTG, leading to the formation of a more complex composite structure.

The changes in the FTIR spectra confirm the successful incorporation of WTG into the PET matrix and the formation of a new functional group, which can potentially enhance the mechanical properties of the composite. These findings highlight the effectiveness of FTIR analysis in elucidating the chemical interactions and structural modifications occurring in PET/WTG composites.

3.3 Mechanical testing

The elongation at break (EB) values for PET/WTG composites with varying concentrations and particle sizes of waste tire granules (WTG) are presented in Figure 3 (a). The graph shows that at pure PET (0% WTG concentration, the EB value is at 10%, indicating the baseline elongation for the composite sample. As the concentration of WTG increases to 5%, there is a slight increase in EB values which suggest an initial enhancement in ductility. At 10% WTG, a significant increase in EB is observed for all particle sizes, with the highest EB for the 250-500 µm particle size reaching 15% indicates an optimal concentration for enhanced ductility. However, at 15% WTG, the EB values decrease for all particle sizes, though they remain higher than the baseline. This suggests that diminishing returns in ductility due to potential particle agglomeration [11]. Smaller particles (250-500 µm) consistently show the highest EB values at each concentration which demonstrate better enhancement of ductility due to better dispersion and interaction within the PET matrix. The study demonstrates that incorporating WTG into PET can significantly enhance the material's elongation at break, particularly at an optimal concentration of 10% with smaller particles providing the greatest improvement. However, higher concentrations of WTG beyond the optimal level can reduce the ductility of the composite. These findings highlight the importance of optimizing WTG concentration and particle size to maximize the mechanical performance of PET/WTG composites.

The impact strength values for PET/WTG composites with varying concentrations and particle sizes of waste tire granules (WTG) are presented in Figure 3 (b). The graph indicates that at pure PET (0% WTG), the impact strength value is 3 J/cm², reflecting the baseline strength. As the concentration of WTG increases to 5%, the impact strength shows a marked improvement by rising to 3.94 J/cm² for the 250-500 µm particle size, 3.52 J/cm² for the 500-710 µm size, and 3.43 J/cm² for the 710 µm-1 mm size. At 10% WTG, there is a significant enhancement in impact strength with the highest values recorded as 6.13 J/cm² for the 250-500 µm size, 5.95 J/cm² for the 500-710 µm particle size and 5.74 J/cm² for the 710 µm-1 mm size. However, at 15% WTG, the impact strength slightly decreases, although it remains above the baseline values, showing 5.97 J/cm² for the 250-500 µm size, 5.84 J/cm² for the 500-710 µm size and 5.44 J/cm² for the 710 µm-1 mm size.

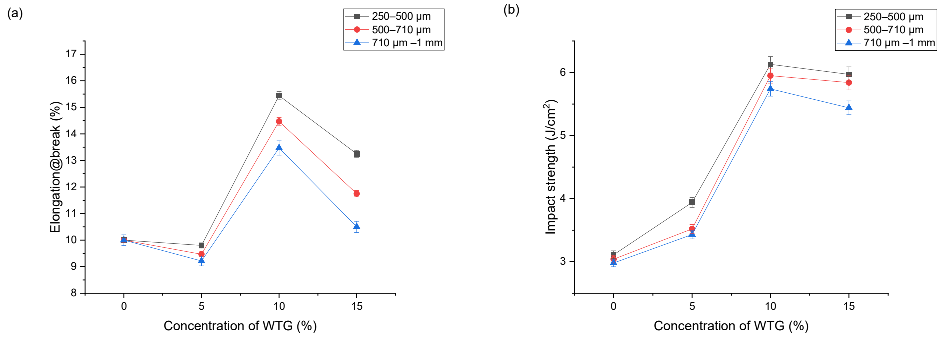

Fig. 3. (a) The elongation properties with different WTG concentrations; **(b)** Impact properties with different WTG concentrations.

The results demonstrate that the addition of WTG enhances the impact strength of PET with the optimal concentration observed at 10%, beyond which the improvements are less pronounced. This indicates that WTG particles effectively reinforce the PET matrix up to a certain concentration and able to improve the material resistance to impact. The varying impact strengths across different particle sizes suggest that the dispersion and interaction of WTG particles within the PET matrix play a crucial role in determining the mechanical properties of the composite. These findings highlight the potential of WTG to improve the impact strength of PET composites and offer a viable solution for developing eco-friendly materials.

4 Conclusion

This research successfully demonstrates the incorporation of WTG into PET to create better properties and eco-friendly composite materials. Scanning Electron Microscopy (SEM) images further validate the proper dispersion and integration of WTG particles within the PET matrix contributing to the improved mechanical performance. FTIR analysis confirms the formation of new chemical entities within the PET/WTG composites indicating effective chemical interactions and structural modifications. The study also reveals that adding WTG to PET significantly enhances both the elongation at break and impact strength of the composites with optimal mechanical properties observed at a 10% WTG concentration. These findings highlight the potential of utilizing recycled WTG to develop sustainable and high-strength PET composites. This approach not only addresses environmental concerns associated with waste tire disposal but also enhances the mechanical properties of PET making it a viable solution for various industrial applications where material performance and sustainability are crucial. Through this innovative method, the study offers a promising avenue for advancing waste management practices and material engineering, paving the way for future research and development in the field of composite materials.

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