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Gamma Irradiation-Induced Modifications in E-Glass Fiber Reinforced Polypropylene Composites: A Structural and Performance Analysis

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ABSTRACT

This study explores the role of gamma irradiation in altering the mechanical properties and microstructure of E-glass fiber-reinforced polypropylene (PP) composites. E-glass fiber, known for its superior strength and durability, was combined with polypropylene to produce composites with varying fiber weight percentages (20-60 wt%). The composites were subjected to 3 kGy gamma radiation, and their tensile strength (TS), tensile modulus (TM), elongation at break (Eb%), and impact strength (IS) were evaluated. Results revealed that the optimal mechanical performance was achieved at 50 wt% fiber content, where gamma radiation improved TS by 16%, TM by 13%, Eb% by 9%, and IS by 13% compared to non-irradiated composites. Improved fiber-matrix adhesion was achieved through the cross-linking effect of gamma radiation on the polymer matrix which leads to better load transfer and mechanical properties. The results of this research highlight the efficacy of gamma irradiation to strengthen E-glass/PP composites for rigorous applications such as aerospace and automotive sectors. The present work emphasizes the importance of considering radiation treatment in composite design, especially in applications exposed to radiation.

Keywords: E-glass fiber, polypropylene, micro structure, mechanical properties, polymer

1 Introduction

Fiber-reinforced composites (FPCs) represent a category of sophisticated materials that integrate fibers with a matrix to achieve enhanced mechanical properties in comparison to individual components. This composite structure harnesses the high ratio of strength-to-weight of fibers and the versatile features of the matrix material, resulting in materials with enhanced performance characteristics appropriate for a variety of uses [1].

FPCs play a pivotal role in modern technology and manufacturing due to their unique combination of characteristics and versatility. Recent advancements underscore their significance across several domains. FPCs are renowned for their superior mechanical properties, including high strength-to-weight ratios, which enhance the performance in demanding applications [2]. Additionally they are possessed with advantages like lightweight, design flexibile, corrosion and chemical resistance, cheap etc [3]-[8].

Fibers including both natural and synthetic can be utilized for fiber polymer composites. Natural fiber composites (NFCs) offer several advantages, including sustainability and reduced environmental impact, but they also face notable limitations that affect their performance and application. One significant limitation is their lower mechanical behavior compared to synthetic fiber composites. Natural fibers, such as jute and flax, generally have lower tensile and impact strength, which can limit their use in high-performance applications where greater load-bearing capacity is required. Recent studies have highlighted that while natural fibers can be competitive in terms of weight and cost, growing conditions, harvesting methods and processing techniques, moisture absorption, durability, and thermal stability in parallel to synthetic FPCs [9]-[13].

Synthetic fibers such as carbon, glass, and aramid offer notable benefits in fiber polymer composites, attributed to their exceptional mechanical properties, uniformity, and resilience. Recent research indicates that synthetic fibers provide outstanding strength-to-weight ratios, rendering them highly suitable for rigorous applications in the aerospace and automotive sectors [14]. They also enhance thermal stability and resistance to environmental factors, such as moisture and chemicals, extending the lifespan of composites in harsh conditions [15]. Furthermore, the precise manufacturing of synthetic fibers ensures uniformity and reliability, which is crucial for applications requiring consistent performance [16]. Advances in processing technologies also enable the manufacturing of high-quality composites with tailored properties, optimizing their functionality across various industries [17].

Glass fiber is a well-known synthetic fiber that is popular for its diverse applications. The foremost broadly utilized glass fiber is E-glass fiber, which offers excellent coverage coverage of mechanical characteristics and can hold its characteristics up to 815ºC. The composition of E-glass fiber is $54.3SiO_2$-$15.2Al_2O_3$-17.2CaO-4.7MgO-8.0BO-$0.6Na_2O$. E-glass fibers offer several advantages in fiber polymer composites, primarily due to their excellent combination of mechanical characteristics, cost-effectiveness, and durability. Recent studies show that E-glass fibers provide high tensile strength and good impact resistance at a lower cost compared to other fibers, making them an economical choice for applications in construction, automotive,

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and marine industries [18]. Their resistance to moisture and chemicals enhances the longevity and reliability of composites in harsh environments [19].

Polypropylene has been extensively employed as a matrix material in fiber-reinforced polymer composites. Straightforwardness, dimensional solidness, tall warm soundness, tall heat-distortion temp, and great affect quality are characteristics of the family of thermoplastic building polymers known as PP that essentially broaden the material's extent of employment. PP works well for filling, blending, and reinforcing as well [20]-[21]. Gamma radiation is an ionizing type of radiation that can enhance surface crosslinking. It reduces the hydrophilic properties of fiber via a hydrophobic matrix. When compared to alternative radiation treatments, gamma radiation offers a number of advantages for composite materials, such as continuous operation, shorter processing times, less air pollution, ambient temperature curing, and increased process control that allows for more design flexibility [22], [23]. For polymer-based composite materials, gamma rays are used to improve the bond between the matrix and the reinforcing fibers. Free radicals produced by gamma radiation in the polymer chain enable cross-linking inside the polymer and hence enhance the characteristics of composite materials [24]-[26].

Despite numerous investigations into the mechanical behavior of E-glass/PP composites, few studies have explored the effects of gamma radiation on these materials. Even though it was noticed that many of the studies fabricated composites with E-glass fiber [27]-[30], but they did not investigate the effect of gamma radiation on these materials. This study addresses a critical gap in composite material research by examining the effects of a specific, moderate gamma irradiation dose (3 kGy) on the mechanical properties of E-glass fiber-reinforced polypropylene (PP) composites. Previous studies have varied significantly in irradiation levels, often focusing on higher doses without investigating the targeted, controlled impact of moderate gamma exposure on fiber-matrix bonding. By isolating the 3 kGy dose, this research demonstrates that gamma irradiation can induce beneficial cross-linking within the PP matrix, resulting in enhanced fiber-matrix adhesion and improved mechanical integrity of the composite. Mechanistically, it has been shown in this paper that gamma rays generate free radicals in the PP matrix which initiates cross-linking that enables stronger stress transfer between fibers and matrix, and this leads to improved composite resilience. These insights highlight the potential of gamma-modified E-glass/PP composites as a durable, high-performance material suitable for demanding applications, especially in aerospace and automotive sectors, where both radiation exposure and mechanical strength are critical. This study not only establishes a new framework for using controlled gamma irradiation in composite design but also sets a benchmark for optimizing fiber loading and irradiation to achieve superior performance in fiber-reinforced composites.

2 Materials and Methods

2.1 Materials

In this study, the E-glass fabric (Fig. 1) was obtained from Saint-Gobain Vetrotex India Limited, with 6K tow dimensions, and was woven in a plain pattern. It had an aerial weight of 200 g/m², a fiber diameter of 12 microns, and a density of 2.54 g/cm³. The highly crystalline polypropylene granules were collected from Polyolefin Company Ltd., Singapore respectively.

2.2 Preparation of composites

PP sheets were prepared by using granules of PP. The PP granules were placed inside two steel plates of a heat press machine (Carver, INC, USA Model 3856). The press was operated at 180°C. About 5 tons of consolidation pressure was applied for 3 minutes; the melting time was about 2 minutes. After three minutes the plates were removed and subsequently allowed to cool for 2 minutes. It was pressed again under 5 tonnes of pressure at ambient temperature. The resulting polypropylene sheet was then trimmed to the required dimensions for composite fabrication.

E-glass fiber-reinforced PP-based composites were prepared by sandwiching two layers of E-glass fabric mats between three sheets of PP. The sandwich was then inserted between two steel plates in the heat press machine and heated at 180°C for 4 minutes to facilitate the softening of the polymer and then applied 6 tones pressure for 6 minutes. In the sandwiching process, the weight ratio of the fibers 20, 30, 40, 50, and 60 wt% were maintained by changing the weight of PP sheets. Fig. 1 is depicting the fabricated composite.

Fig. 1 E-glass fiber reinforced PP-based composite

2.3 Gamma treatment

The application of gamma radiation was utilized to investigate the influence of gamma irradiation on the mechanical properties of the fabricated composites. The E-glass/PP composites were precisely cut into desired size dimensions and securely sealed within an airtight polyethylene bag. The employed source of gamma radiation was Cobalt-60, with an activity of 90 kCi and a dose rate of 0.025 kGy/min. The dose values provided are solely the intended target dose and were derived using an ordinary Harwell Amber Perspex dosimeter, specifically the type 3042F. The applied dosage of gamma radiation was 3kGy, and the subsequent evaluation of their mechanical properties was conducted.

2.4 Mechanical properties of composites

The mechanical characteristics such as tensile strength (TS), tensile Modulus (TM) and elongation at break (Eb%), of the fabricated composites were investigated by using a universal testing machine (H50 KS-0404) according to ASTM D 638-01. The samples were cut into strips with a dimension of (80×10×2.5) mm, measured with slide calipers. For an accurate and precise result, three strips were taken of each sample. Then the strips were placed properly between the jaws of UTM and the operating procedure for the samples was selected using the software. The gauge length and cross-head speed of the machine were 25 mm and 1 mm/s, respectively. The impact strength was evaluated using an impact testing machine (MT-3016) according to DIN-53433. In this study, all results were based on the average values obtained from three samples.

3 Results and Discussion

3.1 Mechanical properties of E-glass/PP composites

The TS, TM, Eb%, and IS of the fabricated composites were examined and the results are shown in Fig. 2. The measured values for the TS, TM, and Eb% of the PP matrix were 21.8 MPa, 1.5 GPa, and 75% respectively. E-glass/PP composites containing 50% fibers demonstrated an increase of 303% TS and 367% TM. Augmented TS and TM were noticed when the fiber loading ratios increased up to a specific limit. If the fiber percentage falls below the optimum value, the load is distributed to more fibers that are well bound to the matrix, resulting in higher tensile characteristics. After transgressing the optimum value, the tensile strength is dropped if the percentage of fibers increased. The transfer of stress between the fiber and the matrix was decreased as the percentage of fiber increased. When the percentage of fibers increased, the gaps between the fibers also grew, leading to a reduction in the effectiveness of stress transfer from one fiber to another. That's why a decrease in TS and TM was observed for the composite with 60 wt% fiber content. In all instances of adding fiber to the composites in this study, Eb% was decreased compared to PP due to the lower Eb% of the E-glass fiber. It was observed that the composite with 50 wt% fiber content exhibited higher IS values. The results indicated that with 50 wt% reinforcement using E-glass fiber, the IS increased by 146%.

According to Khan et al., the TS, TM, Eb%, and IS values for E-glass/PP composites with a 50 wt% fiber content were 91 MPa, 7 GPa, 14%, and 35 KJ/m^2 respectively [27]. Shubhra et al. investigated E-glass fiber reinforced polypropylene resin-based composites and reported 128 MPa TS, 4.35 GPa TM, 14% Eb%, and 19 KJ/m^2 IS for 30 wt% fiber [31]. In another investigation, Khan et al. determined the TS, TM, Eb%, and IS for 20 wt% E-glass/PP composites, which were 32 MPa, 4.79 MPa, 38%, and 18.5 KJ/m^2 respectively [32]. Supportive values of current work have been tabulated in Table 1 and it can be seen that E-glass/PP composites exhibit almost similar mechanical properties as found in different studies.

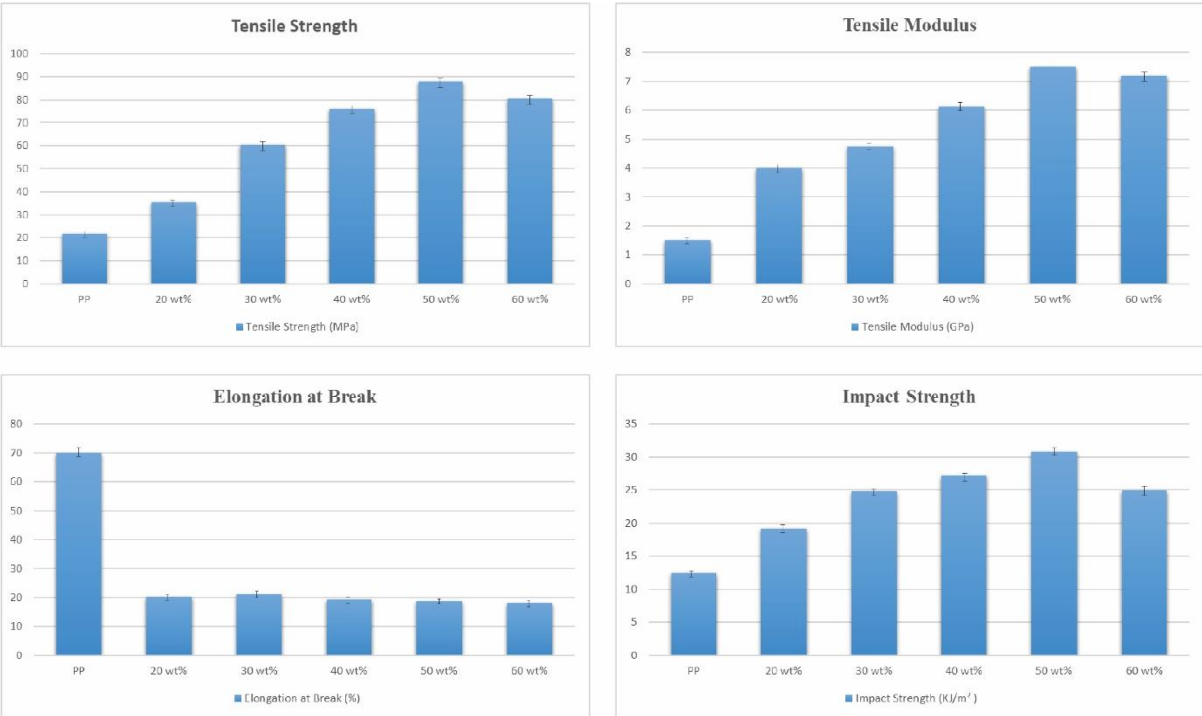

Fig. 2 Mechanical Properties of E-glass/PP composites

Table 1 Supportive values of mechanical characteristics

Fiber proportion (wt%)	Mechanical Properties				Ref.	This Study			
	TS (MPa)	TM (GPa)	Eb%	IS (kJ/m^2)		TS (MPa)	TM (GPa)	Eb%	IS (kJ/m^2)
50	91	7.00	14	35	[27]	88	7.5	18.75	30.806
30	128	4.35	14	19	[31]	60.35	4.75	21.2	24.79
20	32	4.79	38	18.5	[32]	35.56	4	20.21	19.12

Due to the water hate nature of PP and E-glass fibers, it was anticipated that they would bond well with each other, resulting in strong fiber-matrix adhesion. This was the reason of enhanced mechanical properties of the E-glass based composites. This investigation clearly shows that E-glass/PP composites exhibit significantly higher mechanical properties in parallel to the matrix material, indicating strong fiber-matrix adhesion.

3.2 Effect of Gamma radiation on composites

This study involved subjecting the composites to a radiation dose of 3 kGy, followed by an assessment of their tensile strength (TS), tensile modulus (TM), elongation at break percentage (Eb%), and impact strength (IS). In this investigation, mechanical properties were improved with a radiation gamma dose of 3 kGy. Fig. 3 depicts the influence of gamma radiation on the TS of composites. The data indicates that the tensile strength values of E-glass/PP composites were enhanced due to gamma irradiation. The utmost TS value for E-glass/PP composites was achieved at 50 wt% fiber content. Results demonstrated that 50 wt% E-glass/PP composites had a 16% higher TS value than non-irradiated ones. Conversely, composite with 20% fiber content exhibited minimum TS value as seen in Fig. 3 and Table 2.

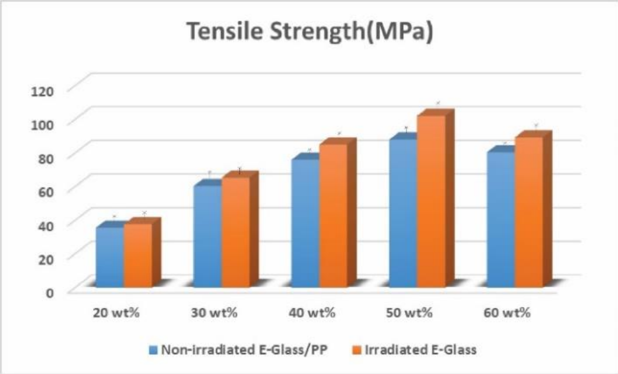

Fig. 3 Effect of gamma irradiation on the TS of composites

Enhanced TM values of the composites were observed at 3 kGy radiation dose. The maximum TM value of E-glass/PP composites was attained at 50 wt% fiber content, leading to a 13% enhancement relative to non-irradiated E-glass/PP composites. Both composites with 40 wt% and 60 wt% fiber content revealed an 11% increase in TM at the above-mentioned gamma dose as seen in Table 2 and Fig. 4. Composites with 50 wt% fiber content exhibited a 9% rise in Eb%, whereas declined Eb% was noticed for the remaining composites. The impact of gamma dose treatment on E-glass/PP composites concerning Eb% is depicted in Fig. 5.

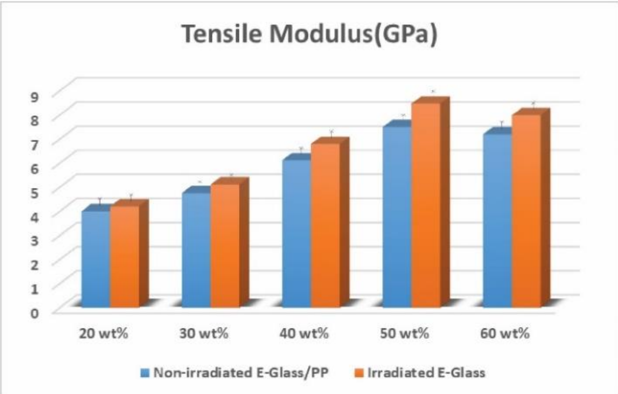

Fig. 4 Effect of gamma irradiation on the TM of composites

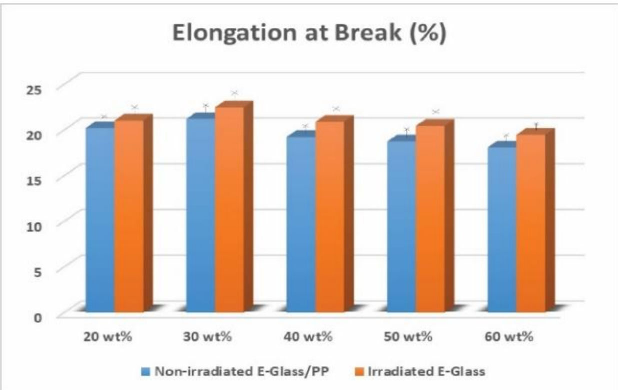

Fig. 5 Effect of gamma irradiation on the Eb% of composites

The use of gamma radiation for treating the E-glass/PP composites also increased the IS values. Fig. 6 and Table 2 are clearly demonstrating the impact of gamma radiation on the IS of composites. The highest IS was noticed at a 3 kGy gamma radiation dose for 50 wt% E-glass/PP composites, showing a 13% increase compared to the composites that were not subjected to gamma irradiation.

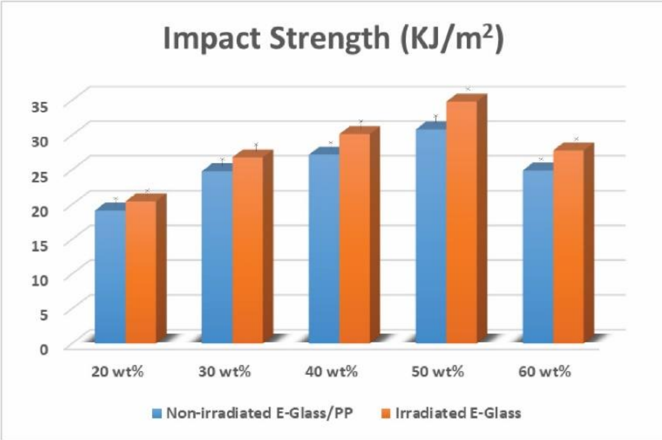

Fig. 6 Effect of gamma irradiation on the IS of composites

Table 2 A comparative overview of the enhanced percentage of gamma irradiated E-glass/PP composites versus their non-irradiated counterparts.

Fiber Proportion (wt%)	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Elongation at Break (Eb%)**	**Impact Strength (KJ/m^2)**
20	6%	5%	4%	7%
30	7%	7.50%	6%	8%
40	12%	11%	8.50%	11%
50	16%	13%	9%	13%
60	11%	11%	7.75%	11.5%

Gamma radiation has previously been shown to have considerable influence on the characteristics of polymeric materials. In polypropylene, gamma irradiation causes the formation of free radicals. The resulting free radicals may react, altering the chemical structure of the polymer and bring change in the mechanical properties of composite materials. Higher doses of gamma irradiation may have an effect on E-glass fibers. Gamma irradiation may influence the polymeric structure of PP solely in E-glass/PP composites, perhaps producing active sites that can contribute to enhance intermolecular PP bonding [31]. For this reason, E-glass/PP composites gained improved mechanical properties in this research experiment due to gamma treatment.

Gamma radiation influences composite materials primarily through the generation of free radicals in the polymer matrix, which then interact with each other, causing crosslinking. The crosslinking within polypropylene (PP) alters the polymer chains that improves fiber-matrix adhesion and thereby enhancing the mechanical properties of the composite [33]-[36].

When polypropylene is exposed to gamma radiation, the high-energy photons ionize the polymer chains. This process generates free radicals, primarily through the scission of C–H bonds. The primary reaction involves the breaking of C–H bonds in the polypropylene chains that results in the formation of macroradicals-

$$\text{Polypropylene (PP)} \xrightarrow{\gamma \text{ radiation}} \text{PP}\cdot + \text{H}\cdot$$

Here, PP· represents the macroradicals formed in the PP chains.

The cross-linking of polymer chains can be achieved through the recombination of generated free radicals with other radicals.

$$PP\cdot + PP\cdot \rightarrow \text{Cross-linked PP}$$

This recombination increases the molecular weight of the polymer, enhancing its mechanical properties and thermal stability [25]-[31].

This study revealed that E-glass/PP composites showed notable improvements in tensile strength, with the highest increase of 16% at 50 wt% fiber content when exposed to 3 kGy of Gamma radiation. This can be attributed to enhanced fiber-matrix bonding due to crosslinking, resulting in better load transfer across the fibers and matrix.

Similar improvements were noted in the tensile modulus. The composite with 50 wt% fiber content saw a 13% increase in TM post-radiation, which reflects the stiffening of the matrix due to enhanced crosslinking and reduced molecular mobility in the polymer.

Gamma radiation resulted in a marginal increase in elongation for the 50 wt% composite, but a general decrease for other fiber contents. The moderate increase in Eb% is likely due to the improved flexibility at the fiber-matrix interface, allowing for better energy absorption.

An increase of 13% impact strength was overt at 50 wt% fiber content after Gamma radiation, which suggests that crosslinking bolsters the composite's ability to absorb energy upon impact, enhancing its resistance to sudden force.

4 Conclusion

The study reveals that gamma irradiation has a noticeable impact on the mechanical properties of E-glass/polypropylene composites. Specifically, it was determined that composites with 50 wt% fiber content showed excellent mechanical behavior as discussed. It was overt that 50 wt% E-glass/PP composite exhibited an increase of 16% TS,13% TM, 9% Eb% and 13% IS in comparison to non-irradiated composites. This alteration in mechanical performance suggests that gamma irradiation might be beneficial in certain scenarios. The findings underscore the potential of gamma-irradiated E-glass/PP composites for high-stress and radiation-prone environments, such as aerospace and automotive applications. Further research could focus on optimizing irradiation doses to tailor properties for specific operational demands, enhancing resilience in extreme settings.

Conflicts of Interest

The authors report there are no competing interests to declare.

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