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AN EXPERIMENTAL INVESTIGATION OF FLEXURAL BEHAVIOR OF POLYPROPYLENE REINFORCED WITH RECYCLED EPOXY POWDER

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***Abstract*:** Polypropylene (PP) is a widely used thermoplastic owing to its good mechanical properties, chemical resistance, and cost-effectiveness, while epoxy composites are extensively employed in high-performance applications but pose recycling challenges after end-of-life disposal. In this study, polypropylene composites reinforced with micro-sized cross-linked epoxy particles were developed as a sustainable approach to reutilize thermoset epoxy waste. The flexural behavior of the composites was investigated at epoxy particle contents of 5%, 10%, 15%, and 20% by weight. The results showed a positive effect of cross-linked epoxy microparticles on the yield flexural strength of polypropylene, with a maximum improvement of approximately 26.3% observed at 20% reinforcement compared to neat PP. X-ray diffraction and scanning electron microscopy analyses confirmed uniform dispersion of epoxy microparticles within the polypropylene matrix.

Keywords: Polypropylene, Cross linked Epoxy, Flexural strength, FTIR, SEM and Mechanical properties.

1. INTRODUCTION

An experimental investigation on polypropylene reinforced with jute–coir fibers reported enhancements in flexural strength, flexural modulus, and hardness with increasing fiber content, albeit at the expense of impact strength [1]. In contrast, the impact and fatigue performance of polypropylene composites was found to improve significantly with the incorporation of alkali–silane treated kenaf fibers [2]. Owing to its versatility, polypropylene is widely used in applications ranging from automotive components and packaging to toys and industrial products. It is a promising polymer due to its high hardness, excellent electrical and chemical resistance, good stress resistance, high melting temperature, and resilience. The growing demand for polypropylene in automotive and construction sectors is expected to drive the expansion of the resin industry [3].

Polypropylene fibers and nano clay have been employed to enhance the impact strength of brittle glass fiber reinforced polymer (GFRP) composites. Along with impact strength, the tensile and flexural properties of GFRP were also evaluated with and without compatibilization. The results revealed that surface treatment of PP fibers with silane agents improved impact strength by approximately 44%, though with a reduction in tensile and flexural strength. However, ultraviolet-assisted maleic anhydride grafted PP fibers improved impact strength while restoring tensile and flexural properties in the nanocomposites [4]. Furthermore, effective compatibility between polymeric or elastomeric fillers and the composite matrix was identified as a critical factor in enhancing the impact strength of multidimensional filler-reinforced epoxy composites [5].

Isotactic polypropylene (iPP) reinforced with hydrophilic micro- and nanoparticles at 5 wt% was processed using screw extrusion followed by injection molding. Mechanical characterization through tensile and unnotched Charpy impact tests indicated considerable improvements in tensile, yield, and impact strength for iPP/nanoparticle composites. In contrast, iPP reinforced with microparticles exhibited significant increases in tensile modulus and yield strength, while elongation at yield and unnotched impact strength were markedly reduced due to non-uniform particle dispersion [6].

In another study, multi-walled carbon nanotubes (MWCNTs) of varying aspect ratios were incorporated at a fixed volume fraction of 1% into a polypropylene matrix using a twin-screw compounding extruder. Notched Charpy impact tests demonstrated a substantial improvement in impact resistance above the glass transition temperature of the matrix, with longer nanotubes proving more effective in enhancing composite toughness than shorter ones [7].

The influence of Fe_3O_3 microparticle size and weight fraction on the mechanical properties of polypropylene composites, particularly tensile yield strength and elastic modulus, was also investigated. The results showed that elastic modulus increased with increasing Fe_3O_3content, while percentage elongation decreased compared to neat polypropylene. An increase in particle size led to reduced mechanical performance due to particle agglomeration. Nevertheless, the incorporation of 20 wt% Fe_3O_3 microparticles with sizes below 33 μm resulted in significant improvements, achieving approximately 300% enhancement in elastic modulus and a 60% increase in tensile yield strength [8].

Additionally, polypropylene composites reinforced with hemp strands (HS) at varying loadings and in the presence of coupling agents were developed. Composites containing 20–30 wt% hemp strands with 8 wt% coupling agent exhibited the highest energy absorption in unnotched specimens, whereas notched samples with 40 wt% hemp strands and 4 wt% coupling agent showed maximum absorbed energy [9]

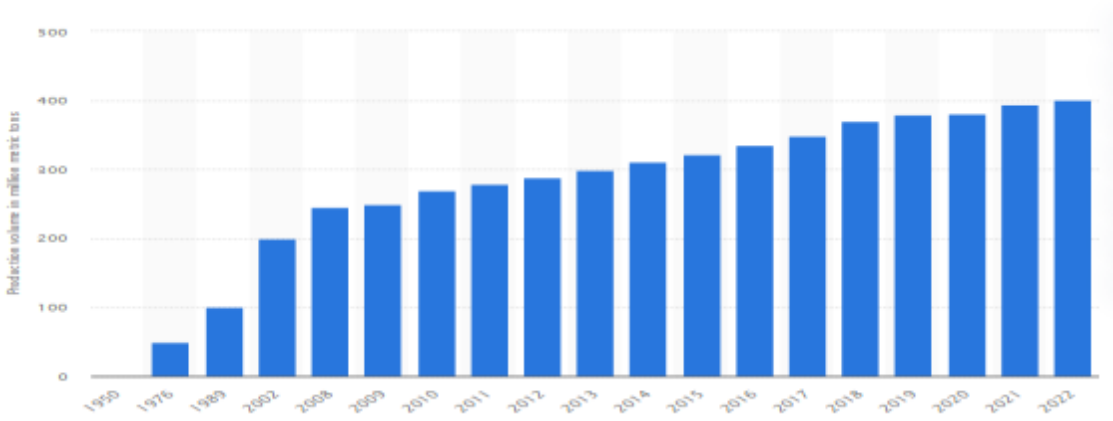


Fig. 1. Global plastics production statistics from 1950 to 2022 in million metric tons [10].

Driven by the rapid replacement of conventional materials in automotive and aerospace applications, global epoxy composite consumption is projected to exceed USD 74 billion by 2032. However, the disposal of epoxy composites at the end of their service life presents a critical industrial challenge, as a significant proportion of these materials is currently sent to landfills, leading to environmental concerns [11,12]. The growing adoption of sustainable technologies, such as electric vehicles and wind energy systems, is further accelerating the demand for fiber-reinforced polymers due to their lightweight and high-performance characteristics. Although epoxy polymers accounted for only about 7.1% of global plastic production in 2021, their contribution to environmental burden is substantial owing to their non-recyclable nature [13]. Consequently, the increasing resource demands of the composite materials industry and the environmental impact of epoxy waste highlight the urgent need for the development of effective and sustainable epoxy recycling strategies.

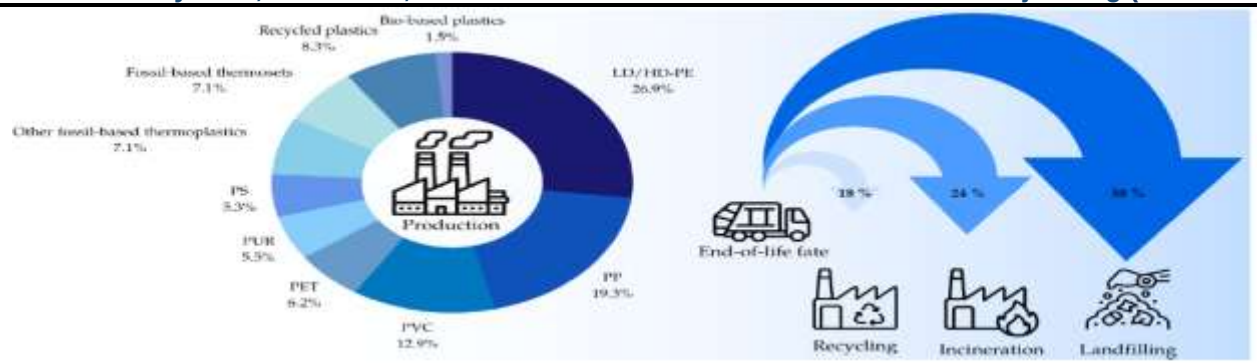


Fig. 2. Worldwide plastic production status during 2021 and methods for dealing with plastic waste after its end of life (status 2017) [3] [14].

The OECD, an intergovernmental organization, in its report Eliminating Plastic Pollution by 2040, identifies four strategic pillars to address plastic pollution, one of which emphasizes the enhancement of plastic recycling. The report recommends increasing the global plastic recycling rate from the current level of approximately 18% to a target of 38%.

In this novel study, an effort is made to recycle cross-linked thermosetting epoxy by utilizing it as a micro-filler in a polypropylene matrix. Cross-linked epoxy microparticles are incorporated at varying proportions to evaluate their influence on the flexural strength, hardness, and notched Izod impact resistance of polypropylene, as well as to determine the optimum filler content for improved recyclability and mechanical performance.

2. MATERIAL AND METHOD

The primary objective of the present experimental work is to investigate the effect of cross-linked epoxy microparticles on the flexural strength, hardness, and impact resistance of a polypropylene matrix. REPOL polypropylene grade H350FG, supplied by Reliance Industries Limited, Jamnagar, was used as the matrix material. The polypropylene raw material, in the form of pellets, is shown in Fig. 3(a). The epoxy resin, supplied as a two-part system by Carbon Black Composites, Mumbai, was mixed thoroughly in a 3:1 ratio using a spatula to obtain a fully cured, cross-linked epoxy block, as illustrated in Fig. 4(a).

Fourier Transform Infrared Spectroscopy (FTIR) was employed to confirm the cross-linking of the epoxy resin. The FTIR spectrum of the cured epoxy, presented in Fig. 3(b), confirms the successful cross-linking of the material. The cured epoxy block was subsequently pulverized using a ball milling process to obtain microparticles with sizes less than 50 µm. Polypropylene–epoxy composite specimens were fabricated by compounding polypropylene with cross-linked epoxy microparticles at weight fractions of 5%, 10%, 15%, and 20% using a micro-compounder injection molding facility at CIPET, Bengaluru. During compounding, the processing temperature and pressure were maintained in the ranges of 200–230 °C and 500–600 bar, respectively.

After fabrication, the specimens were conditioned under laboratory ambient conditions for one week to relieve residual processing stresses. Mechanical testing was carried out at CIPET, Bengaluru, in accordance with relevant ASTM standards, and the obtained results are discussed in detail.

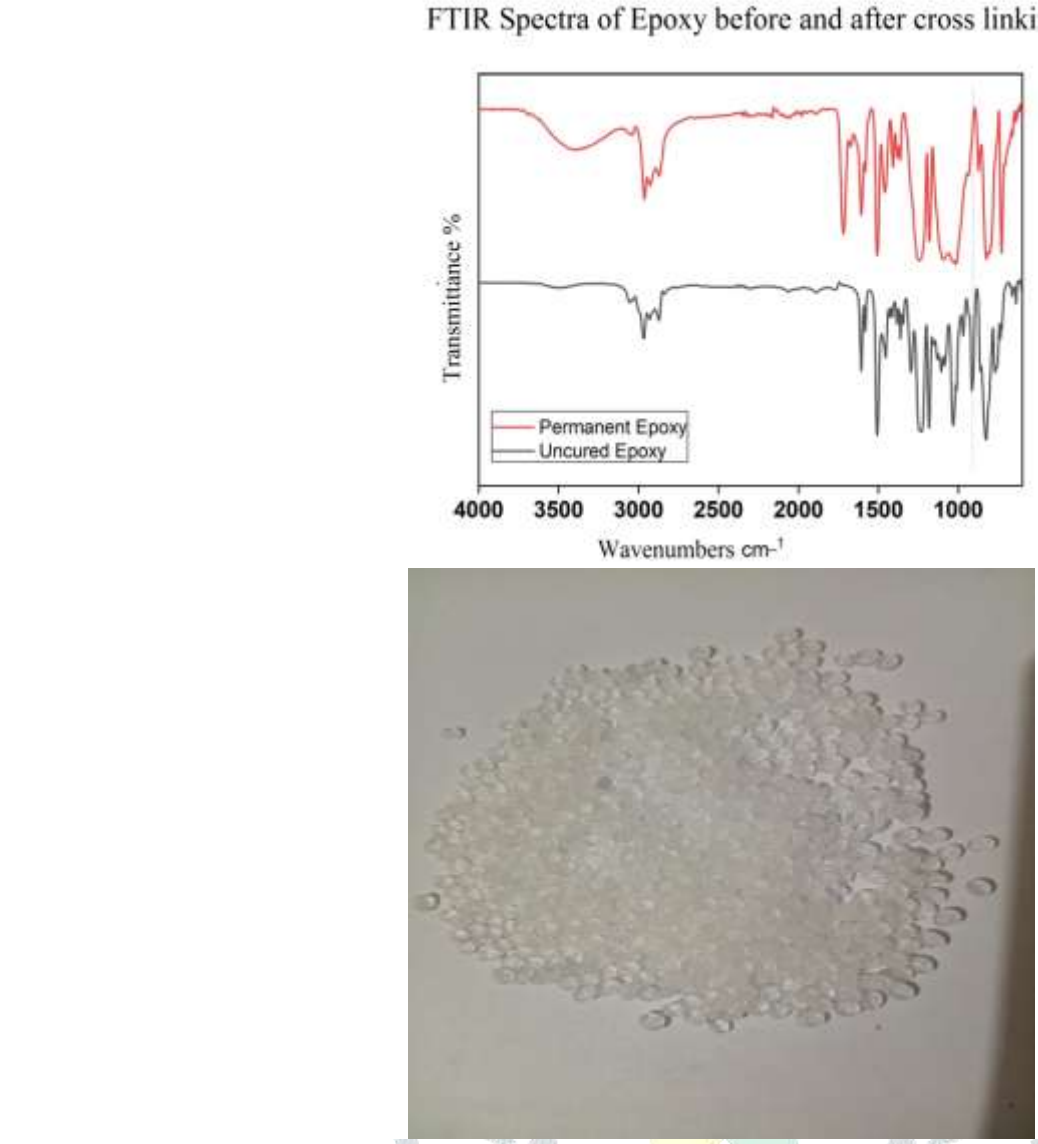
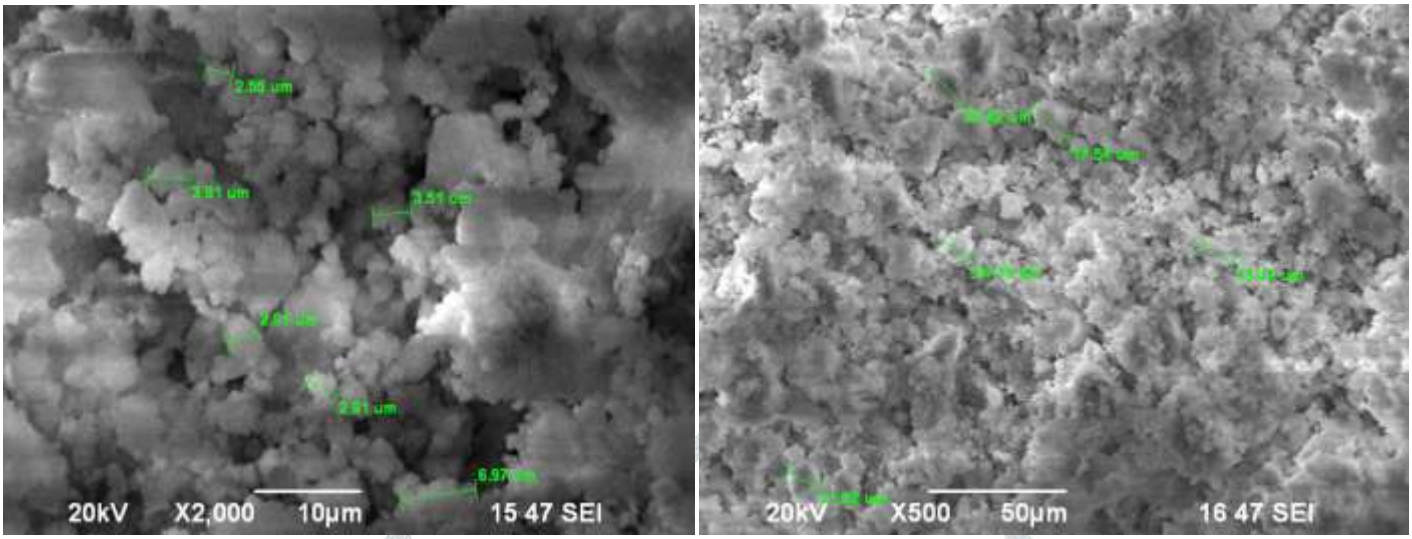


Fig. 3: Polypropylene H350FG Matrix Material Pallets (a), FTIR spectra of Epoxy before and after cross linking (b).

Fig. 4: Production Process of Epoxy Micro Particles from Rectangular Blocks. **a** - Shows Cross Linked Epoxy Blocks, **b** - Shows Epoxy Granules Obtained By Breaking Rectangular Blocks, **c** - Shows Ball Milling of Epoxy Granules, **d** - Shows Sieving (At 50 Microns) of Micro Particles and **e** – Shows Cross Linked Epoxy Micro Particles.



(a) (b)

Fig. 5: SEM Images Showing Particle Size Range of Cross Linked Epoxy Powder Sample. **a** – At 500X and b – At 2000X.

Figure 4 illustrates the step-by-step procedure adopted for the production of cross-linked epoxy microparticles from cured epoxy blocks. The cured epoxy blocks, shown in Fig. 4(a), were initially converted into granules (Fig. 4(b)) by mechanical hammering in an enclosed chamber. These granules were further processed using an industrial grinder to obtain particles suitable for ball milling. As depicted in Fig. 4(c), ball milling was employed to reduce the particle size to the micron scale, making them appropriate for use as reinforcement in a polypropylene matrix.

The epoxy powder obtained after ball milling was subsequently sieved using a 50 µm mesh. The epoxy microparticles collected after sieving are shown in Fig. 4(e). The particle size and morphology of the sieved epoxy powder were characterized using scanning electron microscopy (SEM), as presented in Fig. 5(a) at 500× magnification and Fig. 5(b) at 2000× magnification. SEM analysis confirmed that the epoxy particle size ranged from 2.91 µm to 33.42 µm. Particles retained on the sieve were reintroduced into the ball mill for further size reduction to ensure uniformity.

3. EXPERIMENT RESULTS AND DISCUSSION

Polypropylene–epoxy (PPE) composite test specimens were fabricated by reinforcing the polypropylene matrix with cross-linked epoxy microparticles at weight fractions of 5%, 10%, 15%, and 20% using a micro-compounder (screw extruder) integrated with an injection molding machine. Care was taken throughout both the fabrication and testing stages to ensure consistency and repeatability. For each composite composition, five identical specimens were prepared.

Table 1 presents the sample codes along with the corresponding weight percentages of polypropylene and cross-linked epoxy microparticles used in the composites. In this experimental investigation, flexural testing of the PPE composite specimens was conducted in accordance with ASTM D790 standards. The flexural properties of the composites were evaluated and compared with those of neat polypropylene to assess the influence of epoxy micro particle reinforcement.

Table 1: Shows the Sample Code for Polypropylene–Cross Linked Epoxy Micro Particles (PPE) Composites and Its Compositions.

SL.No	Sample code	PP (wt. %)	Cross linked Epoxy- E (wt.%)
1	A_1	100	0
2	A_2	95	05
3	A_3	90	10
4	A_4	85	15
5	A_5	80	20

3.2 Flexural test:

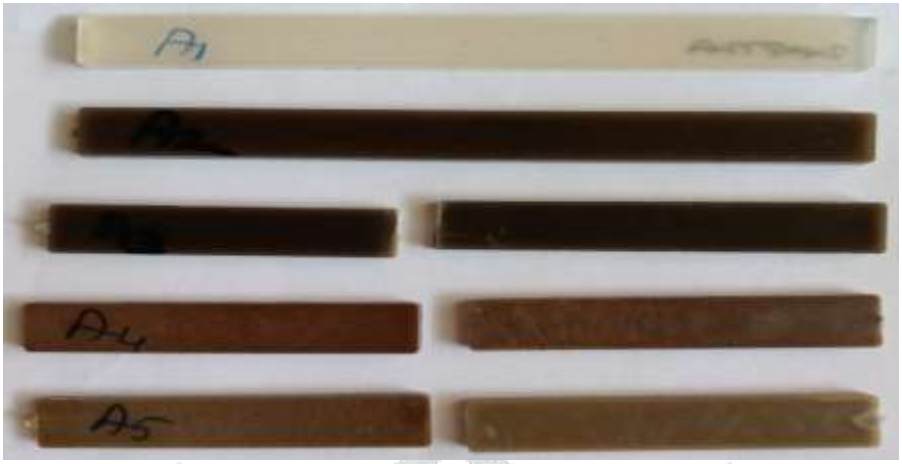


Fig. 6: Flexural testing specimens of all composition after testing.

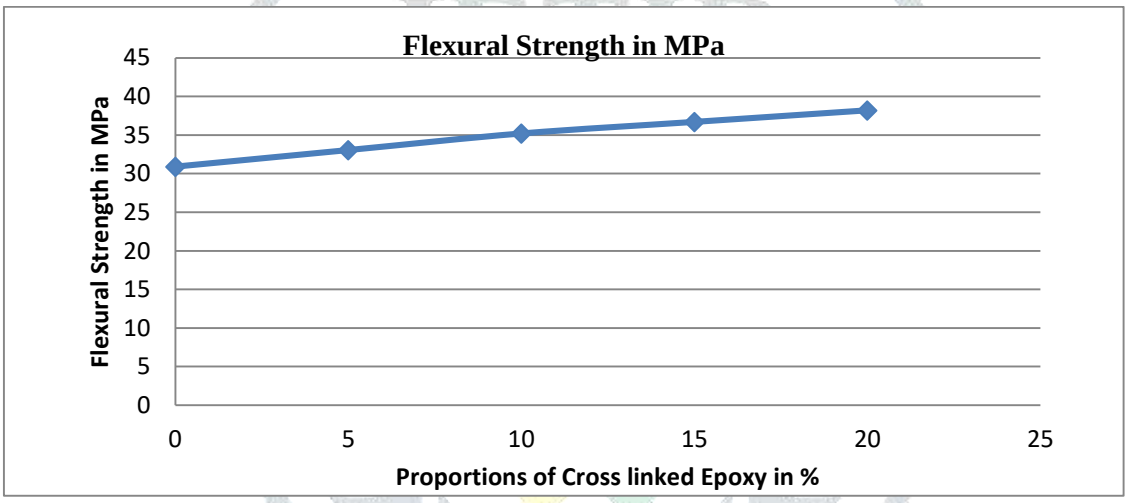


Fig. 7: Flexural strength at yield versus cross linked epoxy proportion.

Figure 7 illustrates the variation of yield flexural strength with the proportion of cross-linked epoxy microparticles. It is evident from the figure that the incorporation of cross-linked epoxy microparticles has a pronounced positive effect on the flexural strength of the polypropylene–epoxy (PPE) composites. The yield flexural strength increases progressively with increasing epoxy content. Neat polypropylene exhibits a flexural strength of 30.9 MPa, which increases to 38.2 MPa for the composite containing 80 wt% polypropylene and 20 wt% cross-linked epoxy microparticles.

Figure 8 presents the scanning electron microscopy (SEM) images of the loaded and fractured surfaces of flexural test specimens corresponding to compositions A1 to A5. Figure 8(a) shows the SEM micrograph of the loaded surface of neat polypropylene, which appears relatively smooth with visible scratch marks, and no fracture is observed at the loaded surface. In contrast, Fig. 8(e) shows the SEM image of the fracture surface of the PPE composite containing 20 wt% epoxy microparticles. The fractured surface exhibits a rough morphology with distinct grooves and ridges, characteristic of brittle fracture behavior in polymer composites. The observed improvement in flexural strength with increasing epoxy micro particle content is attributed to effective load transfer between the epoxy microparticles and the polypropylene matrix, along with enhanced energy absorption prior to failure. The increased energy absorption is evidenced by the rough fracture morphology of the composite specimens [15,16].

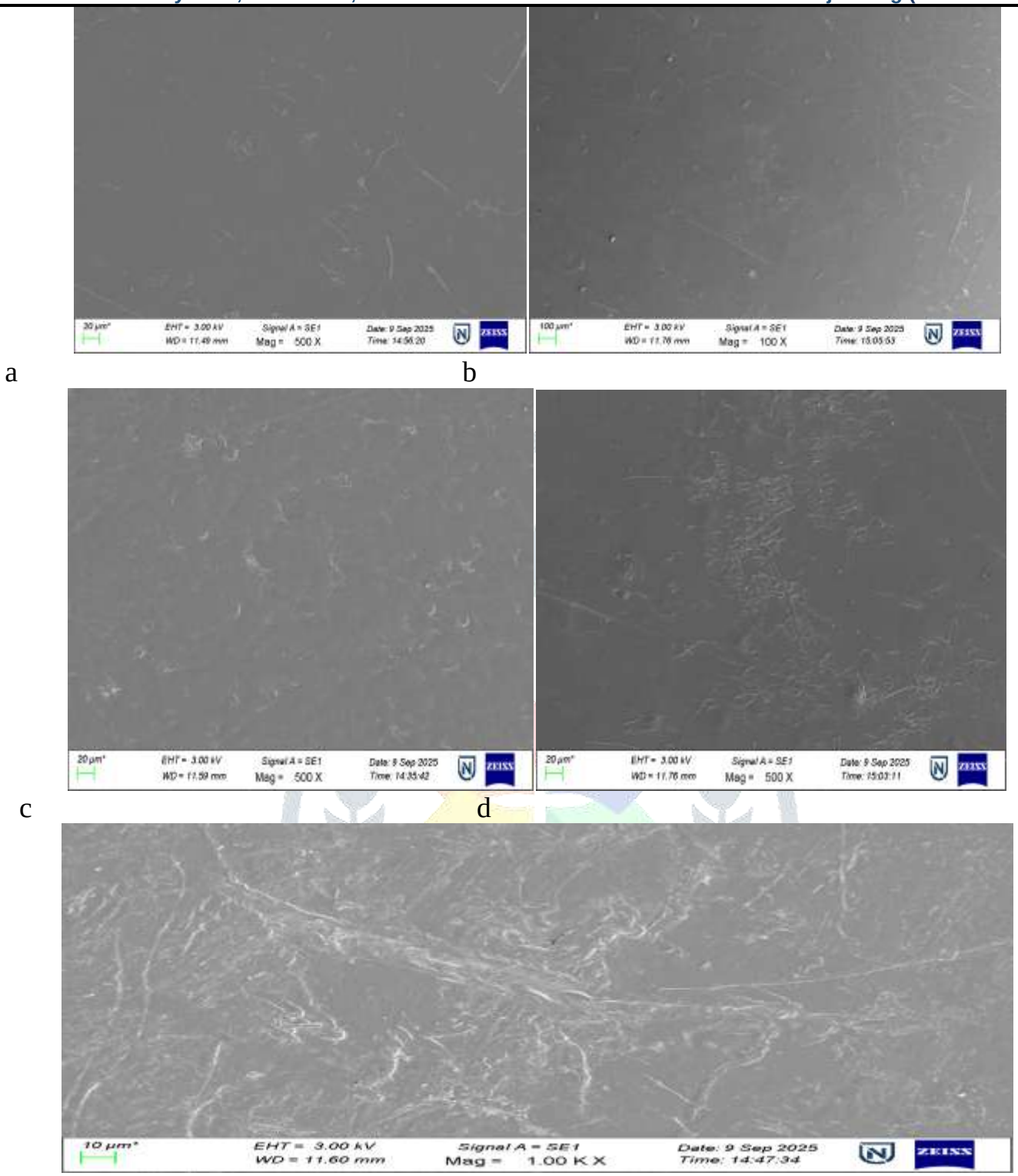


Fig. 8: Scanning Electron Microscopy at fracture surface of the Flexural test specimens of PPE composite for composition A_1, A_2, A_3, A_4 and A_5.

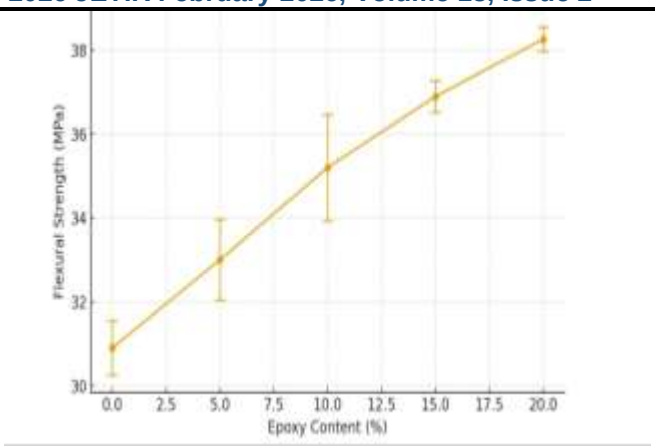


Fig. 9: Flexural strength V/S Percentage Epoxy with Error Bars.

Table 2: Shows the Mean and Standard deviation for Polypropylene–Cross Linked Epoxy Micro Particles (PPE) Composites.

PP (%)	Epoxy (%)	Mean (MPa)	Standard Deviation (MPa)
100	0	30.9	0.65
95	5	33	0.96
90	10	35.2	1.27
85	15	36.89	0.38
80	20	38.26	0.29

Figure 9 illustrates the flexural strength of polypropylene–epoxy (PPE) composites at different weight fractions of cross-linked epoxy microparticles, with corresponding error bars. The mean values and standard deviations of the flexural strength for all compositions are summarized in Table 2. The results indicate a steady increase in flexural strength from 30.9 MPa for neat polypropylene to 38.26 MPa for the PPE composite reinforced with 20 wt% cross-linked epoxy microparticles. The relatively low standard deviation values demonstrate good consistency and reproducibility of the experimental results.

To evaluate the statistical significance of the observed variations, a one-way analysis of variance (ANOVA) was performed. The calculated F-value of 58.11 indicates that the variation in flexural strength due to changes in epoxy content is substantially greater than the variation arising from experimental error. Furthermore, the p-value of 9.94×10^{-11} is significantly lower than the commonly accepted significance level of 0.05, confirming that the differences in flexural strength among the various composite compositions are statistically significant. These findings clearly demonstrate that epoxy content has a significant influence on the flexural strength of PPE composites.

Table 3: Shows the Tukey HSD Post Hoc Test for Polypropylene–Cross Linked Epoxy Micro Particles (PPE) Composites composition (Flexural strength)

Tukey HSD Results						
Group1	Group2	Mean diff	p- Value	Lower	Upper	Reject
0	5	2.38	0.003	0.73	4.03	TRUE
0	10	4.46	0.001	2.81	6.11	TRUE
0	15	5.99	0.001	4.34	7.61	TRUE
0	20	7.25	0.001	5.6	8.9	TRUE
5	10	2.08	0.02	0.43	3.73	TRUE
5	15	3.61	0.002	1.96	5.26	TRUE
5	20	4.87	0.001	3.22	6.52	TRUE
10	15	1.53	0.101	-0.12	3.18	FALSE
10	20	2.79	0.004	1.14	4.44	TRUE
15	20	1.26	0.169	-0.39	2.91	FALSE

Table 3 presents the results of the Tukey's Honestly Significant Difference (HSD) post hoc analysis for the polypropylene–cross-linked epoxy microparticle (PPE) composites. The Tukey HSD test confirms that the flexural strength of PPE composites containing 5%, 10%, 15%, and 20% epoxy microparticle reinforcement differs significantly from that of neat polypropylene, as indicated by the rejection of the null hypothesis.
Furthermore, the analysis reveals no statistically significant difference in flexural strength between PPE composites reinforced with 10% and 15% epoxy microparticles, nor between those containing 15% and 20% reinforcement, as the null hypothesis is not rejected in these comparisons.

4. CONCLUSIONS

The influence of filler content on the mechanical performance of polypropylene–epoxy (PPE) composites was investigated, and the following conclusions were drawn:
1. The flexural behavior of polypropylene–epoxy composites is strongly influenced by the proportion of cross-linked epoxy microparticles incorporated into the matrix.

2. An increase in the cross-linked epoxy microparticle content results in a corresponding enhancement in the flexural strength of the composites.

3. For applications in the automotive and aeronautical sectors requiring high flexural strength, a reinforcement level of 20 wt% cross-linked epoxy microparticles is recommended, as it provides improved mechanical performance while simultaneously promoting the recycling of epoxy waste and contributing to material sustainability

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