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A Study on Tensile Characterization of Polypropylene Reinforced with Recycled Epoxy Particles

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Abstract

Polypropylene is a thermo plastic, tensile properties of polypropylene are crucial in the real world applications as they determine structural integrity and durability. Epoxy is a thermosetting plastic finds applications in various fields like aerospace, automobile, food packing etc. A major concern is the disposal of epoxy composites after their service life, since most of the waste is sent to landfills, causing land pollution and soil infertility. In this experimental study, polypropylene composites (PPE) were fabricated with varying weight percentage (5%, 10%, 15%, and 20%) of recycled micro-epoxy particles. The composites performance was evaluated under tensile loading. The findings revealed a moderate improvement of 15% in the tensile modulus. The tensile strength was declined by 7.2% for 20% recycled epoxy proportionate and percentage elongation also decreased drastically about 52.5% with increasing epoxy particle content. The reuse of waste epoxy particles in the polypropylene matrix leads to sustainability and circular economy. The Fourier-Transform Infrared Spectroscopy (FTIR) test confirms the cross linking of the epoxy. Scanning Electron Microscopy (SEM) was employed to examine the micro structure of the composite and also to analyse the material failure behavior. The SEM images at fracture surface shows material fails due to both ductile and brittle fracture. The SEM results confirmed that the recycled micro-epoxy particles were uniformly dispersed in the Polypropylene matrix material.

Keywords: Tensile properties, Polypropylene, Recycled Epoxy, Micro-compounder injection molding, and SEM.

INTRODUCTION

Polypropylene is a versatile and widely used polymer due to its affordability, processability, and notable strength, making it applicable in multiple fields, including the automotive industry, where stiffness and dimensional consistency are crucial. The reinforcement of fibers in polymer matrices as filler materials has gained significant attention in recent research, as they offer enhanced strength and improved properties. Short fibers have been extensively used as reinforcements in polymer matrices, providing improved mechanical properties and performance. The reinforcement of short fibers in polymer matrix composites (PMC) has been explored in various studies, demonstrating their capabilities to amplify the characteristics of the matrix material. Fibers, classified as short or continuous, have been increasingly used as filler materials in polymer matrices, leveraging their high strength and suitability for reinforcement [1, 2].

Polypropylene (PP) is a polymer synthesized from propylene through a catalytic process. PP's

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high temperature resistance is a significant benefit, rendering it ideal for producing products like vessels, funnels, buckets, bottles, and trays. With its exceptional mechanical properties and color-free nature, polypropylene outperforms polyethylene in many aspects [3]. With crystallinity levels ranging from 40-60%, Polypropylene (PP) is a budget-friendly thermoplastic that offers a compelling mix of properties, including flame resistance, transparency, high thermal deflection temperature, Geometric accuracy, and reusability, suiting it to a diversified class of applications [4].

Many research investigations have explored the use of natural fibers such as Kenaf, Banana, Abaca, wood, and cellulosic fibers as reinforcements, while recent research focuses on inorganic fibers like glass and carbon fiber due to their superior stiffness and strength. Inorganic fibers, particularly glass and carbon fibers, have gained attention due to their ability to tailor the polymer composites mechanical properties significantly. The material response under tensile load is a critical property in the design of components, and its measurement is essential for understanding the behavior of FRP Composites. In contrast to metals, the fiber-reinforced polymer composite material response to tensile load relies heavily on uniform distribution and adhesiveness of fibers with the base material. The attributes of polypropylene can also be tailored by introducing micro and nano fillers like Silicon carbide, aluminium carbide, talcum powder, mica etc. The interfacial bonding between the fibers and base material is crucial in ascertaining fiber-reinforced polymer composites performance. Making dispersion and interaction are crucial factors in determining tensile strength. The glass and carbon fibers have become popular choices as reinforcements in FRP composites for various applications, several studies demonstrates their effectiveness in enhancing mechanical properties [5, 6, 7].

Epoxy is a thermoset polymer, widely used due to its high strength and chemical stability, making it ideal for industries like aerospace, automotive, electronics etc...[8]. Growing demand for lightweight material in sustainable technologies is increasing the use of epoxy polymers, which increase the production of polymeric waste. However, their disposal poses an environmental challenge as they are non-biodegradable and current recycling methods are insufficient [9, 10].

The new OECD report mentioned the potential of exhaustive global approaches like improving plastic waste collection, sorting and recycling, to suppress plastic use and waste to reduce drastically the plastic leakage into the environment. By adopting these mix of policies during the entire lifecycle of plastics—from production to disposal—countries could achieve a remarkable 96% reduction in plastic leakage by 2040 [11]. Rather than focusing on isolated policies, a comprehensive strategy targeting all stages of the plastics lifecycle offers the best chance for a sustainable future.

The global production of plastic during the year 1950 was about 2 MMT which is increased dramatically to 400.3 million metric tons [12]. The worldwide requirement of plastic was approximated 624.8 billion USD in the year 2023 and is expected to increase its demand at a CAGR of 4.2% from year 2024 to 2030(Compound annual Growth rate). The plastic usage is increasing day by day by substituting metals, glass, wood etc. and is predicted to navigate the world polymeric market in the forthcoming years. Due to its adaptability and performance, polypropylene is a preferred resin in a spectrum of industrial applications. This versatile material is employed in a wide area of applications, including packaging such as bottles, containers, packaging films etc..., automotive parts such as bumpers, dashboards etc.., toys manufacturing, and industrial components such as gears, pumps etc. Polypropylene is promising polymer which has a very good hardness, electrical and chemical resistance, stress resistance, a high liquefaction point, and adaptability. Growing demand for polypropylene in the key sectors such as construction industries and automotive is poised to boost the overall growth of the resin industry [13]. Polypropylene (PP) is manufactured from propene (or Propylene) monomer, is a low-density, stress-resistant thermoplastic. The polypropylene was discovered by Italian scientists during the mid-1950s, $(C_3H_6)_n$ is the chemical formula for this linear hydrocarbon resin and presently Polypropylene ranks as the second most produced plastic globally, surpassed only by polyethylene. The world consumption volume of polypropylene was approximately about 79.01 MMT in the year 2022.

The Polypropylene demand is anticipated to surge about 104.99 MMT by 2030 with a forecasted CAGR of 3.6% during 2023-2030 [14]. With China and India at the forefront, the Asia-Pacific region is likely to emerge as a market's dominant player. The market is also driven by the increasing focus on sustainability and recycled polypropylene. One of the key drivers behind this growth is its versatility [15].

Due to the rapid replacement of conventional materials in automotive and aerospace applications, the Epoxy Composites consumption is expected to attain a market value of 74 billion USD by 2032. The Disposal of epoxy composites after service life is the vital problem the industry is facing, because of major portion goes to land filling which leads to land pollution and infertility [16] [17]. The demand for Fiber-reinforced polymers is increasing due to their critical role in sustainable technologies, including electric vehicles and renewable energy infrastructure and lightweight construction materials to improve the efficiency [18]. It is a serious concern even though epoxy polymers accounted only for about 7.1% of world plastic production in 2021 [19]. To supply the resources required for the composite material fabrication and also to minimize the impact of epoxy waste on ecology, the development of efficient epoxy recycling technology is essential.

The increasing demand for polypropylene in consumer goods, chemicals, automobile body parts, fabrics industry, pharmaceuticals, and agro products has led to a rise in polypropylene production, which in turn has increased ecological challenges connected with polypropylene production and waste management. As a result, various life cycle assessment (LCA) studies have been undertaken to assess the environmental footprint associated with polypropylene production and waste management practices. Additionally, many methods for reusing this waste have been discussed in the context of the Gulf Cooperation Council region [20].

The mechanical properties of polypropylene and Acrylonitrile Butadiene Styrene (ABS) blend polymers can be modified with carbon black nanoparticle. The reinforcement of carbon black nanoparticle improves the structural and mechanical behavior of the polypropylene/ABS blend. Authors have reported 2.5 wt% of carbon black nano particle loading yields better tensile properties, while 5 wt% of carbon black yields better impact strength [21].

Authors experimentally investigated the mechanical characteristics of hybrid composite of SiC nano particle reinforced Carbon/basalt fiber polyester composite. The reported results revealed that, the mechanical properties of hybrid composite was improved by 20% for 15% SiC nano particle loading [22]. A new hybrid composite laminate was fabricated by reinforcing saw dust particles in the Basalt/Kevlar fiber added epoxy matrix material. The reported results shows that the highest tensile strength was obtained for 15 wt% of saw dust reinforced hybrid laminate [23]. A hybrid composite was fabricated by incorporating an inorganic nano particle such as Alumina (Al_2O_3) in a short carbon fiber added Polypropylene composite. It was found that better mechanical properties were obtained for 10 wt% and 15 wt% of short carbon fiber [24].

The work published to Eliminate Plastic Pollution by 2040 by OECD, which is an intergovernmental organization has recommended four pillars among them enhancing the recycling of plastic is one. The recycling of plastic should be increased and must reach a target to 38% from present level of 18%.

Artificial intelligence can be introduced for sustainable supply chain management in polymer composites. The AI-enabled frame work integrates predictive modeling, optimization and real-time sustainability data to support eco-friendly material selection and efficient resource utilization. The aim is to reduce environmental impact, enhance recyclability and improves operational performance in composites manufacturing [25]. This AI-driven frame work can also be employed for developing smart, sustainable polymers, enabling efficient materials discovery, personalized properties, and improved healthcare applications aligned with global sustainability goals [26].

The recycled epoxy phase enhances chemical compatibility which results in uniform transfer of stress throughout the composite. This pyramidal reinforcement system favors a semi-interpenetrating polymer network (SIPN), resulting in enhanced stiffness, strength and wear resistance without interfering with the processability of the composite. According to a review of recent literature, such reinforcement strategies have resulted in improvements in polymer performance by a significant margin. Authors reported tensile strength of PP composites reinforced with natural fibers, which was 35 % higher [27]. Nevertheless, these investigations largely concentrated on composites that were reinforced with natural and artificial fiber and/or micro and nano particles. Recycled epoxy micro-particles as fillers in a PP matrix material have not yet been studied to a large extent, and especially in a micro-compounder injection-molding setup [28].

In this work, an attempt is made to fill this research gap by using Cross linked Epoxy as a micro-filler in a polypropylene matrix material at various proportions, to investigate its impact on the tensile behavior of polypropylene. The resultant material has high structural integrity and less environmental impact. Moreover, using recycled epoxy instead of virgin resin, the study contributes to a sustainable materials engineering field and the circular economy as transformed polymer waste is used as a performance enhancing agent. The objectives of the research are thus directed at: (i) the formation of PP-Epoxy composites with the help of the scalable and repeatable fabrication process; (ii) the mechanisms of the reinforcement on the Tensile properties; (iii) the correlation of the microstructural characteristics with the tendencies of the properties; and (iv) the identification of the optimal reinforcement proportions that would result in the balanced performance.

MATERIAL AND METHOD

The primary intent of this investigation is to study the consequences of recycled epoxy micro particles proportion on tensile properties of Polypropylene. REPOL Polypropylene H350FG supplied by reliance industries limited, Jamnagar is used as matrix material which is manufactured using Unipol PP process. The Unipol PP process manufactures polypropylene using a gas phase fluidized bed reactor and a high-performance stereo specific catalyst system. Fig 1(a) shows Polypropylene raw material in the form of pallets. Epoxy resin obtained in two parts supplied by carbon black composites, Mumbai is thoroughly mixed using spatula with a mix ratio of 3:1 to get cross linked rectangular epoxy block as illustrated in fig 2(a). Fourier Transform Infrared Spectroscopy (FTIR) test is employed to ensure cross linking of epoxy material. FTIR of Cured and Uncured epoxy is as shown in fig 1(b). From the figure it can be observe that, the transmittance percentage for cured epoxy is more than uncured epoxy, changes in peak positions with increased peak width and also new peaks formed which indicates new functional groups formed during curing, ensures the cross linking of epoxy.

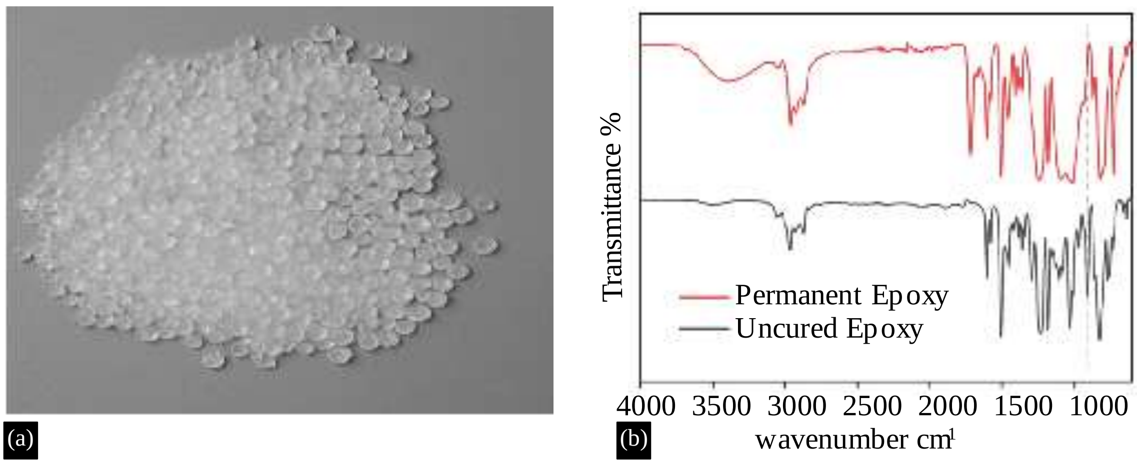


Figure 1. (a) Polypropylene H350FG Matrix Material Pallets, (b) FTIR Spectra of Epoxy before and After Cross Linking (curing). "Author's own Image"

This cross linked epoxy material is powdered to less than 50 microns using Ball milling. The polypropylene-Epoxy Composite test specimens were fabricated by compounding polypropylene with cross-linked micro epoxy powder at weight percentages of 5%, 10%, 15%, and 20% using a micro-compounder injection molding facility available at CIPET, Bengaluru. The temperature and pressure during mixing of matrix and reinforcement material was maintained at 200°C to 230°C and 500 to 600 bars respectively in the micro compounding machine.

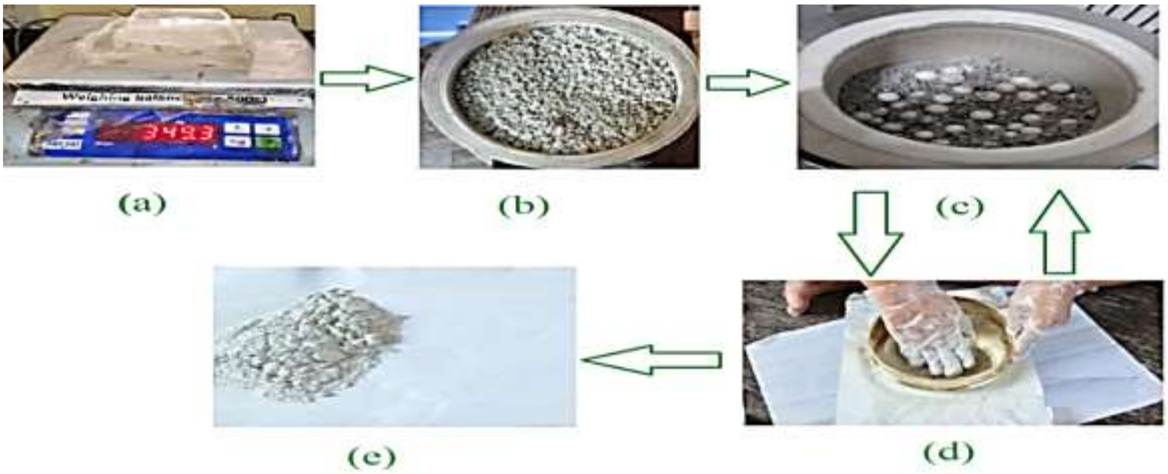


Figure 2. Graphical Abstract of Production Process of Epoxy Micro Particles from Rectangular Blocks. (a) Shows Cross Linked Epoxy Blocks, (b) Shows Epoxy Granules Obtained By Breaking Rectangular Blocks, (c) - Shows Ball Milling of Epoxy Granules, (d) Shows Sieving (At 50 Microns) of Micro Particles and (e) Shows Cross Linked Epoxy Micro Particles. "Author's own Image"

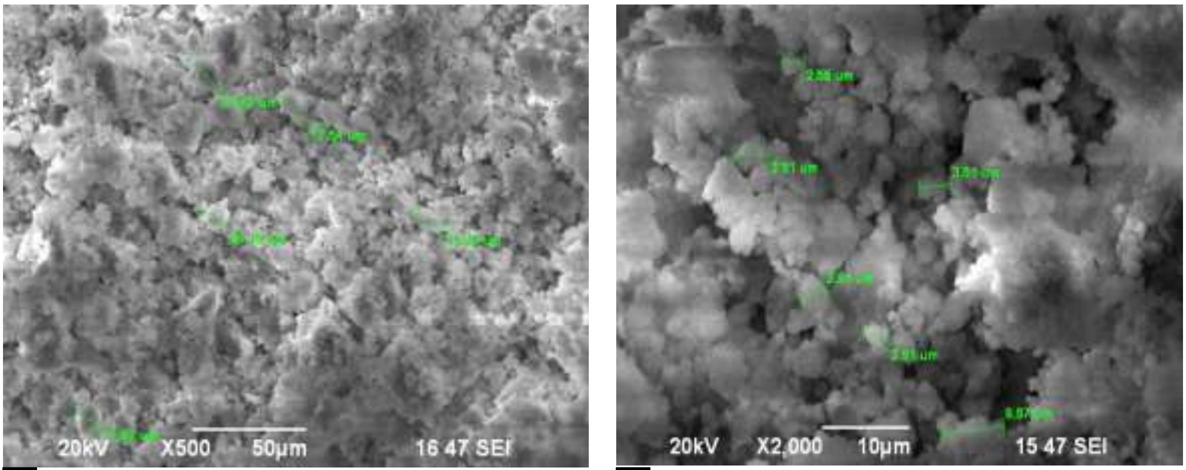
Specimens were kept in the laboratory conditions for a period of one week after fabrication for relieving the processing stresses. Testing is also done at CIPET Bengaluru according to ASTM D638 standards. Test specimens dimensions are given in the Table 1. Universal Testing Machine M/S DAK system inc., India, Model No: UTB9103 having a load capacity of 100N to 100KN and cross head speed ranging from 0.05 – 500 mm/min. was used to conduct the tensile experiment. The tensile test was conducted under standard laboratory conditions of 23±2 °C temperature and 50±5% relative humidity.

The results of these tests are reported and discussed in details.

Table 1: Dimensions of Tensile Test specimens as per ASTM638 Type V Standards.

SL. No	Parameter	Dimensions in mm
1	Overall length (Lo)	63.75
2	Gauge length (Lg)	7.62
3	Thickness (t)	3.2
4	Distance between Grips	25.4
5	Grip section Width	9.53
6	Radius of fillet (R)	12.7

Figure 2 shows the steps followed during the production process of cross linked micro epoxy particle from cross linked epoxy blocks. The epoxy blocks as shown in figure 2(a) is converted into granules as shown in figure 2(b) by hammering in an enclosed chamber. An industrial grinder is used to convert this granule into particles which is suitable for feeding the ball mill. In ball milling as shown in figure 2(c), the size of the particle is reduced to microns suitable to be used as reinforcement in Polypropylene matrix. The micro particle powder obtained from ball mill is sieved using a 50 micron sieve. Figure 2(e) shows the epoxy micro particles obtained from sieve. The size of these epoxy particles is ensured by the Scanning Electron Microscopy as shown in figure 3(a) at 500X and 3(b) at 2000X magnification. The scanning Electron Microscopy ensures the size of epoxy particles which varies from 2.91micron to 33.42 microns. The retained cross linked epoxy particles in the sieve is taken back and put it in the ball mill for further processing to reduce its size.



(a) (b)

Figure 3. SEM Images Shows Cross Linked Epoxy Particle Size Range. (a) – At 500X magnification; (b) – At 2000X magnification. "Author's own Image"

Table 2. Illustrates the Sample Code and Compositions of Polypropylene–Recycled Epoxy Microparticles (PPE) Composites.

SL. No	Sample code	PP (wt. %)	Cross linked Epoxy- E (wt.%)
1	A1	100	0
2	A2	95	5
3	A3	90	10
4	A4	85	15
5	A5	80	20

EXPERIMENT RESULTS AND DISCUSSION

The test specimens of Polypropylene–recycled Epoxy (PPE) composite were fabricated by loading recycled micro epoxy powder at a proportion of 5%, 10%, 15% and 20% in a Polypropylene matrix using micro compounder (screw extruder) injection moulding machine; utmost care had been taken during the fabrication as well as testing. It is also confirmed that six (06) specimens were fabricated and tested for each proportion of PPE composite, the mean of all six specimens test results are considered and comparative study was also carried out.

The test condition procedure followed was as per 24, the gauge length is 7.62mm, Grip length is 25.4mm, speed of the extensometer is 10mm per minute, thickness of the specimen is 3.2mm and load cell range is 0-10000N. The test findings are compared with the pure polypropylene. The above Table 2 shows the sample code and wt. % of constituents of PPE composites.

Tensile Strength

Figure 4 shows six tensile test specimens before and after testing for A_5 composite. Figure 5 shows a test specimen after testing for each composite of A_1 to A_5. Figure 6 illustrates Yield tensile strength of Polypropylene-Epoxy (PPE) composite against weight percentage of cross linked micro epoxy particles with error bars. From the figure it can be observed that, cross linked micro epoxy particles have strong impact on tensile strength of the PPE composites.

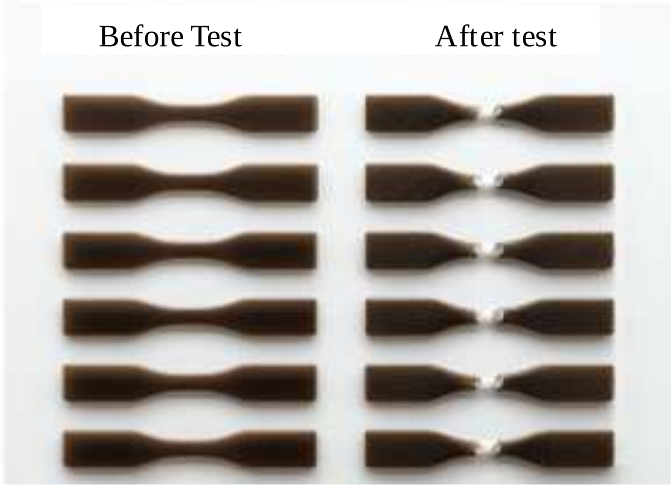


Figure 4. Tensile Test Specimens for A5 Composition before and after Testing. "Source: "Author's own Image"

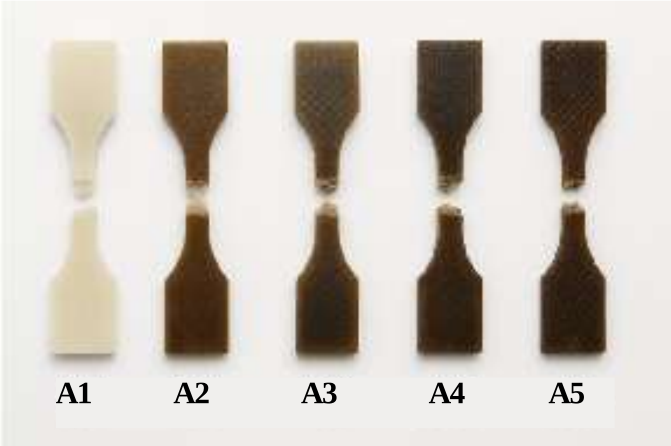


Figure 5. Tensile Test Specimens of PPE Composite after Testing. A1 – Pure polypropylene, A2 – 95/5 PP/Epoxy composite, A3 - 90/10 PP/Epoxy composite, A4 - 85/15 PP/Epoxy composite and A5 - 80/20 PP/Epoxy composite. "Author's own Image"

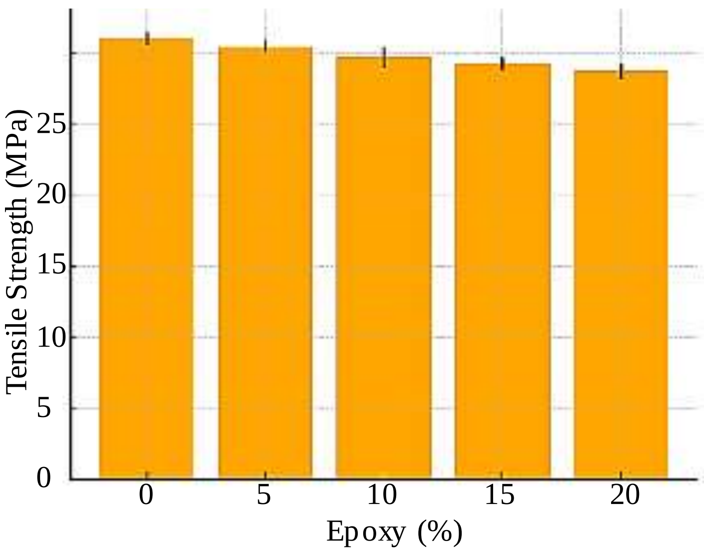


Figure 6. Yield Tensile Strength Versus Cross Linked Micro Epoxy Particles loading. (With Error Bars). "Author's own Image"

Table 3. Shows the Mean and Standard deviation for Polypropylene–Cross Linked Micro Epoxy Particles (PPE) Composites.(Tensile strength)

Polypropylene (PP) %	Epoxy (E) %	Mean (MPa)	SD (MPa)
100	0	31.08	0.48
95	5	30.50	0.42
90	10	29.75	0.73
85	15	29.29	0.44
80	20	28.77	0.58

The tensile strength trend is negative, in which tensile strength reduces slightly with increasing reinforcement of cross linked micro epoxy particles. The Mean tensile strength of neat Polypropylene is 31.07MPa reduced to 30.5 MPa, 29.9MPa, 29.3MPa and 28.76MPa (Mean of all six specimens) for composite with 5%, 10%, 15% and 20% of cross linked micro epoxy particles loading respectively. The tensile strength of PPE composite is compared with pure polypropylene, composites strength reduces about 7.4% for 20% cross linked micro epoxy particles loading. This decline is in line with the results reported by Wan Hemidon Wan Badaruzzaman *et al*. (2022), the tensile strength of composite more than 10 wt% of $CaCO_3$ Powder loading started to reduce considerably. Similar results also reported by N sathiya narayanan et.al (2024), the ultimate tensile strength of a GFRP after 5 wt% of Mg and Al_2O_3 powder reinforcement declines significantly. Similarly Praveen kumara Jagadeesh *et al*. (2023) reported, tensile strength of PE loaded with 30% of basalt powder was decremented by 10.2%. The possible reason for marginal mitigation in tensile strength of the PPE composites with the epoxy loading could be that, micro epoxy particles reinforcement led to a brittle phase, insufficient interfacial adhesion between cross linked micro epoxy particles and Polypropylene matrix material and also Microvoids, Microcracks and Porosity which acts as a crack initiation site [29]-[31].

Table 3. Shows the Mean and Standard deviation for Polypropylene–Cross Linked Micro Epoxy Particles (PPE) Composites. The Mean represents average value of all six specimens. The Standard deviation represents the specimen test results consistency. A very low standard deviation of 0.42MPa is obtained for 5 wt % cross linked micro epoxy particles loading, shows more consistent results. The composite with 10 wt % cross linked epoxy particles loading has greater variation in the results which is having a highest standard deviation of 0.73MPa. The overall standard deviation (SD) for the samples groups is ±0.73MPa, which shows the data is precise and trustworthy, the measurements are less prone to outliers and reliable conclusions can be drawn from the results. One way ANOVA was performed on the reported test results to analyse the significance of the differences between groups. The value of F is 13.91. This higher F-value denotes a significant difference between group means compared to the variance within groups. The p-value is 1.1 × 10^-5, the results are statistically significant among the groups. The epoxy content has a significant impact on the tensile strength of the PPE composite, leads to marginal reduction in tensile strength. Tukey HSD post hoc test is also performed to investigate which groups differs significantly.

Table 4 Shows the Tukey HSD Post Hoc Test results for PPE Composite. The test would provide a p-value and a confidence interval (Lower and Upper) for the group comparison, indicating whether the difference between the two groups is statistically significant or not. Tukey HSD test for the reported results confirms that, there is no significant difference in tensile strength of PPE composite between 0% & 5%, 5% & 10%, 10% & 15% and 15% & 20% epoxy loading sample groups as rejection is False and adjusted p value is more than 0.05. The test also confirms that there is a significant difference among other groups as rejection is true and adjusted p value is below 0.05.

Percentage Elongation

Figure 7 shows Percentage elongation of Polypropylene-Epoxy (PPE) composite with a weight percentage of cross linked micro epoxy particles. From figure it can be observed that, cross linked micro epoxy particles have inverse impact on Percentage elongation of the composite. The Percentage elongation of the composite decreases with increase in cross linked micro epoxy particles loading. The Mean percentage elongation of neat Polypropylene is 9.34% reduced to 8.3%, 7.3%, 5.8% and 4.43% for composite with 5%, 10%, 15% and 20% of cross linked micro epoxy particles loading respectively. The Percentage elongation of PPE composite is compared with pure polypropylene, the composite elongation reduces by 52.5% for 20% micro epoxy particles loading. These results were looking analogous to those reported by Onuoha *et al*. (2017), who showed that the recycled PP composites percentage elongation at break decremented by 50% for 25% periwinkle shell powder loading. Similar results were also reported by Praveen kumara Jagadeesh *et al*. (2024), who exhibits about 37.22% decrement in percentage of elongation of Polypropylene loaded with 30% of basalt powder. The same Authors also reported that, about 57.30% decrement in percentage of elongation of Synthetic Epoxy (SE) loaded with 30% of basalt powder. The reported results were also in good agreement with results reported by Soydal U *et al*. (2018) and Ozsoy I. *et al*. (2015). The possible reason for the reduction in percentage elongation could be that, restriction of Polymer chain mobility due to addition of rigid epoxy micro particles, Poor interfacial bonding between Polypropylene matrix material and cross linked micro epoxy particles which creates stress concentration points, leads to crack initiation at the earlier stage which restricts plastic deformation, Blending of cross linked micro epoxy particle with Polypropylene leads the composite to become stiffer but losses ductility and with the increase in tensile modulus, the PPE composite becomes rigid, which restricts the matrix material's ability to deform under the same load [32] – [35].

Table 4. Shows the Tukey HSD Post Hoc Test for Polypropylene–Cross Linked Epoxy Micro Particles (PPE) Composites composition (Tensile strength).

Group-1	Group-2	Mean Difference	p- Value adjusted	Lower	Upper	Reject
0	5	-0.58	0.4829	-1.626	0.466	FALSE
0	10	-1.3333	0.0057	-2.3348	-0.3319	TRUE
0	15	-1.79	0.0004	-2.836	-0.744	TRUE
0	20	-2.312	0	-3.358	-1.266	TRUE
5	10	-0.7533	0.2037	-1.7548	0.2481	FALSE
5	15	-1.21	0.0183	-2.256	-0.164	TRUE
5	20	-1.732	0.0006	-2.778	-0.686	TRUE
10	15	-0.4567	0.6594	-1.4581	0.5448	FALSE
10	20	-0.9787	0.0575	-1.9801	0.0228	FALSE
15	20	-0.522	0.5817	-1.568	0.524	FALSE

Table 5 shows the percentage elongation Mean and Standard deviation for PPE Composites. The Mean represents average value of all six specimens test results. The Standard deviation represents the test results consistency. A very low standard deviation of 0.6% is obtained for 5 wt % cross linked epoxy particles, shows more consistent results. The composite with 15 wt % cross linked epoxy particles has greater variation in test results which is having a high standard deviation of 1.0%. The overall standard deviation (SD) for the samples groups is ±1.0%, which shows the data is precise and trustworthy, the measurements are less prone to outliers and reliable conclusions can be drawn from the results. One way ANOVA was performed on the reported test results to analyse the significance of the differences between groups. The value of F is 30.00. This higher F-value indicates significant difference between group means compared to the variance within groups. The p-value is 3.35 × 10^-8, the results are statistically significant among the groups. The epoxy content has a significant impact on percentage elongation of the composite. Tukey HSD post hoc test is performed to investigate which groups differs significantly.

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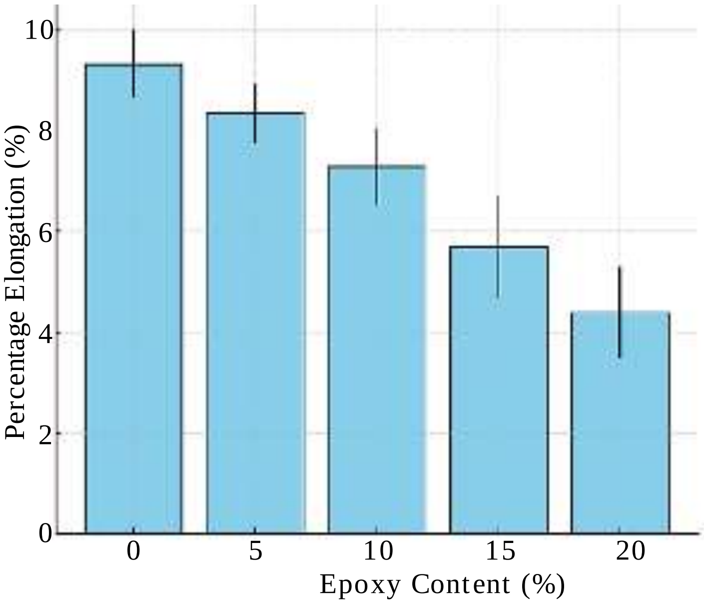

Figure 7. Percentage Elongation at Yield versus Cross Linked Micro Epoxy Particles Loading with Error Bars. "Author's own Image"

Table 5. Shows the Mean and Standard deviation for Polypropylene–Cross Linked Micro Epoxy Particles (PPE) Composites- Percentage Elongation.

Polypropylene PP %	Epoxy E %	Mean %	Standard. Deviation %
100	0	9.33	0.6
95	5	8.36	0.6
90	10	7.29	0.7
85	15	5.71	1.0
80	20	4.41	0.9

Table 6 Shows the Tukey HSD post hoc test results for Polypropylene–Cross Linked Epoxy Micro Particles (PPE) Composite. Tukey HSD test confirms that, there is no significant difference in Percentage elongation of PPE composite between 0% & 5%, 5% & 10% and 15% & 20% epoxy loading as rejection is False and adjusted p value is more than 0.05. The test also confirms that there is a significant difference among other groups as rejection is true and adjusted p value is below 0.05.

Table 6. Illustrates the Tukey HSD Post Hoc Test for Polypropylene–Cross Linked Epoxy Micro Particles (PPE) Composites composition (Percentage Elongation).

Group-1	Group-2	Mean Difference	p-value adjusted	Lower	Upper	Reject
0	5	-0.974	0.3485	-2.5069	0.5589	FALSE
0	10	-2.044	0.0058	-3.5769	-0.5111	TRUE
0	15	-3.624	0	-5.1569	-2.0911	TRUE
0	20	-4.926	0	-6.4589	-3.3931	TRUE
5	10	-1.07	0.2632	-2.6029	0.4629	FALSE
5	15	-2.65	0.0004	-4.1829	-1.1171	TRUE
5	20	-3.952	0	-5.4849	-2.4191	TRUE
10	15	-1.58	0.0414	-3.1129	-0.0471	TRUE
10	20	-2.882	0.0001	-4.4149	-1.3491	TRUE
15	20	-1.302	0.1208	-2.8349	0.2309	FALSE

Tensile Modulus

Figure 8 shows the tensile modulus of Polypropylene-Epoxy (PPE) composite against weight percentage of cross linked micro epoxy particles. From the figure it can be observed that, cross linked micro epoxy particles have strong positive impact on tensile modulus of composite. The tensile modulus of the composites improves with supplement of cross linked micro epoxy particles. The Mean tensile modulus of neat Polypropylene is 1290MPa increases to 1340MPa, 1380MPa, 1430MPa and 1480MPa for composite with 5%, 10%, 15% and 20% of cross linked micro epoxy particles loading respectively. Tensile Modulus of composite is compared with pure polypropylene, increases about 14.7% with 20% cross linked micro epoxy particles loading. These results were in agreement with results reported by Praveen kumara Jagadeesh *et al*. (2024), who showed about 29.6% increment in tensile modulus of Polypropylene loaded with 30% of basalt powder. The authors also reported that, the elastic modulus of Synthetic Epoxy (SE) and Bio-Epoxy (BE) was increased about 56.3% and 57.0% respectively with 30% basalt powder loading. These results were similar to those reported by Essabir H *et al*. (2016), Ashori A *et al* (2016) and Ebadi-Dehaghani H *et al*. (2015). The possible reason for increase in tensile modulus could be that, the PPE composite become stiffer due to blending of high density cross linked micro epoxy particles with Polypropylene matrix but losses its ductility. This improvement in tensile modulus is likely attributed to the enhanced surface area of micro epoxy particles within the polymer matrix, enabling greater elastic deformation under tensile forces [33] [36]-[39].

Table 7 Shows the Mean and Standard deviation for Polypropylene–Cross Linked Micro Epoxy Particles (PPE) Composites. The Mean represents average value of all six test specimen results. The Standard deviation represents the test results consistency. A very low standard deviation of 60.4MPa is obtained for 15 wt% cross linked epoxy particles, shows more consistent results. The composite with 10 wt% and 20 wt% cross linked epoxy particles has greater variation in measurement values, having a highest standard deviation of 176 MPa. The overall standard deviation (SD) for 0%, 5% and 15% Epoxy loading samples groups is ±71.0MPa, which shows the data is precise and trustworthy, the measurements are less prone to outliers and reliable conclusions can be drawn. One way ANOVA is also performed. The value of F is 3.25. This F-value indicates a no significant difference between group means compared to the variance within groups. The p-value is 0.0328 which is lesser than threshold value of 0.05. The results are statistically significant among the groups. The epoxy content has a significant impact on percentage elongation of the PPE composite. Tukey HSD post hoc test is performed to investigate significant differences between the sample groups.

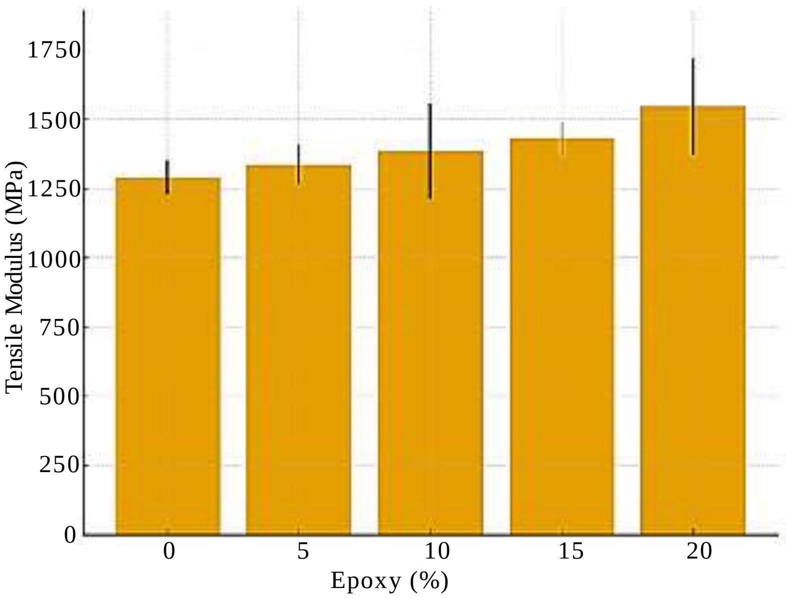

Figure 8. Yield Tensile Modulus versus Cross Linked Micro Epoxy Particles Loading with Error Bars. "Author’s own Image"

Table 7. Shows the Mean and Standard deviation for Polypropylene–Cross Linked Micro Epoxy Particles (PPE) Composites- Tensile Modulus.

Polypropylene PP %	Epoxy %	Mean (MPa)	Standard Deviation (MPa)
100	0	1290	61.6
95	5	1336	71.0
90	10	1384	172.1
85	15	1431	60.4
80	20	1544	176.0

The Table 8 Shows the Tukey HSD Post Hoc Test results for Polypropylene–Cross Linked Epoxy Micro Particles (PPE) Composite. Tukey HSD test confirms that, the 20% epoxy group had a significantly higher tensile modulus compared to pure Polypropylene group as rejection is True and p=0.0251 which is lesser than threshold value of 0.05, while other pair wise comparisons were having no significant differences as p value is more than 0.05 and rejection is False.

The statistical analysis conducted in this study is subjected to several limitations. The number of specimens tested for each composition was limited to six, which may influence the reliability of the derived conclusions. Variations arising from composite fabrication processes, such as inconsistencies in mixing, curing or recycled epoxy particles distribution, can introduce scatter in the measured tensile properties. The ANOVA procedure relies on assumptions of normality, homogeneity of variance, and independence, and any deviations from these assumptions may affect the robustness of the statistical outcomes. In addition, only selected factors and parameter ranges were examined, thereby limiting the generalizability of the findings to broader material systems.

Table 8. Shows the Tukey HSD Post Hoc Test for Polypropylene–Cross Linked Epoxy Micro Particles (PPE) Composites composition (Tensile Modulus)

Group-1	Group-2	Mean Difference	p- value adjusted	Lower	Upper	Reject
0	5	46	0.97	-182.85	274.85	FALSE
0	10	94	0.74	-134.85	322.85	FALSE
0	15	141	0.38	-87.85	369.85	FALSE
0	20	254	0.03	25.15	482.85	TRUE
5	10	48	0.97	-180.85	276.85	FALSE
5	15	95	0.73	-133.85	323.85	FALSE
5	20	208	0.09	-20.85	436.85	FALSE
10	15	47	0.97	-181.85	275.85	FALSE
10	20	160	0.26	-68.85	388.85	FALSE
15	20	113	0.59	-115.85	341.85	FALSE

FRACTOGRAPHY OF TENSILE TEST SPECIMENS

The below Figure 9 indicates the Scanning Electron Microscopy at fracture surface of tensile specimens. Fig 9(a), (b), (c), (d) and (e) shows Scanning Electron Microscopy images of sample A1, A2, A3, A4 and A5 at fracture surfaces respectively.

Figure 9(a) shows the Scanning Electron Microscopy at fracture surface of Pure Polypropylene at 500X magnification. In thermoplastic polymers, crazing is a deformation mechanism involving localized plastic deformation with fibrils and micro voids. The surface looks relatively smooth with river-like patterns and ridges, rather than deeply dimpled or rough. There are regions of cleavage facets, suggesting brittle fracture zones. Crack paths running across the surface can be observed, indicating a direct propagation of cracks without much energy absorption.

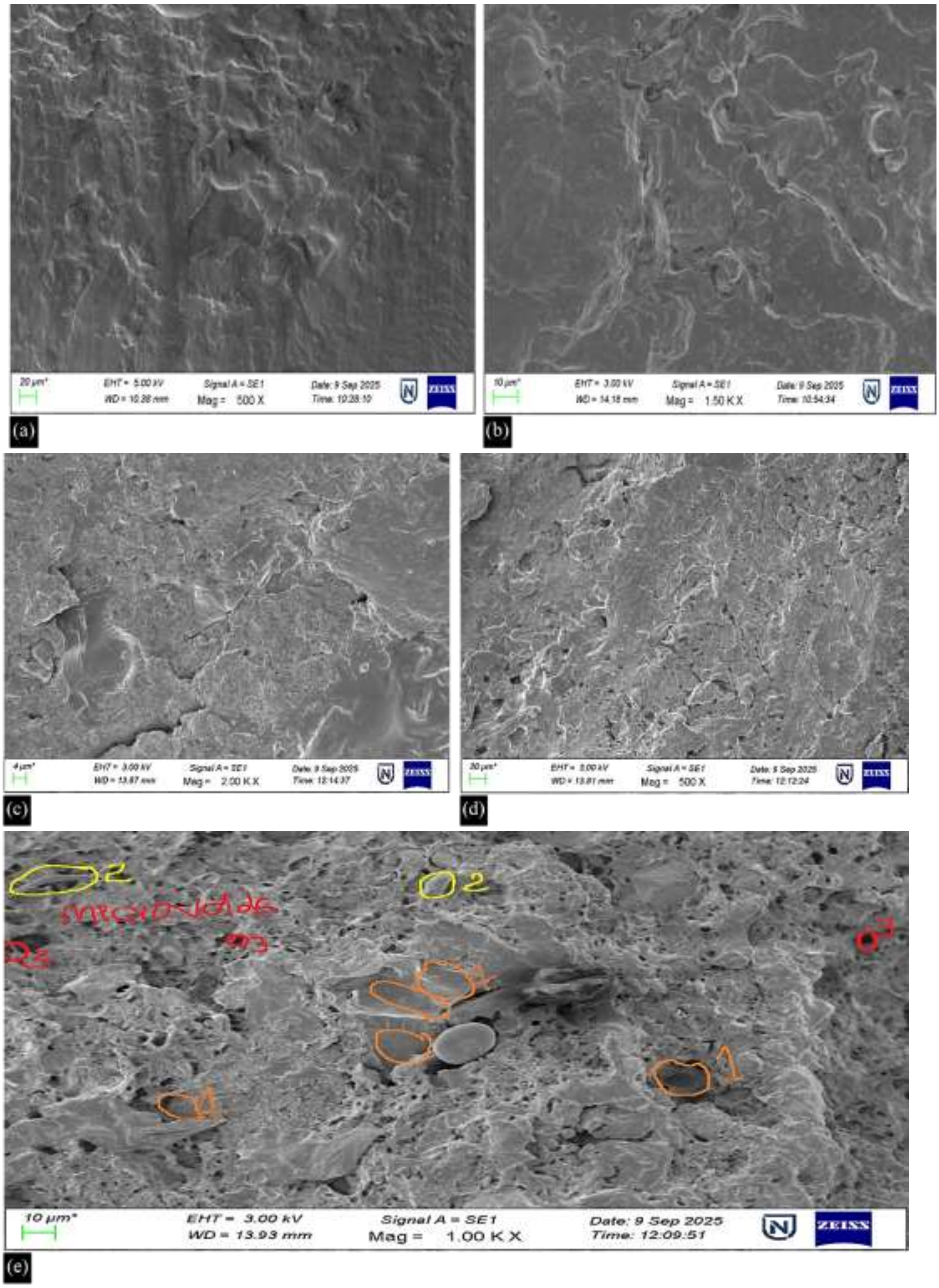

Figure 9. Scanning Electron Microscopy Images at Fracture Surface of Tensile Specimens. (a) Pure polypropylene -A1, (b) 95/5 PP/Epoxy composite - A2, (c) 90/10 PP/Epoxy composite - A3, (d) 85/15 PP/Epoxy composite - A4 and (e) 80/20 PP/Epoxy composite - A5. "Author's own Image"

SEM images of tensile test specimen with 20% of cross linked micro epoxy particles loading (A_5) is taken in to study the fracture behavior as this composition shows the lowest Tensile strength and Percentage elongation and also highest tensile Modulus properties compared to other proportions.

Figure 9(e) shows SEM at fracture surface of specimen A_5 at 1000X magnification. It can be observed that, there is no much appreciable deformation takes place before specimen fractures. It also ensures the uniform distribution of cross linked Micro Epoxy particles in the matrix material. Micro Epoxy particle separation (1), matrix material cracking and breaking (2), Microvoids (3), hackles, de-bonding (4) and cleavage facets represents the brittle fracture but small amount of dimple or rough surface and layered zone indicates ductile fracture. Considering both aspects it is concluded that the specimen exhibits both brittle and ductile fracture behavior.

CONCLUSIONS

In this novel work a new composite material is successfully manufactured using micro-compounding injection moulding machine by loading recycled thermoset (Epoxy particles) as filler in a thermoplastic (Polypropylene) matrix material. The high percentage of micro epoxy particles loading (more than 10%) inside the molecular chain of Polypropylene polymer had a remarkable impact on week intermolecular forces, stress concentration leads to crack initiation at the early stages (as shown in figure 9(d) & (e)) and load bearing capacity of the Polypropylene leads to lowering the Yield tensile strength [29]-[31] and percentage elongation of PPE composite [33]-[35]. In this unique framework, the micro epoxy particles enhances the Tensile modulus of the composite, which might have increased due to restricted movement of molecules in the polymer matrices and matrix material become stiffer due to blending of high density fillers[36]-[39]. With the minor alteration of tensile properties of composite, it possible to reuse 10% of epoxy, which implies that at this proportion, the mechanical properties of polypropylene are marginally altered. For applications in aeronautics and automotive industries where high tensile modulus is required, 20% of cross-linked epoxy can be reused. It promotes epoxy recycling which leads to sustainability. The micro epoxy content has strong impact on percentage elongation of composite as the value of F=30, followed by tensile strength where the value of F=13.91 and least affected on tensile modulus as the value of F=3.25. Mechanical properties reported were verified by SEM micrographs that revealed a homogeneous dispersion of reinforcement, excellent fiber-matrix bonding, and fracture attributes of ductile and brittle nature. The agglomeration and poor wettability were caused by excessive reinforcement loading (>15 wt. % Epoxy) and local stress concentration resulted in decreased performance.

LIMITATIONS AND FUTURE SCOPE

Fabrication of the new composite material of Polypropylene (PP) reinforced with recycled micro epoxy particles involves multiple scientific and engineering challenges due to fundamentally different chemical and physical properties of the two materials such as incompatibility between phases, processing temperature mismatch etc. Another key challenge is that reducing the size of recycled epoxy particle to micro size is tedious and energy consuming for lab level productions, but it can be overcome by scale up the production process. The development of polypropylene composites reinforced with cross-linked epoxy micro-particles opens up a diverse range of future research opportunities. By addressing challenges related to interfacial adhesion, particle dispersion, and recyclability, and by exploring novel functionalization and hybridization strategies, this field holds significant potential for next-generation lightweight, multifunctional, and sustainable materials across automotive, packaging, electrical, and structural applications. Another area for investigation is that, the present study uses micro sized fillers; the size of the fillers can be reduced to nano scale which increases the surface area. These studies can facilitate the identification of optimal formulations that balance rheological and mechanical properties. Another key area for further study is that, hybrid composite can be fabricated by loading different fibers and nano fillers with the optimized proportion of micro epoxy particles in a PP matrix desired by the applications.

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