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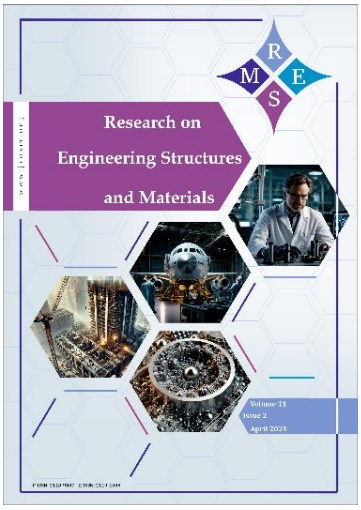

Fabrication and mechanical behavior of Kevlar® fabric-reinforced epoxy matrix composites modified by potassium titanate whiskers

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Online Publication Date: 20 August 2025

URL: http://www.jresm.org/archive/resm2025-632me0120rs.html
DOI: http://dx.doi.org/10.17515/resm2025-632me0120rs

Journal Abbreviation: *Res. Eng. Struct. Mater.*

To cite this article
Ravikiran K B, Sudheer M. Fabrication and mechanical behavior of Kevlar® fabric-reinforced epoxy matrix composites modified by potassium titanate whiskers. *Res. Eng. Struct. Mater.*, 2025; 11(6): 3393-3404.

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Research Article

Fabrication and mechanical behavior of Kevlar® fabric-reinforced epoxy matrix composites modified by potassium titanate whiskers

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Article Info

Article History:

Received 20 Jan 2025

Accepted 15 Aug 2025

Keywords:

Aramid epoxy;
Whiskers;
Hand lay up;
Mechanical tests;
Polymer matrix composites

Abstract

Polymer matrix composites have become quite popular in the field of materials engineering owing to their high strength to weight ratios and cost effectiveness. Several synthetic fibers have been employed as reinforcement with thermoset resin as the matrix in order to achieve improved mechanical or tribological performance of the composite. A secondary reinforcement known as filler is believed to further enhance these properties. In this paper, the influence of Potassium Titanate Whiskers (PTW) as reinforcing fillers on the mechanical performance of Kevlar ® /Epoxy composite combination has been discussed. Composite samples were fabricated by hand lay-up method followed by compression by altering the weight percentage of the whiskers in the order of 0%, 2%, 4%, 6% and 8%. Mechanical tests like tensile, flexural, impact and hardness were conducted on the developed composite samples as per ASTM standards. The results indicated that the inclusion of PTW into Kevlar® /Epoxy system influenced the mechanical properties of the composites. Compared to the unfilled composites, the tensile strength increased by 6.39%, flexural strength increased by 6.32%, impact strength increased by 22.96%, and Shore D hardness value increased by 9.62% for 2 wt. % PTW. However, the mechanical properties showed a declining trend beyond PTW loading of 2 wt. %. Selected tensile specimens were analyzed through Scanning Electron Microscope (SEM) images to understand their failure mechanisms.

1. Introduction

Polymer Matrix Composites (PMC), sometimes referred to as organic matrix composites are a class of composites which have become increasingly popular in recent times due to their ease in processing compared to metal or ceramic matrices, possessing of lesser weight and exceptional mechanical performance. As a result, these polymer composites are employed in a variety of applications ranging from household to aeronautical, from construction to military, from marine to electronics and so on [1,2]. The polymer used in a PMC may be either a thermoplastic or a thermosetting material. Though thermoplastics offer several advantages including lower cost than most of the metallic matrices, their non bio-degradable nature poses a greater challenge. On the other hand, though thermosets cannot be reshaped or recycled, they are highly cost effective compared to their thermoplastic counterparts and are ideal for high temperature applications.

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DOI: http://dx.doi.org/10.17515/resm2025-632me0120rs

Thermosetting polymers like phenolic, polyimide, polyurethane etc. have been used as matrix materials elsewhere [3-5]. Epoxy is a polymer which has become increasingly popular among the thermosetting resins, owing to its exceptional adhesion, tensile strength and chemical stability. It is noteworthy to mention that a few researchers have also attempted the fabrication of polymer composites with epoxy resin modified by additives, curing agents or fillers in order to improve the mechanical performance of the epoxy matrix [6-10].

It is a well-known fact that a composite material comprises of a particle or a fiber phase along with the matrix phase. In recent times, Fiber Reinforced Polymer (FRP) Composites are employed in applications like construction, automotive, aerospace, marine [11]. The fiber reinforcements are either naturally available or are synthetic. Natural fibers offer advantages like biodegradability and ease of processing. In spite of this, their incompatible quality, absorption of moisture and reduced impact properties restrict their usage to some extent. Contrary to this, the synthetic fibers being more durable and wear resistant have gained popularity in tribological applications. Literatures reveal that fibers of banana, rice husk, kenaf, chicken feather, cotton, sisal, jute have been used as natural reinforcements, while those made of glass, carbon, basalt, Kevlar® have been used as synthetic reinforcements. Kevlar® is a type of aramid fiber which offers greater tensile strength than carbon fibers, possesses excellent chemical resistance, lesser weight and is nearly unaffected by moisture. Hence, it is a popular material for body armors, ballistic garments and boats [12]. In addition to the matrix and fiber phases, it is customary to incorporate one or more materials as fillers within the matrix phase in order to further improve the mechanical or tribological performance of the PMC. The resulting composite is generally termed as a hybrid composite material. Fillers may be inorganic, organic or metallic with their sizes varying from micron to nano levels. In recent times, filler materials in the form of whiskers have gained significant attention, particularly for tribological applications. These whiskers are a type of single crystal acicular materials when observed under microscope. However, they appear in powdery form with their length ranging from a few to hundred microns. They have a definite aspect ratio and are nearly defect-free due to their small diameter. Whiskers when reinforced with polymers are known to exhibit extraordinary mechanical and physical properties [13]. Whiskers of SiC, Si_3N_4, Aluminum Borate, $CaCO_3$, ZnO, MgO, $CaSO_4$, SiO_2, TiO_2 etc. have been employed as fillers elsewhere [14]. Among the aforementioned whiskers, ceramic whiskers like SiC, ZnO, MgO etc. dominate the metallic whiskers owing to their enhanced strength capabilities and are widely employed with polymer matrices. Potassium Titanate whisker (PTW) is one such inorganic ceramic whisker which possesses outstanding mechanical properties and is a cost effective alternative to SiC in most of the applications involving friction and wear. They have a tunneling structure which makes them chemically and physically stable [15]. Though PTW are used as thermal and electrical insulating materials, yet their most popular application continues to be as a reinforcement in polymer composites. Currently, polymer resins employed with PTW include Polyetheretherketone (PEEK), Polyamide-6, Polyamide-66, Acrylonitrile Butadiene Styrene (ABS), Poly Vinyl Chloride (PVC) and polycarbonate (PC). S.C. Tjong et. al [16] developed ABS/PC blended composites with PTW as reinforcement. Mechanical tests revealed that the tensile strength of ABS/PC as well as ABS blends increased with the PTW content. But the tensile strength of PC/PTW blends decreased with the whisker content. This was attributed to the decomposition of PC during compounding, which was further stimulated by these whiskers. The results also emphasized on the fact that PTW can be used to increase the strength of the ABS/PC composites up to 40 wt. % PC. M. Sudheer et al. [17] investigated the mechanical properties of Glass/Epoxy filled with PTW and observed that the tensile strength of the filled composite decreased by 11 % compared to the unfilled composite. These whiskers restricted the plastic deformation of epoxy, thereby lowering its failure strain under tensile conditions. However, a small quantity of graphite added into PTW filled composites improved the tensile strength by 6%. H. Bettegowda et al. [18] developed polyethersulfone (PES)/short carbon fiber (SCF) composite with PTW and ultra-high molecular weight polyethylene (UHMWPE) as fillers. The results of mechanical tests revealed that adding 5 wt. % PTW improved the tensile and flexural properties of the composite, but decreased its impact property. B. Suresha et al. [19] performed mechanical tests on carbon/epoxy system modified with PTW fillers. Results indicated that inclusion of PTW improved the tensile strength as well as modulus of the composites up to 5 wt. %, beyond which it reduced. While aspect ratio and stress between the interfaces remain the same, the increase in tensile properties is owing to the increase in the interaction between the filler and the matrix. There exists only a limited work in literatures reported on studying the effect of incorporating these whiskers as reinforcing fillers in an epoxy polymer matrix. This paper attempts to present a study of the influence of PTW addition on the mechanical properties of Kevlar®/epoxy composites.

2. Experimental Details

2.1. Materials

In this study, two different types of reinforcements were incorporated into the epoxy matrix namely, a woven fabric and a whisker. High strength and high modulus plain woven Kevlar® fabric having aerial density 220 GSM and filament diameter 12 μm was used as the macro scale reinforcing filler. It was procured from CF Composites, New Delhi, India. PTW of diameter 0.2—2.5μm and length 10—100μm was used as the micro scale ceramic reinforcing filler, procured from Hangzhou Dayangchem Co. Ltd., Hong Kong. Room temperature curing epoxy LY556 was used as the matrix material and HY951 as the amino based hardener. The polymer was supplied by M/S Herenba Instruments & Engineers, Chennai, India. The epoxy and hardener were mixed in the proportion 10:1 by weight, as provided by the supplier. Some of the salient properties of fiber, matrix and filler materials used in the study, as provided by the respective suppliers, is presented in Table 1. The Kevlar ® fibers and PTW were used for fabrication of the PMC without subjecting them to any surface modifications.

Table 1. Salient material properties

Property (Unit)	Kevlar®	Epoxy	PTW
Tensile strength (GPa)	3.097	0.093	7
Young's Modulus (GPa)	105	3	280
Density (g/cc)	1.44	1.15	3.185

2.2. Methodology

The composite samples were prepared adopting hand layup technique followed by compression in a Universal Testing Machine (UTM) by varying the filler weight percent in the order of 0 %, 2 %, 4 %, 6 % and 8 %. (600 kN, Model UTN60, Fuel Instruments & Engineers Pvt. Ltd., Maharashtra, India). Two mild steel plates of 400 x 600 x 10 mm^3 were used as the top and bottom mold plates. The mold plates were tightly wrapped with PVC (Poly Vinyl Chloride) sheets leaving no air gap between the mold plate and the sheets. Duct tapes were adhered on the center of the bottom mold plate upon which the fiber layers are laid, so as to form a boundary around the sample. This was also done in order to ensure that there was little or no resin starving regions in the sample. The PVC sheets were then applied with wax coating for easier release of the sample from the mold plates.

To begin with, 9 layers of Kevlar® fibers of size 300 x 300 mm were cut from the fabric roll and weighed. The choice of the number of layers was based on the sample calculations to achieve the recommended thickness of 3 mm. The fiber weight percent was kept constant at 50 % and different samples were fabricated by altering the weight percent of PTW. A known quantity of PTW fillers were added to a ceramic crucible and preheated to 80° C for 2 hours in a hot air oven to get rid of any moisture present. It was then allowed to cool down to ambient temperature outside the oven. Hao et. al [20] reported that whiskers are vulnerable to damage during processing because of their large aspect ratios, and hence high speed mixers are not suitable. So, after 24 hours, the whiskers were steadily introduced into epoxy and continuously stirred using mechanical mixing method until uniform dispersion was achieved. The amino based hardener was then added to the resin-whisker mixture in the ratio 1:10. This mixture was applied on the 9 plies of Kevlar® fabric one after another and subjected to rolling for uniform adhesion of individual layers. Care was taken to ensure that enough time was available for coating all the layers. After the final layer was laid, it was allowed to settle for 15 minutes and finally the top mold plate was placed over it. This was followed by subjecting the mold plates to compression in an UTM under a load of 250 kN. The sample was released from the mold plate after 24 hours of curing time. The fabricated samples had dimensions 300 x 300 x 3 mm^3. For comparison, Kevlar®-epoxy composite samples without the inclusion of whiskers were also fabricated using hand layup.

Following the identical conditions and methodology, three samples for every weight percent of PTW was prepared. Each sample so prepared was carefully machined to obtain three specimens for conducting mechanical tests like tensile, flexure, impact and hardness as per ASTM standards. All specimens were machined using a switch board cutting machine. A flowchart showcasing the various stages of fabrication is presented (Fig. 1).

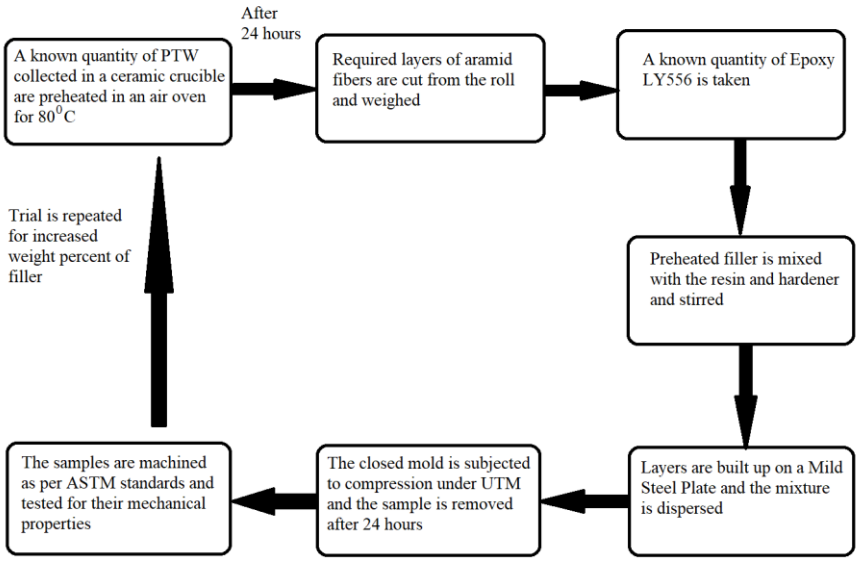


Fig. 1. Flowchart describing the various stages of fabrication

The details of the fabricated composite samples with regard to their composition and designation is presented in Table 2.

Table 2. Composition and designation of composites

Composite designation	Composition of materials		
	PTW (wt. %)	Kevlar® fibers (wt. %)	Epoxy (wt. %)
EK0	0	50	50
EK2	2	50	48
EK4	4	50	46
EK6	6	50	44
EK8	8	50	42

2.3. Mechanical Tests

All the mechanical tests were performed as per ASTM standards and at room temperature. R. F. Faidallah et. al [21] conducted studies on the efficacy of various geometries of the tensile specimen and concluded that a rectangular section specimen exhibited greater tensile strength as it eliminated the stress concentration effect at the gripping ends and the specimen would fail near the gauge length portion. Keeping this in mind, the tensile test was conducted on a Computerized twin screw UTM (Model Vector, International Equipments, Mumbai, India) according to ASTM D 3039 using a rectangular specimen having dimensions 150 x 12.5 x 3 mm^3. The loading capacity of the UTM was 1000 kg with a resolution of 0.1 kg, the cross travel was 1000 mm and the cross head speed was 2 mm/min. The Izod Impact test was conducted as per ASTM D256—10 on a Computerized impact tester (25 J, Model LT-160, International Equipments, Mumbai, India) with specimen dimensions 60 x 12.5 x 3 mm^3 using R4 hammer, resolution 0.05 J and a V-notch of 2 mm (Motorized notch cutter, International Equipments, Mumbai, India). Three-point flexure test was performed on the same computerized twin screw UTM as per ASTM D790–10 with specimen dimensions 90 x 12.5 x 3 mm^3, span length of 50 mm, cross head speed of 2 mm/min, and the travel limit was also set to 50 mm to reduce the waiting time after performing the test. Shore D hardness test was conducted as per ASTM D2240 using a Shore D Durometer (Model 560–10D, Gain Express, Hong Kong) having measuring range from 0–100 Shore D units (HD), resolution of 0.5 HD and 30° cone indentor, indentation depth of up to 2.5 mm and measuring force of up to 44.5 N. The images of tensile, flexure and impact test specimen before conducting the test for 2 wt. % PTW is shown (Fig. 2) and Fig. 3 illustrates the various mechanical tests conducted along with the fractured tensile test specimen.

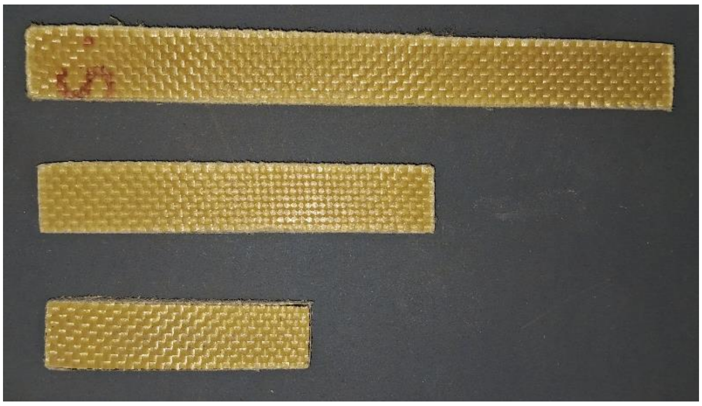


Fig. 2. The machined tensile, flexural and impact test specimen (2 wt. % PTW)

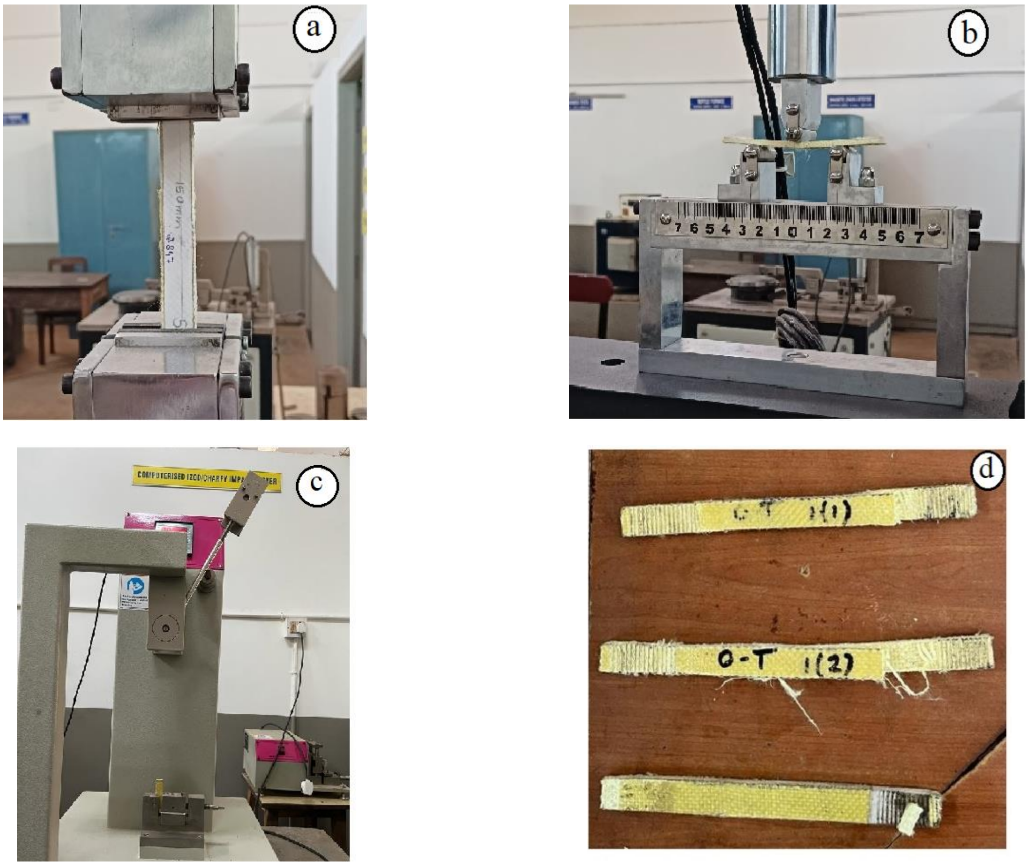


Fig. 3. (a) Tensile test (b) Flexure Test (c) Izod impact test (d) Broken tensile test specimen

3. Results and Discussion

The results reported in this section represent the average values of the mechanical properties of the three samples. From every sample, three specimens were taken for conducting each of the mechanical tests.

3.1. Hardness

The Shore D hardness measurements indicated a significant enhancement in surface resistance with the incorporation of PTW into the Kevlar®-epoxy composite system. Specifically, the composite designated EK2 exhibited a hardness of 76 HD reflecting a 9.62% increase over the unfilled composite EK0 (69 HD). This increase in hardness could be attributed to the moderate hardness (Mohs scale 4) of PTW, which when introduced into a softer epoxy matrix, resists the surface deformation of the composite and improves resistance to surface indentation. Few studies [22] reveal that at lower filler concentrations (typically up to 3 wt. %), the whiskers tend to disperse uniformly within the matrix, facilitating effective reinforcement of the surface. However, a reverse trend was observed in the EK4 composite, where the hardness decreased by approximately 5.26% compared to EK2. This decline is likely a consequence of the poor dispersion of these whiskers at higher filler loading, which can promote agglomeration and generate localized stress concentration. Such zones not only deteriorate load transfer capability but also introduce microstructural weaknesses that reduce the material's ability to resist indentation. As the PTW content increased further in EK6 and EK8, the hardness values stabilized around 71–72 HD. This plateau suggests that beyond a certain threshold, the reinforcing effect of PTW becomes saturated, and additional filler content contributes marginally to mechanical improvement. Nevertheless, the EK8 composites exhibited 3.96% higher hardness than neat epoxy (EK0).

3.2. Impact Strength

The Izod impact test results revealed that the incorporation of PTW significantly influenced the impact strength of the Kevlar®-epoxy composites. The results indicated that the EK2 composite demonstrated an impact strength of 1.828 J/mm reflecting a 22.96% increase compared to the unfilled composite EK0 (1.487 J/mm). These whiskers being quite rigid serve as reinforcement, acting as a barrier to crack growth particularly at lower concentrations thereby increasing the composite's impact energy absorption. At these concentrations, the whiskers are more likely to be uniformly dispersed, forming an efficient interface for stress transfer and acting as effective barriers to crack initiation and growth. However, a decline in impact performance was observed at higher filler loadings. The EK8 composite exhibited a reduced impact strength of 1.412 J/mm, which is 5.04% lower than that of EK0. This suggests that higher concentration of PTW decreased the capability of Kevlar®/Epoxy composites to curb the impact load. This could be likely due to agglomeration of whiskers and such clustering can act as stress concentrators, resulting in weakened performance of the composite under impact conditions. These findings are consistent with prior studies [23] indicating that high loadings of ceramic fillers, particularly those with high aspect ratios like PTW, tend to embrittle polymer matrices and reduce their impact energy absorbing capacity. Interestingly, intermediate PTW loadings showed a non-monotonic trend with intermittent increases in impact strength, which may be indicative of the formation of a semi-continuous whisker network within the matrix. Such a microstructure could enhance load transfer efficiency, thereby boosting its toughness temporarily. The variation of impact strength and Shore D hardness values with respect to the whisker content is illustrated in Table 3.

Table 3. Impact strength and hardness of various composites

Composite designation	Material property(Unit)	
	Impact strength (J/mm)	Shore D hardness (HD)
EK0	1.487 ± 0.72	69
EK2	1.828 ± 0.76	76
EK4	1.295 ± 0.42	72
EK6	1.722 ± 0.52	71
EK8	1.412 ± 0.38	72

3.3. Tensile Properties

Table 4 presents the variation of tensile strength, tensile modulus and percentage elongation at break with respect to the whisker content. The tensile test results revealed a notable influence of PTW incorporation on the mechanical performance of Kevlar®-epoxy composites. The EK2 composite exhibited a 6.39% increase in tensile strength compared to the neat epoxy composite (EK0), suggesting that at low filler concentrations, PTW effectively reinforces the matrix. This increasing trend is more likely because of the efficient bonding of PTW with epoxy and an adequate dispersion of these whiskers, which must have improved the composite's load transfer capabilities and resistance to crack growth. However, as the PTW content was increased to 4 wt.% (EK4), the tensile strength dropped significantly, by approximately 23.66%. This degradation in strength can be attributed to several factors. Firstly, these ceramic whiskers increase the viscosity of the matrix at higher loading which result in poor wetting and void formation during processing. Secondly, increased PTW content might have possibly made the matrix more brittle, reducing the composite's tensile strength. Beyond 4 wt.% PTW loading, the tensile strength plateaued, with no significant recovery observed even at 8 wt.% (EK8), which exhibited a 16.87% reduction in tensile strength relative to EK0.

Table 4. Tensile properties of various composites

Composite designation	Material property (Unit)		
	Tensile modulus (GPa)	Tensile strength (MPa)	Percentage elongation (%)
EK0	3.48 ± 0.25	368.8 ± 34.63	12 ± 0.78
EK2	3.86 ± 0.57	392.3 ± 39.35	12 ± 1.35
EK4	3.26 ± 0.47	299.5 ± 28.26	15 ± 0.42
EK6	3.29 ± 0.42	314.0 ± 48.45	18 ± 1.09
EK8	3.41 ± 0.29	306.5 ± 22.48	12 ± 0.85

The decline at higher loadings can be linked to the splintered shape of these whiskers which act as regions of stress concentration in the matrix leading to easier crack propagation, thereby compromising with the composite's tensile performance. Fig. 4 presents the stress-strain curve under tensile loads for varying PTW content. In contrast to tensile strength, the tensile modulus displayed a different trend. The EK2 composite showed a 10.72% increase in modulus compared to EK0, indicative of enhanced stiffness due to the rigidity of PTW. However, with increased filler content, the modulus for EK4 declined and then stabilized, with the EK8 composite exhibiting only a marginal 2.15% reduction relative to EK0.

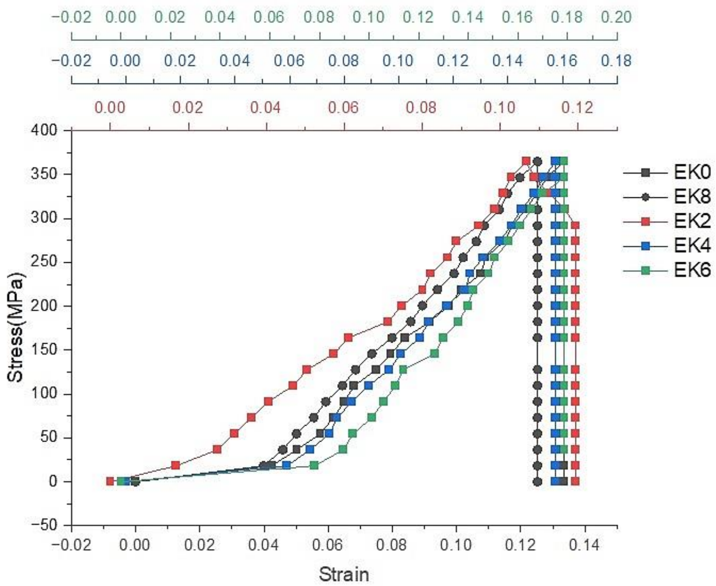


Fig. 4. Stress-Strain curve under tensile loads

This behavior suggests that while stiffness initially benefits from whisker reinforcement, excess filler diminishes the overall load transfer efficiency possibly due to filler agglomeration. The percentage elongation at break followed a moderately increasing trend with filler content. EK2 composite exhibited 12.29% elongation, which was marginally higher than EK0 (12.16%), while EK4 and EK6 composites showed elongations of 15 % and 18 % respectively. This increase may be attributed to a toughening mechanism wherein dispersed PTW locally hinder crack propagation. However, the EK8 composite showed only a minimal 2.03% increase in elongation relative to EK0, indicating a saturation point beyond which further PTW addition promotes brittleness. Notably, the overall variation in tensile strength mirrored the trend observed in impact strength, emphasizing the correlation between filler content, dispersion quality and mechanical performance.

3.4. Flexural Properties

The three-point bending test results revealed that the flexural response of the Kevlar®-epoxy composites followed a trend similar to that observed in the tensile strength results, underscoring the influence of PTW content on the composite's structural performance. The EK2 composite exhibited a 6.32% increase in flexural strength compared to the unfilled EK0, suggesting that low concentrations of PTW can effectively enhance resistance to bending stresses. This improvement may be attributed to the relatively uniform dispersion of whiskers at lower loading levels, which ensures better interfacial bonding with the epoxy matrix. The manageable surface area of PTW at these concentrations reduces the likelihood of weak interfacial zones and promotes efficient stress transfer during flexural deformation. However, the flexural strength of EK4 dropped sharply, showing a 36.33% reduction relative to EK2. This sharp decline could be linked to poor interfacial adhesion between epoxy and PTW and/or possible micro void formation during processing. At elevated PTW loadings, the increased surface area of the whiskers becomes difficult for the matrix to adequately wet, leading to regions of poor stress continuity. Furthermore, the rigid ceramic whiskers can introduce stress concentration points that act as failure initiation sites under bending loads. There is a compromise between an initial improvement followed by subsequent decline in properties particularly in whisker reinforced composites. These results emphasize the importance of maintaining an optimal PTW concentration to maximize mechanical performance. While small amounts of filler can improve load-bearing capability by reinforcing the matrix and minimizing crack growth, excessive filler content undermines the integrity of the composite by disrupting the stress transfer pathway and introducing microstructural flaws. The trend in flexural modulus further supports this behavior. The base composite (EK0) exhibited a flexural modulus of 9.72 GPa, which increased to 12.71 GPa in EK2, indicating enhanced stiffness due to rigid PTW inclusions. However, the modulus decreased to 8.93 GPa in EK4, suggesting that the adverse effects of poor filler distribution and interface quality offset the inherent stiffness of the whiskers. Interestingly, the modulus increased again in EK6 to 10.13 GPa, potentially due to partial restoration of network continuity among whiskers. For the EK8 composite, although the flexural strength was reduced by 13.66% compared to EK0, the flexural modulus still exhibited a 7.32% increase. This indicates that while the material became stiffer overall, its ability to withstand flexural stress without fracture was compromised, pointing again to the embrittlement and defect formation at higher filler loadings. The variation of flexural strength and flexural modulus with respect to the whisker content is presented in Table 5. A bar chart with error bars indicating the variation of tensile, impact and flexural properties of the composites with respect to the whisker content is presented in Fig. 5.

Table 5. Flexural properties of various composites

Composite designation	Material property(Unit)	
	Flexural modulus (GPa)	Flexural strength (MPa)
EK0	9.72 ± 1.64	129.80 ± 9.82
EK2	12.71 ± 1.45	138.01 ± 16.18
EK4	8.93 ± 1.14	87.86 ± 12.05
EK6	10.13 ± 0.57	105.73 ± 11.55
EK8	10.43 ± 1.81	112.06 ± 10.21

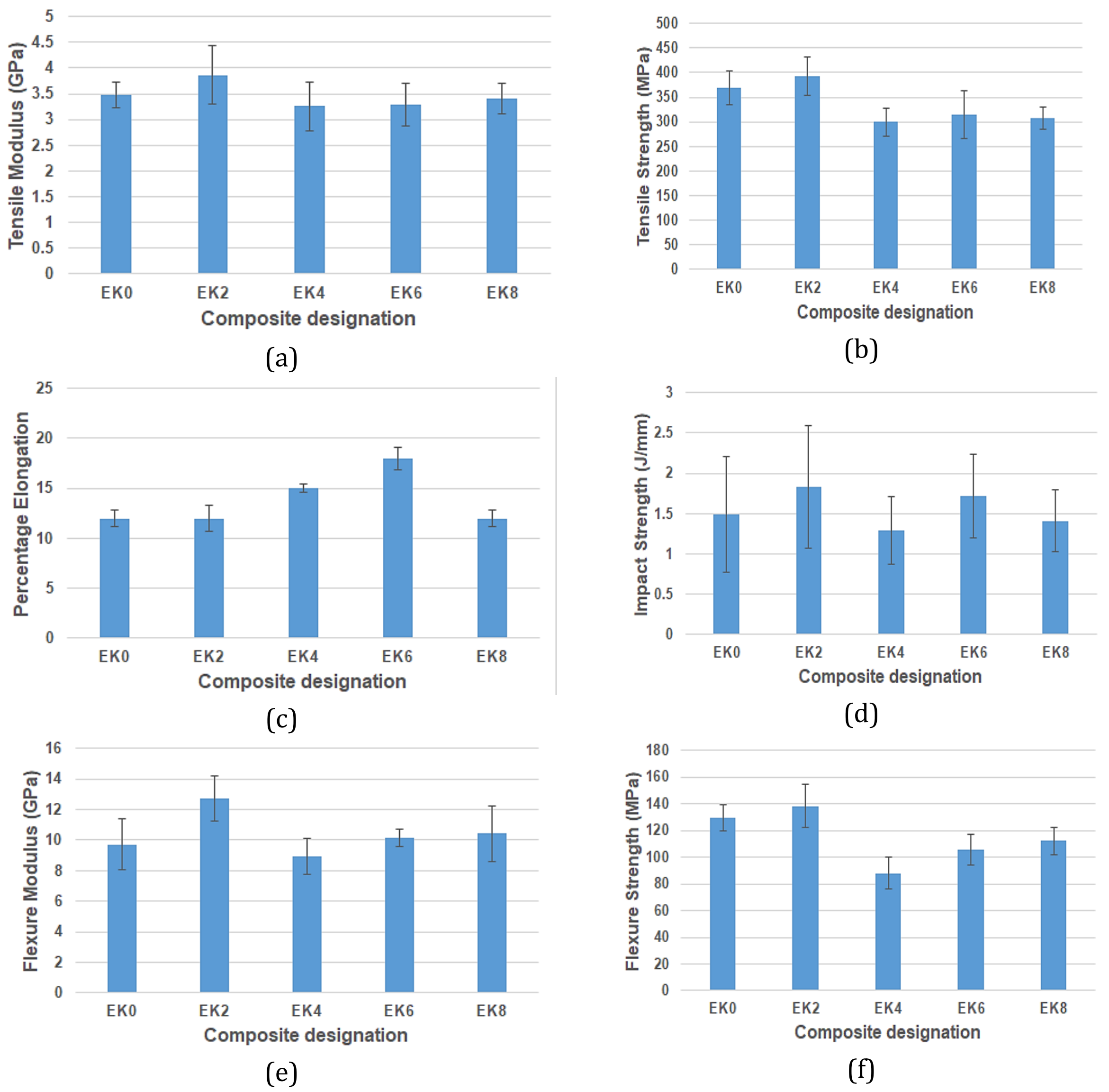
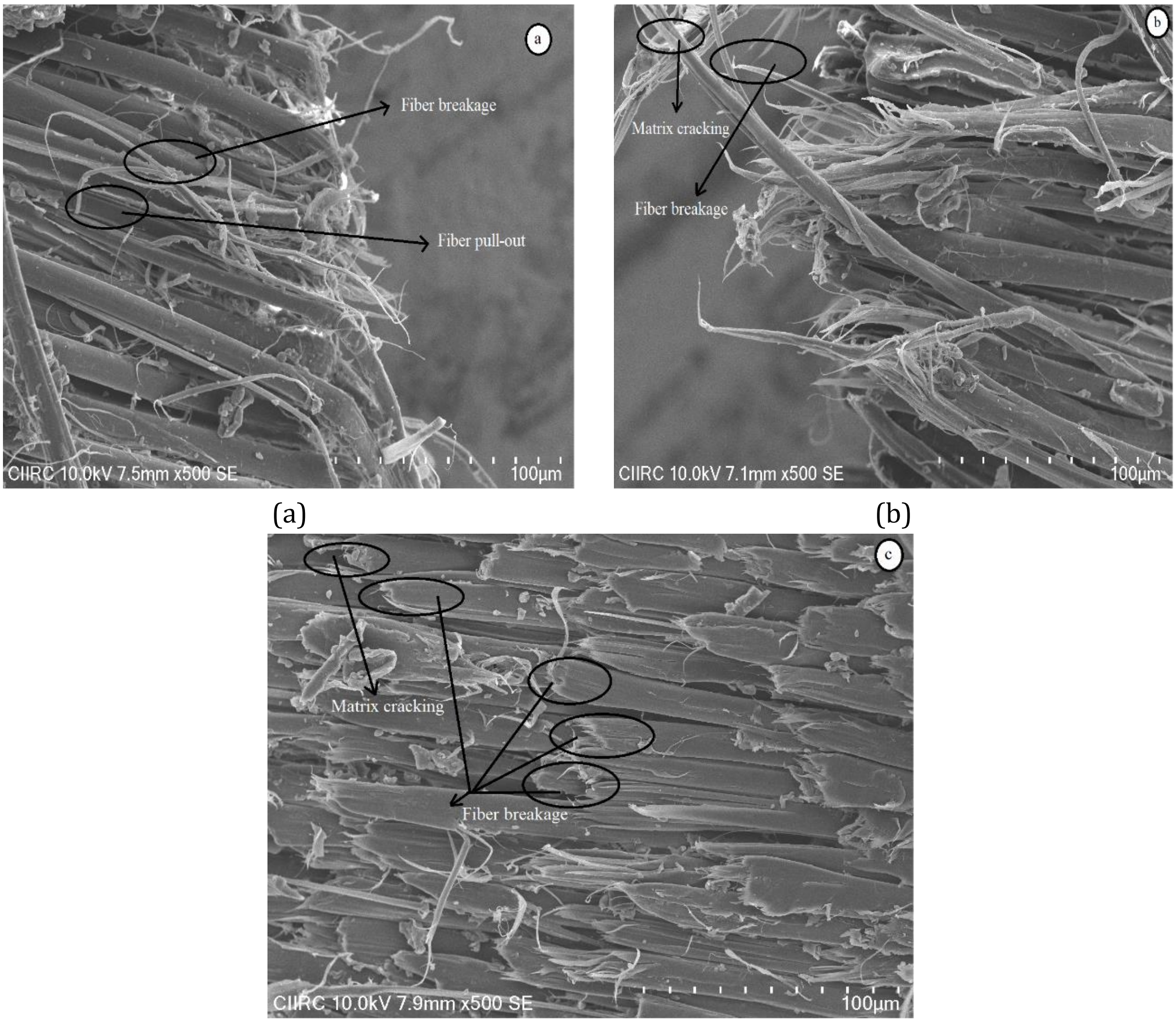


Fig. 5. Bar chart showing the variation of tensile (a – c), impact (d) and flexural (e – f) properties with whisker content

3.5. Morphology of Fractured Tensile Test Specimen

Fig. 6 presents the complete details about the fractured surfaces of selected tensile test specimens. Scanning Electron Microscope (SEM) images of 0 wt. %, 4 wt. % and 8 wt. % PTW (Model SU3500, Hitachi, Tokyo, Japan) was examined. The SEM image in Fig. 6(a) reveals relatively smooth fiber surface with the fibers being pulled out and they appear clean. This suggests minimal matrix adhesion to the fiber surfaces and the failure mainly involves fiber pull-out due to poor interfacial bonding. Fig. 6(b) reveals that the fibers are still pulled out, but with more matrix fragments adhered to the surface of the fibers when compared to 0 wt. % PTW, indicating an improvement in the fiber-matrix bonding. Although PTW were introduced into the composite at increased weight fractions, their presence was not noticeably evident on the fractured surfaces of tensile specimen captured through SEM. This absence could be attributed predominantly to poor wetting of these whiskers by the epoxy matrix, resulting in weak interfacial bonding. During tensile failure, weakly bonded whiskers are more vulnerable to get separated from the matrix and be dislodged from the fracture plane, either during crack propagation or consequent specimen handling. In addition, a number of regions in the specimen showed slender voids and sharp interfaces around potential whisker sites, demonstrating pull-out mechanisms. There are also evidences of matrix micro cracks and complex fractured surfaces. Fig. 6(c) reveals more fiber breakage rather than fiber pull-out, and there appears an increased roughness in the fractured surfaces. Similar surface morphology was observed for all the other specimens.



(a) (b) (c)

Fig. 6. SEM images of fractured surfaces of selected tensile specimen (a) 0 wt. % (b) 4 wt. % and (c) 8 wt. % PTW

4. Conclusions

This paper presents the fabrication methodology and mechanical performance of Kevlar®/Epoxy/PTW composites. The effect of incorporation of PTW on the mechanical properties like tensile strength, impact strength, flexural strength and hardness for the fabricated Kevlar®/Epoxy composite was studied. Following conclusions can be arrived at, from the experimental results obtained:

- Inclusion of PTW as reinforcing fillers has clearly influenced the mechanical performance of Kevlar®/Epoxy. The EK2 composites displayed maximum enhancement in the tensile and flexural modulus by 10.72% and 30.72% respectively compared to Kevlar®/Epoxy. At lower concentrations, these whiskers efficiently bond with epoxy and also get well dispersed. This in turn influences the load transfer capacity of the composite and improves their resistance to crack propagation. Likewise, the Shore D hardness of EK2 enhanced by 9.62% and its impact resistance enhanced by 22.96% compared to EK0. However, there was only a marginal variation in hardness with further addition of PTW.
- The tensile, impact and flexural strengths of the Kevlar®/Epoxy composites modified with PTW declined with the further addition of fillers beyond 2 wt. %. This reduced yield in most of the mechanical properties could be attributed to several factors like stress concentration,

matrix embrittlement, poor interfacial adhesion due to increased viscosity of the matrix, possible micro void formation during processing etc. In general, PTW can still be used as an effective reinforcing agent for thermoset resin like epoxy. However, a decision regarding optimum content of PTW is to be made, so that it does not cost on its mechanical properties.

- SEM images of the fractured tensile specimen revealed the possible failure modes like fiber pull-out, matrix micro crack and fiber breakage. It also indicated an improvement in the fiber-matrix bonding with the increase in PTW content, however, agglomeration of these whiskers at higher loading might have contributed to the decrease in the mechanical properties beyond 2 wt.%.

Acknowledgement

The authors thank M/S Mangala Switch Board Cuttings, Mangaluru, India for their help in carrying out the machining of the test specimens. The authors acknowledge St Joseph Engineering College, Mangaluru, India for providing composite testing facilities. The authors express their sincere gratitude to Centre for Incubation, Innovation, Research and Consultancy (CIIRC), Jyothy Institute of Technology, Bengaluru, India for providing the SEM facilities. The authors wish to thank all those who contributed in executing the work and in preparing the article.

References

[1] Oladele IO, Onuh NL, Siengchin S, Sanjay MR, Adelani SO. Modern Applications of Polymer Composites in Structural Industries: A Review of Philosophies, Product Development, and Graphical Applications. Applied Science and Engineering Progress, 2024; 17:1-1. https://doi.org/10.14416/j.asep.2023.07.003

[2] Nagaraja KC, Rajanna S, Prakash GS, Rajeshkumar G. Mechanical properties of polymer matrix composites: Effect of hybridization. Materials Today: Proceedings, 2021; 34:2-536. https://doi.org/10.1016/j.matpr.2020.03.108

[3] Jafari F, Farsani RE, Khalili SMR. Optimization of Mechanical and Thermal Properties of Elastomer Modified Carbon Fibers/Phenolic Resin composites. Fibers and Polymers, 2021; 22-1986. https://doi.org/10.1007/s12221-021-0934-9

[4] Shen S, Li H, Yang L, Li N, Wu J, Zhao T. High-throughput screening the micro-mechanical properties of polyimide matrix composites at elevated temperatures. Polymer Testing, 2022; 107. https://doi.org/10.1016/j.polymertesting.2022.107483

[5] Kubena M, Elias M, Zajíckova L, Poduska J, Kruml T. On the Tensile Tests of Polyurethane and Its Composites with Carbon Nanotubes. Advances in Materials Science and Engineering, 2019. https://doi.org/10.1155/2019/6598452

[6] Derewonko A, Fabianowski W, Siczek J. Mechanical Testing of Epoxy Resin Modified with Eco-Additives. Materials, 2023; 16. https://doi.org/10.3390/ma16051854

[7] Bharadwaja K, Rao SS, Rao TB, Pydi HP. Evaluation of Mechanical Properties for Epoxy Resin in Nano Composite Diffusion. Advances in Materials Science and Engineering, 2023. https://doi.org/10.1155/2023/8598585

[8] Shalwan A, Alajmi F, Alajmi N. The Impact of Filler Content on Mechanical and Micro-Structural Characterization of Graphite-Epoxy Composites. Journal of Materials Science and Chemical Engineering, 2022; 10-19. https://doi.org/10.4236/msce.2022.106003

[9] Bharadwaja K, Rao SS, Rao TB. Epoxy/SiO2 nanocomposite mechanical properties and tribological performance. Materials Today: Proceedings, 2022; 62:4-1712. https://doi.org/10.1016/j.matpr.2021.12.172

[10] Riahipour R, Nemati MS, Mohamad MZ, Abadyan MR, Tehrani M, Baniassadi M. Mechanical properties of an epoxy-based coating reinforced with silica aerogel and ammonium polyphosphate additives. Polymers and Polymer Composites, 2022; 30. https://doi.org/10.1177/09673911211069019

[11] Rajak DK, Pagar DD, Menezes PL, Linul E. Fiber-Reinforced Polymer Composites: Manufacturing, Properties, and Applications. Polymers, 2019; 11:10. https://doi.org/10.3390/polym11101667

[12] Amir SMM, Sultan MTH, Jawaid M, Ariffin AH, Mohd S, Salleh KAM, Ishak MR, Shah AUM. Durability and Life Prediction in Biocomposites, Fibre-Reinforced Composites and Hybrid Composites, Woodhead Publishing, Cambridge, UK, 2019.

[13] Shahabaz SM, Mehrotra P, Kalita H, Sharma SS, Naik N, Noronha DJ, Shetty N. Effect of Al2O3 and SiC Nano-Fillers on the Mechanical Properties of Carbon Fiber Reinforced Epoxy Hybrid Composites. Journal of Composites Science, 2023; 7:4. https://doi.org/10.3390/jcs7040133

[14] Sun Q, Li W. Inorganic-Whisker-Reinforced Polymer Composites: Synthesis, Properties and Applications, CRC Press, Florida, USA, 2015. https://doi.org/10.1201/b18845

[15] Sudheer M, Vishwanathan K, Raju K, Bhat T. Effect of potassium titanate whiskers on the performance of vacuum molded glass/epoxy composites. Journal of Reinforced Plastics and Composites, 2013; 32-1177. https://doi.org/10.1177/0731684413485827
[16] Tjong SC, Jiang W. Mechanical and thermal behavior of poly(acrylonitrile-butadiene-styrene)/polycarbonate blends reinforced with potassium titanate whiskers. Polymer Composites, 2004; 20:6-748. https://doi.org/10.1002/pc.10398
[17] Sudheer M, Hemanth K, Raju K, Bhat T. Enhanced Mechanical and Wear Performance of Epoxy/glass Composites with PTW/Graphite Hybrid Fillers. Procedia Materials Science, 2014; 6-975. https://doi.org/10.1016/j.mspro.2014.07.168
[18] Bettegowda H, Mahesh V, Mahesh V, Dixit AC. Characterization of Potassium Titanate Whisker and UHMWPE-reinforced Polyethersulfone/Short Carbon Fiber composites: Mechanical, thermal, and structural insights. Polymer Composites, 2025. https://doi.org/10.1002/pc.29493
[19] Suresha B, Harshavardhan B, Ravishankar R. Tribo-performance of epoxy hybrid composites reinforced with carbon fibers and potassium titanate whiskers. AIP Conference Proceedings, 2018; 1943:1-020069. https://doi.org/10.1063/1.5029645
[20] Hao X, Gai G, Lu F, Zhao X, Zhang Y, Liu J, Yang Y, Gui DY, Nan CW. Dynamic mechanical properties of whisker/PA66 composites at high strain rates. Polymer, 2005; 46-3528. https://doi.org/10.1016/j.polymer.2005.02.042
[21] Faidallah RF, Hanon MM, Vashist V, Habib A, Szakál Z, Oldal I. Effect of Different Standard Geometry Shapes on the Tensile Properties of 3D-Printed Polymer. Polymers, 2023; 15:14. https://doi.org/10.3390/polym15143029
[22] Mostovoi AS, Ledenev AN, Panova LG. Modification of epoxy matrix by whiskers of potassium polytitanate. Inorganic Materials : Applied Research, 2017; 8-755. https://doi.org/10.1134/S2075113317050197
[23] DeArmitt C, Hancock M. Particulate-Filled Polymer Composites, RAPRA Technology Limited, UK, 2003.