Silicon (2019) 11:2731–2739
https://doi.org/10.1007/s12633-018-0064-1

ORIGINAL PAPER

Mechanical Strength Behavior of Hybrid Composites Tailored by Glass/Kevlar Fibre-Reinforced in Nano-Silica and Micro-Rubber Blended Epoxy

R. Gokuldass[1] · R. Ramesh[2]

Received: 3 October 2018 / Accepted: 27 December 2018 / Published online: 8 January 2019

Abstract
The present work aims to investigate the mechanical properties and fracture toughness of woven fabric Glass/Kevlar based hybrid composite tailored using modified epoxy with micro rubber and nano silica. The principal aim of this work is to clarify the importance of hybrid fibre/filler addition and stacking sequence of fibre reinforcement in epoxy matrix. The epoxy was modified with addition of 9% micro rubber and 11% of nano silica by weight fraction. Both glass and kevlar woven mats were made by hand weaving and the composites were prepared using hand lay-up method. The fracture toughness results revealed that the exclusive addition of rubber particles in epoxy reduces the strength and modulus but improved fracture toughness. Further tailoring the hybrid composite by adding nano silica of 11 wt.% increased tensile and flexural modulus. The highest tensile and flexural strength of 275 and 162 MPa was observed for composite, which contain nano silica as reinforcement at accumulate layer stacking sequence. The fractograph results revealed the dispersion of nano additions and fracture characteristics of hybrid composites. These mechanically toughened epoxy composites could be used in high damping mechanical applications.

Keywords Glass/kevlar · Nano-silica · Micro-rubber · Tensile strength · Fracture toughness

1 Introduction

Glass fibers exhibit better tensile and compressive strength, and offers great resistance to chemical, heat, moisture, and fatigue properties. Glass fibers are also an excellent resin adhesion and economical. However, glass fibers have low impact strength, low strength to weight ratio and high density compared to other synthetic fibers. Therefore glass fibers are often combined with Kevlar fiber or carbon fiber. The favorable properties of Kevlar fibers are low weight, excellent strength to weight ratio, high impact resistance and great flexibility. Nevertheless, it has poor compressive strength, sensitive to moisture and relatively expensive. Hybridizing both glass and Kevlar fibers would produce a material, which has good impact resistance and tolerance, high strength and lightweight but decreases its compressive strength. Since the compressive strength of polymer composites depends on the properties of the resin system, in the present research, a stiffer and tougher resin system was developed by incorporating fillers to provide better lateral support to the fibers and enhance the resistance to crack initiation and propagation. Arun prakash et al. [1] studied and concluded the effect of filler addition into glass-epoxy composite. They reported that the addition of iron(III) oxide particles along with E-glass fibre increased the tensile, flexural, impact and inter-laminar shear strength. Guru Raja et al. [2] investigates the performance of Glass fiber/Aramid fiber/Epoxy sap crossover edge handle covers with different fiber introductions to portray the malleable properties. They confirmed that the ductile properties for 0°/90° orientation were more than ±45°& 60°/30° oriented composites. Thus, the 0°/90° orientation could be suitable in the field of Automobile, Marine, and Aerospace because of the heap conveying limit. Manjunath et al. [3] observed the tractable exhaustion properties of a glass fiber supported polymer (GFRP) with elastic molecule changed epoxy framework.

✉ R. Gokuldass
gokuldass@yahoo.com

[1] Department of Mechanical Engineering, Anna University, Chennai, Tamilnadu 600025, India

[2] Professor, Department of Mechanical Engineering, Sri Venkateswara College of Engineering, Sriperumbudur 602117, India

They affirmed that the expansion of 9% weight of elastic miniaturized scale molecule in the epoxy network enhanced the weakness life of a glass fiber strengthened plastic composites by 3 times. The addition of 10% wt. of silica nanoparticles in the epoxy grid of GFRP polymer demonstrates a relative impact in the wear properties. The break sturdiness increased to a great extent in FRP polymer composites with crossbreed epoxy network, i.e., rubber micro particles and silica nanoparticles. Park et al. [4] fabricated a phosphoric acid solution treated Kevlar/epoxy laminated composites and determined mechanical, fracture, and impact energy properties. They reported that the chemical treatment significantly improved the degree of adhesion at interfaces between fibers and resin matrix, resulting in improved mechanical and interfacial strength with high fracture energy. Valenca et al. [5] evaluated the mechanical behavior of epoxy composite reinforced with Kevlar plain fabric and glass/Kevlar hybrid fabric. Their results from the mechanical tests showed that the structures developed with the hybrid material of Kevlar and glass fibers possess highest values of mechanical strength and specific stiffness. Liang et al. [6] found that the incorporation of nano-fillers into polymer resin system and FRP composites improved the compressive behaviors of composite systems. Although in certain conditions, the compressive strength decreased with the increase of filler content, nevertheless the strength values were still higher compared to pure epoxies. Arun prakash et al. [7] indicated that addition of SS-304 and AL-6061 metal wire mesh into glass-fibre epoxy composite improved mechanical and drop load impact behavior of composite material. The inclusion of metal wire mesh along with glass fibre in epoxy matrix observed sudden impact energy under sudden load, which increased its stability. These literatures strongly indicated a better load bearing property of the nanocomposites. The present research aims to develop a new hybrid resin system which could be based on silica nanoparticles, and micro rubber for the fabrication of hand weaved hybrid Kevlar/glass fiber composites. The silica nano particles could be used as filler, since it possesses high hardness, very high melting and boiling points and also high crystalline structure. This crystalline silica could acts as load observer in polymer composites under external loading conditions. Moreover the cost and production of silica nanoparticles are comparatively cheaper and easier than other types of particles. Similarly the micro rubber filler material could be selected as dispersant, since it holds very lower density, high abrasion resistance, high ductility and cheaper in cost. The matrix could be modified by blending pure epoxy resin (E100) with micro rubber and nano silica (E80-S11R9) based on rule of mixture. The lamina of 3 layers could be arranged in a systematic manner as three stacking sequences. The laminate stacking sequences could be designed based on the strength requirements. Since fibers play crucial role in load transfer, their system of arrangement needs to be analyzed well in manner. The proposed fibre arrangements could be symmetric layering [GG/KK/KK/GG], alternate layering [GG/KK/GG/KK] and accumulate layering [GG/GG/KK/KK]. When the fibres are arranged subsequently one by one from the bottom and top side then the arrangement of fibres could be called as symmetric layering, but when the lamina (fibre layer) is get arranged one by one throughout the segment then the fibre arrangement could be called as alternative layering. Similarly when the fibres are accumulated fully in one side with another fibre in other side then the corresponding type could be called as accumulate layering. There are more different types of fibre orientations could be possible based on strength expectations. When high damping resistance required for composites then the fibre orientation could be in mixed direction. The 360° placed 45° fibre yarns resists maximum damping force by, which the composites could be a high damper material. The hand layup cum compression molding method could be selected since, it needs low process parameters like limited pressure, and no elevated temperature constrains and eases of processing. The testing and validation of various composites could be done based on ASTM standards. The test samples could be prepared by shearing process since, the process contain simple process constrains like lower pressure involvement, limited power requirements. These mechanically strengthen and toughened epoxy polymer matrix composites could be used in automobile, structural and high impact resistance prone zones. The high damping resistance of these materials wooing their application in automobile, structural, space shuttles and domestic applications.

2 Experimental Work

2.1 Materials

The epoxy matrix used in this research was a liquid DGEBA (LY556, Huntsman India Ltd) with average molecular weight of 190 g/mol. Triethylenetetramine (TETA, HY951, Huntsman India Ltd.), a low viscosity amine with viscosity of 20 cps and density of 0.98 g/cm^3 was used as curing agent. The Glass fibre (MIL-Y-1140H) of 344 GSM and Kevlar (49) of 244 GSM yarns were purchased from Ms. Fibre India Pvt. Ltd., Chennai, India. Nano-silica and micro-rubber of dimensions 25 nm and 5 μm were selected as fillers and purchased from Evonik Industries AG, Germany and Sigma Aldrich, USA respectively. The curing catalyst TETA was purchased from MERCK India Ltd.

2.2 Preparation of Modified Epoxy with Micro-Rubber and Nano-Silica

Modified epoxy resin of homogeneous dispersion of micro-rubber and nano-silica in was prepared using

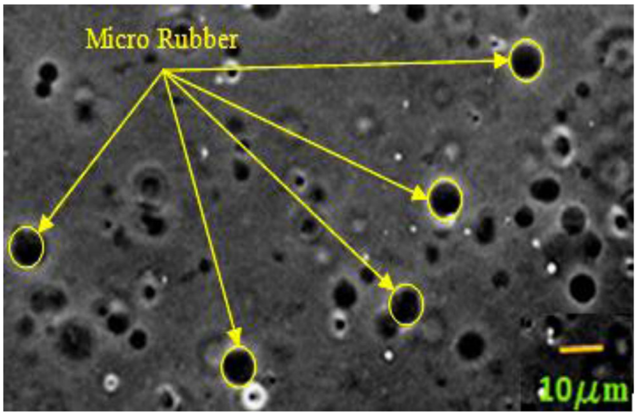


Fig. 1 Homogeneous dispersion of 9 wt.% micro rubber in epoxy resin

thermo-mechanical blending method. In this the resin was pre-heated to the temperature of 80 °C and maintained at the temperature. The nano-silica of 11 wt.% was then dispersed into pre-heated epoxy resin and stirred thoroughly using a mechanical stirrer. The resulted colloidal suspension was then mixed with micro-rubber (CTBN) of 9 wt.% followed by gentle stirring for about 30 min. The particle's dispersion morphology in matrix medium was analyzed using a HR-TEM (FFT Tecnai 20, USA) at an accelerated voltage of 200 kV. The colloidal suspension was dissolved in Ethyl-acetate then a drop of sample was kept on the holy copper grid (200 mesh) and transmission images of particle dispersions were captured. The additional attachment for analyzing the elemental presentation (EDAX) also used for confirming the elements presents. Figure 1 shows the TEM image of micro rubber dispersed epoxy resin at 10 μm scale. The particles are well dispersed and no agglomerations were observed. Similarly Fig. 2 shows the EDAX report and TEM images of nano-silica dispersed epoxy resin. The particles are uniformly distributed and no particle cluster was observed.

2.3 Fabrication of Hybrid Laminates

The woven fabric form of E-glass (MIL-Y-1140H) and Kevlar 49 were prepared using handloom weaving method. In this both the yarns of specific quantities were taken for weaving with average roving diameter as 0.32 mm. In glass fibre woven fabric weaving, both weft and warp consist of similar glass fibre yarns and they were weaved by average speed of 1 square meter for every 8 h. Similar weaving trend was foloowed in kevlar also but the time taken for weaving 1 square meter was near 9 h. This incremental in time taken was because of high stretchability of kevlar than glass fibre. The Fig. 3a, b shows the optical microscope image of warp and weft formation of glass and Kevlar fibre-mat made by handloom weaving method.

2.4 Preparation of Hybrid Epoxy Composites

The epoxy hybrid nano composites were prepared using hand lay-up method in the size of 300 mm × 300 mm, which contain eight layers of fiber layup. Nine sets of hybrid E-glass/Kevlar weave fiber were made with virgin epoxy, epoxy blended micro rubber (9 wt.%) and nano silica (11 wt.%) and epoxy with micro rubber (9 wt%) to form the hybrid resin composites. Three stacking sequence was used to prepare the nine sets of hybrid composite samples for a mechanical test in accordance with ASTM standards. To balance the weight from the basic neutral axis, symmetric concerning the neutral axis [GG-KK-KK-GG], asymmetric concerning the neutral axis [GG-KK-GG-KK] and accumulated layering sequences [GG-GG-KK-KK]. Two forms of fiber orientations, $[(0^0,90^0)/(0^0,90^0)]4$ s and $[(-45^0,45^0)/(0^0,90^0)]4$ s by, which the laminates were fabricated can be seen in Table 1. Laminates are prepared by a hand-layup process using compression molding. The stacking sequences of each composite designation are shown in Fig. 4. The prepared composites were cured at room temperature for 12 h and post cured for 24 h. After

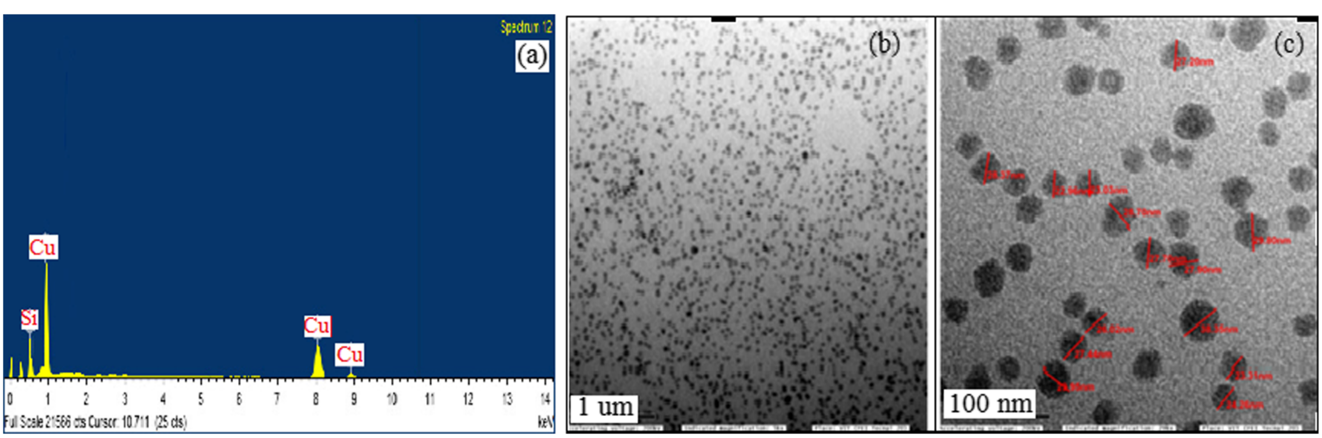


Fig. 2 TEM images of nano silica dispersed epoxy (**a**) EDAX energy peak intensity of nano silica 11 wt.% in epoxy, (**b**) Low magnification 1.0 μm, (**c**) High magnification 100 nm

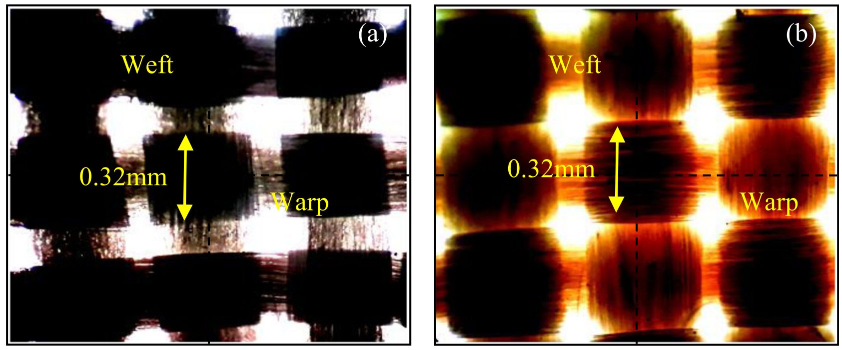


Fig. 3 Warp and weft image of (**a**) E-glass and (**b**) kevlar yarns

curing, the specimens were cut based on ASTM standards for various testing. The tensile, flexural and fracture toughness test has been conducted with a universal testing machine (Instron 3382, UK) with cross head speed of 5 mm/min following ASTM D3039, D 790 and D 5045 standards. Test specimens were carefully cut from the fabricated laminates by using vigor saw computing device and finished to exact measurements.

3 Results and Discussions

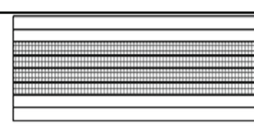
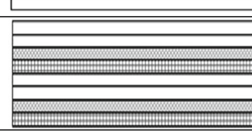
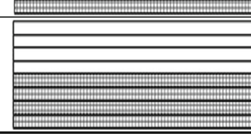
3.1 Hardness

Figure 5 shows the shore-D hardness graph of various composites tested. It is observed that sample A_1 measures hardness of 58.6 whereas A_3 and A_2 composite designations gives higher average hardness value of 61.2 and 65.2. This is the improvement of 4.2% and 10% for composite designation A_3 and A_2 respectively. This is because additions of hard silica nanoparticles, which gives high fracture modulus on composite surface. The improved hardness also attributes the cross-linking effect of epoxy resin after addition of silica nanoparticles. Since additions of oxides may increase the cross-linking density of epoxy resin hence, higher hardness is observed. The silica nano particles tend to be present in the voids of epoxy base resin, which significantly reduces the free space between the molecules of epoxy resin thereby higher hardness is observed [8, 9].

3.2 Tensile Properties

The stress strain plots for various composition and stacking sequences of prepared FRP laminates were shown in Fig. 6. The response curves reveal that there is difference in characteristic behavior among the samples for different loading conditions. It is observed that the additions of hybrid fibre and hybrid particles into epoxy resin increased the tensile strength and modulus. The tensile strength of virgin epoxy composite measures 165 MPa whereas additions of glass/kevlar hybrid fibre into epoxy resin increased its tensile and modulus along with nano silica. It is noted that the addition of micro rubber alone into epoxy resin decreased the tensile strength and modulus. This decrement in tensile stress and modulus is because of clustering effect of micro rubber, which could agglomerate and increase the stress concentration [10]. But addition of nano silica in epoxy composites gives very highest tensile strength of 275 MPa this is 40% of improvement. Similar improvements also were noted for various composites, which contain nano silica and micro rubber. The presence of nano silica acts as bridging element, which could transfer the load

Table 1 laminar arrangement of composites

Stacking Sequence	Weight %	Preferred Fibre orientation	Proffered stacking Sequence	Layer arrangement	Sequence Remarks
A_1	E100	$[(0^0,90^0)/(0^0,90^0)]4S$	GG/KK/KK/GG		Symmetric layering & Aligned orientation
A_2	E80S11R9**				
A_3	E91R9*				
B_1	E100	$[(-45^0,45^0)/(0^0,90^0)]4S$	GG/KK/GG/KK		Alternative layering along with alternative orientation
B_2	E80S11R9				
B_3	E91R9				
C_1	E100	$[(0^0,90^0)/(0^0,90^0)]4S$	GG/GG/KK/KK		Accumulated layering aligned orientation
C_2	E80S11R9				
C_3	E91R9				

* Epoxy 91% wt and Micro rubber 9% wt; ** Epoxy 80% wt, Micro rubber 9% wt and Nano silica 11% wt

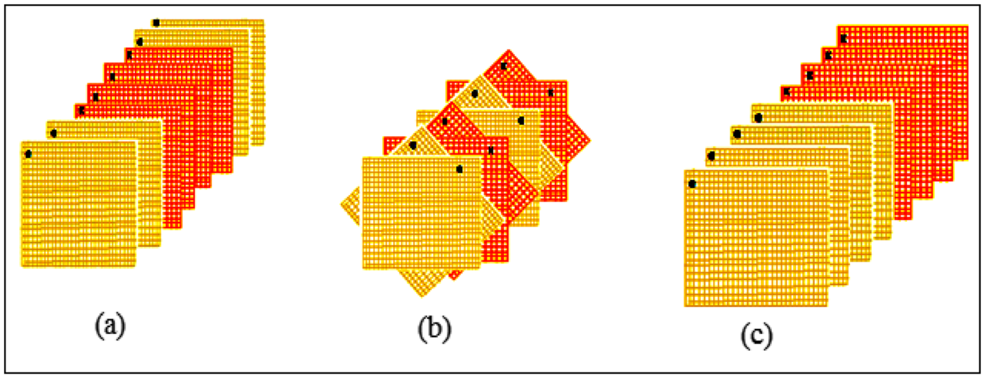


Fig. 4 Layered laminates prepared for the stacking sequences and orientation (**a**) [(0^0,90^0)/(0^0,90^0)]4 s [GG-KK-KK-GG]S1, (**b**) [(−45^0,45^0)/(0^0,90^0)]4 s [GG-KK-GG-KK] S2, (**c**) [(0^0,90^0)/(0^0,90^0)]4 s [GG-GG-KK-KK] S3

effectively [11]. Figure 7 shows the tensile modulus of various composites fabricated. The tensile modulus of virgin resin measures 2.23 GPa. But the additions of micro rubber and nano silica greatly improved the tensile modulus. The improvement of 80%, 85%, 77%, 80%, 83%, 75%, 78%, 86% and 78% were observed for composite designations A_1, A_2, A_3, B_1, B_2, B_3, C_1, C_2 and C_3 respectively. This improvement in tensile modulus is the cause of adding rubber particles in epoxy resin along with nano-silica. The enforced rubber particles may reduce the interfacial strength whereas the inclusion of silica nanoparticles increased the modulus. Similarly the addition of hybrid glass/kevlar in epoxy matrix greatly support to external loads. The load sharing phenomenon of glass/kevlar hybrid fibre in epoxy matrix is the cause of this improvement [12–14]. Arun praksh et al. [7] conducted the experiment on similar cases. They done the study with hybrid E-glass and SS-304/AL-6061 wire mesh. They reported that additions of as-received metal wire mesh into bare epoxy resin decreased the tensile strength and modulus. The decrement of near 30% was observed in their research. But additions of hybrid e-glass/kevlar fibre reinforcements in epoxy resin composite increases the load bearing phenomenon by transferring load effectively. These changes are attributed due to the wetting property of fibre with matrix. The E-glass/kevlar has good wetting response against to epoxy matrix, which could improve the mechanical properties. Similar results were seen in tensile modulus also. The as-received metal hybrid wire mesh in epoxy resin increased the cross-linking density along the interfacial area where the fibre and matrix met, which could increase the brittleness of matrix. In high brittleness the matrix couldn't bear for maximum bending load. But in glass/kevlar hybrid composite, due to more wetting the adhesion between matrix and fibre gets increased thus led to high mechanical strength due to low cross-linking density and flexible matrix molecules [15].

3.3 Flexural Strength

Figure 8 shows the flexural strength of various composites fabricated. The flexural strength of pure epoxy resin measures 110 MPa. But addition of glass/kevlar hybrid fibre into epoxy resin improved its flexural strength. Further addition of micro rubber of 9 wt.% into epoxy resin decreases the flexural strength. It is observed from tensile modulus results that, a combination of hybrid E-glass/kevlar composite with the addition of Nano silica and micro rubber filler (A_2, B_2, and C_2) shown greater values in flexural strength than virgin epoxy and micro rubber. As the load increased gradually the presence of nano silica bounded on the free voids of epoxy resin creates continuity in matrix molecular structure to load

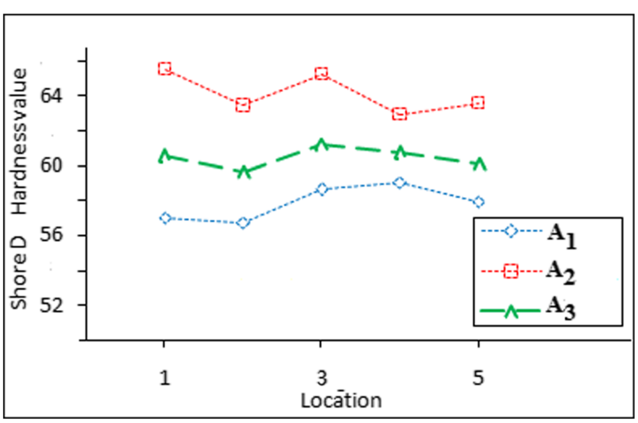


Fig. 5 Shore D hardness of composites

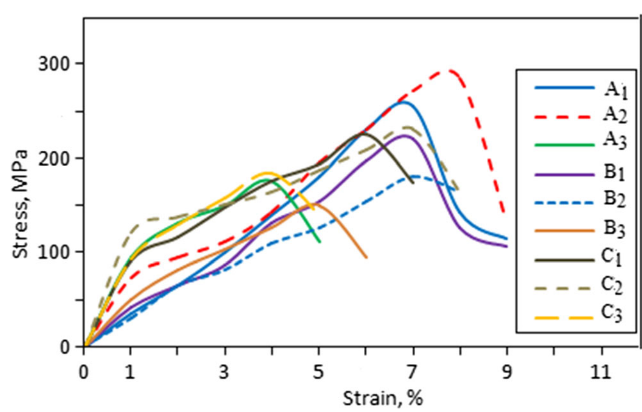


Fig. 6 Stress vs. Strain curve of tensile test

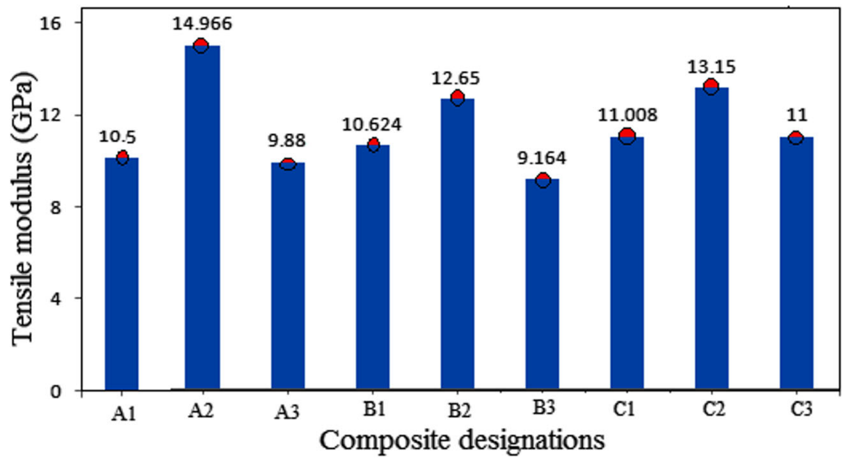


Fig. 7 Tensile modulus of composites

transfer. Similarly the glass/kevlar hybrid fibre on matrix transmits maximum load in uniform manner, thus larger flexural strength is observed [16]. The improvement of 30%, 19%, 14%, 29%, 18%, 11%, 32%, 27% and 15% were observed for composite designations A_1, A_2, A_3, B_1, B_2, B_3, C_1, C_2 and C_3 respectively.

Similarly Fig. 9 shows the flexural modulus of hybrid glass/kevlar and micro rubber/nano silica reinforced epoxy resin composites. The flexural modulus of pure epoxy measures 2260 MPa or 2.26 GPa. The additions of hybrid fibre into epoxy resin greatly increased the flexural modulus by resisting the matrix molecules not to stretch. The reinforced hybrid fibre in epoxy resin absorbs most of the bending load in uni-axial direction thus improved flexural modulus were seen [17]. The improvements of 80%, 78%, 77%, 79%, 81%, 61%, 85%, 87% and 77% were observed for composite designations A_1, A_2, A_3, B_1, B_2, B_3, C_1, C_2 and C_3 respectively. Arun praksh et al. [7] reported the effect of adding hybrid E-glass and SS-304/AL-6061 wire mesh into epoxy resin. They showed a downward trend in flexural strength and modulus when reinforcing as-received glass fibre and metal wire-mesh. This reduction is the cause of increased cross-linking density, which reduces the flexural strength of composites. But in composite, which contain hybrid glass/kevlar and nano silica improved the toughness of composite material by dispersing the applied load uniformly. Similar improvements were noted even in flexural modulus. The additions of nano silica keep the epoxy matrix as more flexible by moderating the cross-linking density. Thus improved results were observed in flexural strength and modulus was observed. Hence the additions of high wettability of glass fibre and kevlar reinforcements are making the composites tougher and strengthen.

3.4 Fracture Toughness Results

Table 2 shows the fracture toughness of various composites fabricated. The table gives results of young's modulus, fracture toughness and energy release rate. Elasticity play's significant role in energy absorption and constantly increases the amount of work per unit. Local driving force for crack extension measures through stress intensity (MPa√m). Fracture toughness testing is conducted to observe elasticity of the combined E-glass/Kevlar composite with micro rubber epoxy (A_3, B_3, and C_3). It is observed that they shown greater values

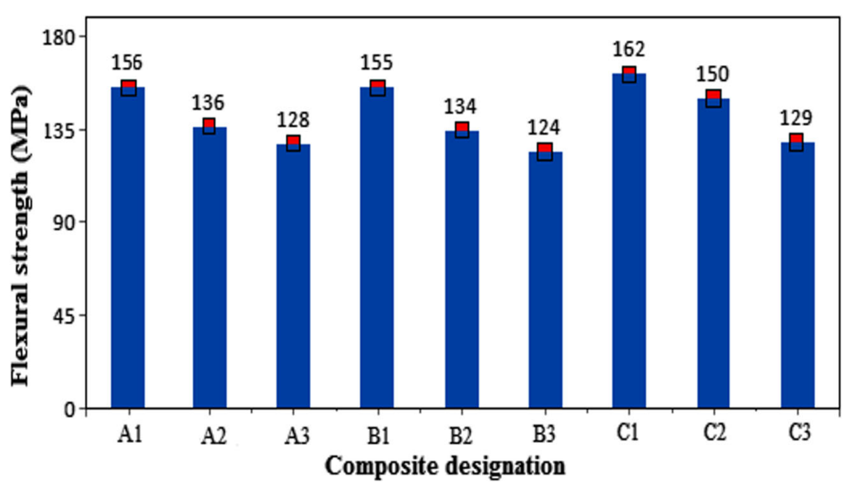


Fig. 8 Flexural strength of composites

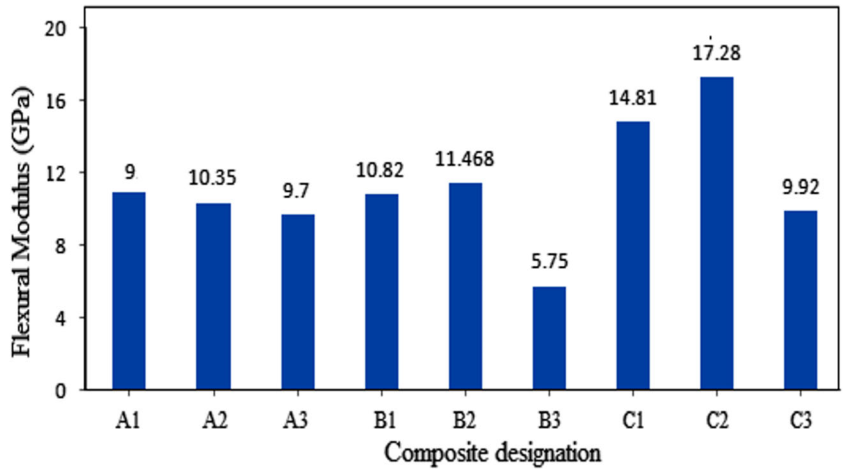


Fig. 9 Flexural modulus of composites

than virgin epoxy and nano silica/micro rubber added composite (Table 2). For each extraction, the toughness, global moisture uptake and surface morphology of fractured surface were analyzed.

The samples were tested as per ASTM D5045 standard for measuring plane strain fracture toughness. Further comparisons of the two composites, micro rubber 9 wt.%/nano silica 11 wt.% (R9, S11) and micro rubber 9 wt.% show that the ternary composite demonstrates an optimized balance between modulus and toughness. From Table 2, it is seen that with 9 wt% rubber and 11 wt% silica, the stiffness increases drastically than neat epoxy. Fracture behavior of woven Glass Kevlar composites is quite different. The predominant fracture mechanism played in fractured portion of hybrid epoxy composite is the cause of delamination along the interface between the matrix and the woven layers. The pure epoxy does not adhere very well to the glass/Kevlar, which causes the interfacial delamination. Lower blending of rubber particles in epoxy resin resulting in reduces the fracture toughness value [18, 19]. Reduction in the tensile stress and the elastic modulus was observed by using epoxy resin along with micro rubber. This is attributed to the reducing the cross-linking density of the polymeric network as micro rubber hinders and occupies the bonding region. But additions of nano-silica along with 9 wt.% of micro rubber increased the interfacial bonding due to high adhesion behavior. Since the nano-silica has tendency of adhering with neighboring molecules, which enforces maximum adhesion between fibre and matrix. Thus high fracture toughness is observed. When the load is applied to the composites the chemical link in interfacial contact area at fibre and matrix get increases and transfer the load uniformly to the adjust phase, which in-turn increases the fracture toughness [20, 21].

3.5 Morphology of Failure Specimen

Figures 10 and 11 show the fractograph of fractured composite specimens. The hybrid fiber laminate composite are studied in optical microscope. The optical microscope used for taking the images was Moticam S 100, CHINA. The instrument has a magnification capability of 43.5X and high aperture. The microscopic fractograph analysis of various composites was done using a scanning electron microscope (HITACHI, S1500, JAPAN). The samples were coated with gold for improving the electron flow. It is noticed that all the test samples were failed almost perpendicular to the loading axis and also the matrix material found to detach from the fibres, indicating an interfacial cleavage under tensile loading. The interfacial bonding strength between fibre and matrix is comparatively lower than single phase composite area. There is no fibre fragments were produced in the fractured zone, which indicates poor adhesion of fibre and matrix. Thus in all the composites the interfacial cracking and opening mode of failure is dominated and failure the specimen [22, 23]. Anyway the epoxy matrix which contains nano silica of 11 wt% gives little improvement on interfacial

Table 2 Fracture toughness results

Sl. No	Sequence Name	Maximum load N	Young's modulus (E) MPa	Fracture Toughness (K_1c) MPa.$\sqrt{m}$	Energy Release Rate (G_1c) MJ/m^2
1.	A_1	460.0 ± 0.26	627.0 ± 0.15	20.4 ± 0.12	0.638 ± 0.075
2.	A_2	463.9 ± 0.47	699.2 ± 0.68	21.6 ± 0.09	0.583 ± 0.041
3.	A_3	529.4 ± 0.31	615.9 ± 0.71	24.6 ± 0.17	0.861 ± 0.007
4.	B_1	629.0 ± 0.17	780.0 ± 0.34	28.1 ± 0.69	0.957 ± 0.071
5.	B_2	628.4 ± 0.12	1062.8 ± 0.18	29.2 ± 0.91	0.704 ± 0.095
6.	B_3	709.7 ± 0.06	649.10 ± 0.29	32.9 ± 0.42	1.466 ± 0.061
7.	C_1	597.3 ± 0.89	1121.8 ± 0.75	27.2 ± 0.75	0.746 ± 0.057
8.	C_2	532.5 ± 1.23	1127.5 ± 0.49	26.7 ± 0.39	0.476 ± 0.019
9.	C_3	664.7 ± 0.42	864.00 ± 0.84	30.9 ± 0.14	0.781 ± 0.039

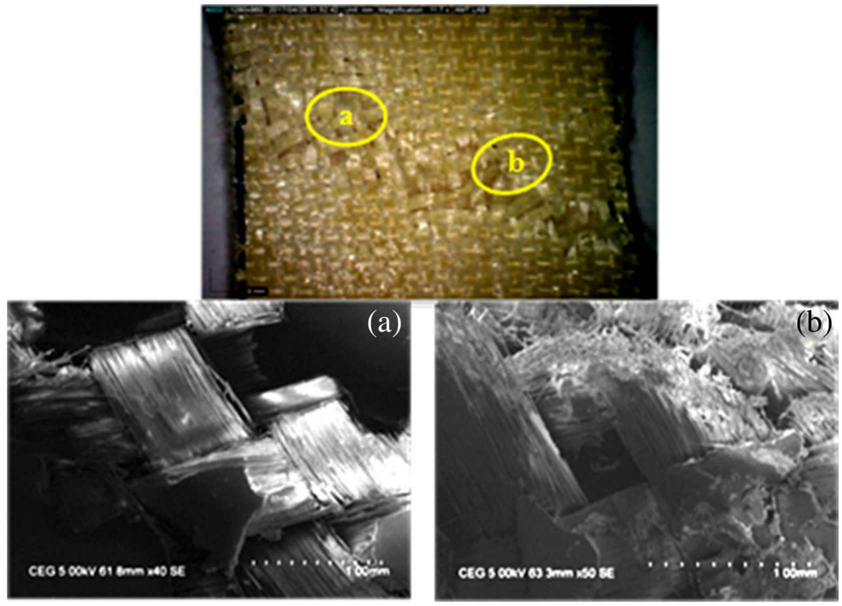


Fig. 10 SEM image of Tensile Fractured Surface of (GG/KK/GG/KK) [(−45°,45°)/(0°,90°)] 4 s

bonding due to silica nano particles. Thus addition of silica in epoxy matrix gives noteworthy improvement in interfacial bonding strength and fracture toughness. It is found from the work of Arun praksh et al. [7] regarding the surface treatment of fibers and wire mesh for effective bonding characteristics. The authors reported that the surface-treated reinforcements give much improved mechanical properties than as-received reinforcements in epoxy matrix. Authors of reference study also strongly pointed out the strength improvement after the surface treatment of fibres. The improved adhesion is the cause of such improvement, which could be enhanced using silane surface modification.

4 Conclusion

A new hybrid resin system was developed based on silica nanoparticles and micro rubber for the fabrication of hand weaved

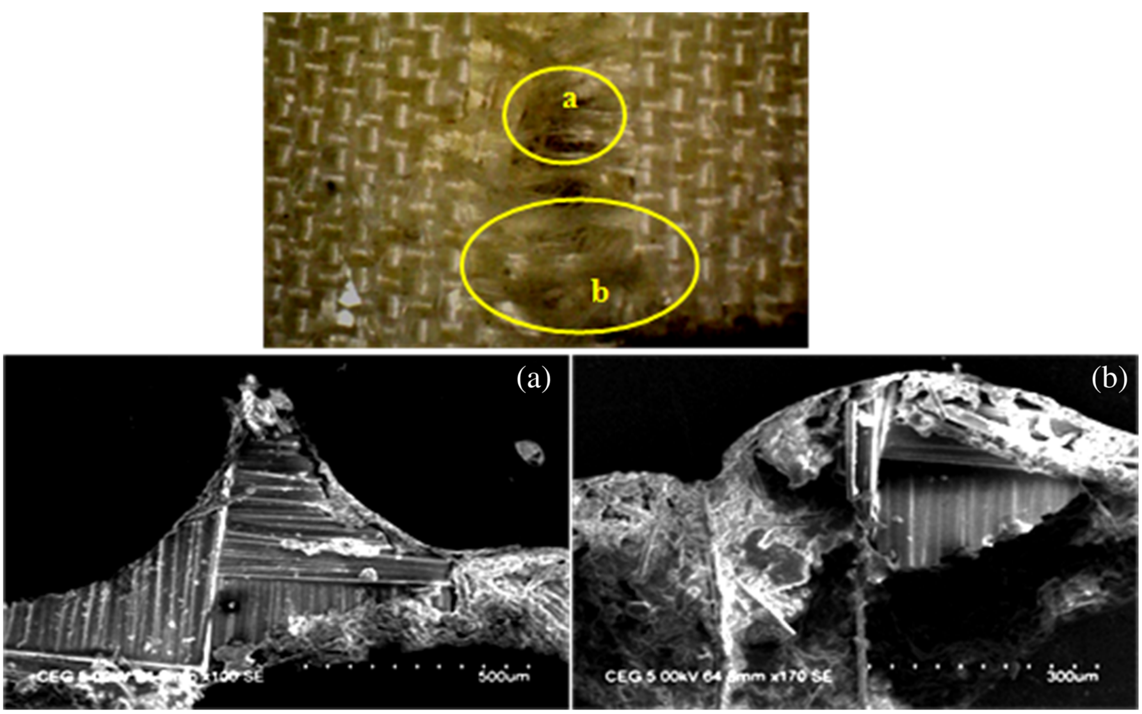


Fig. 11 SEM image of Flexural Fracture Surface (GG-GG-KK-KK) [(0°,90°)/(0°,90°)] 4 s

hybrid Kevlar/glass fiber composites for high load withstanding application. The stacking sequence and orientation of fibre influences the mechanical behavior of E-glass/Kevlar hybrids at axial and bend loading conditions. The mechanical properties of hybrid E-Glass/Kevlar composite with Nano silica and micro rubber found to be higher than composites contain only fibre reinforcement. The fracture toughness results explicated that the combination of E-Glass/Kevlar composite with micro rubber epoxy is of higher value than plain epoxy and hybrid Nano silica/micro rubber epoxy. The stacking sequence of [(0°, 90°)/(0°, 90°)]4S GG/GG/KK/KK was found to be giving good mechanical properties than other stacking sequences. The SEM fractograph revealed interfacial cracking phenomenon in various composites. The composite, which contain hybrid glass/kevler fibre and nano silica of 11 wt.% possesses greater interfacial bonding than other composites. These fracture toughness and mechanical strength improved epoxy hybrid composites are highly preferred in automobile body manufacturing, machinery lateral body manufacturing, air-craft vehicle manufacturing industries, structural, electronic components (computer bodies) and domestic sectors. As a future research, surface modification of various reinforcements using silane coupling agent could be performed for knowing the effect of interfacial bonding behavior between matrix and fibre and their importance in mechanical properties. Also the sudden impact failures in laminates and wear resistance of epoxy composite could be analyzed with inclusion of metal wire-meshes of various ductile materials such as stainless steel, aluminum and copper in surface-modified condition.

Compliance with Ethical Standards

Conflict of Interest The authors have no conflict of interest.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

References

1. Arun Prakash VR, Rajadurai A (2016) Thermo-mechanical characterization of siliconized E-glass fibre/hematite particles reinforced epoxy resin hybrid composite. Applied Surfcae Science 384(16):99–106
2. Guru Raja M. N & A.N. Hari Rao, 2013, "Effect of an Angle-Ply Orientation on Tensile Properties of Kevlar/glass Hybrid Composites", Volume-2, Issue-3, 891–899
3. Manjunath CM (2010) The tensile fatigue behavior of a glass fiber reinforced plastic composite using a hybrid toughened epoxy matrix. J Compos Mater 156(4):60–67
4. Park S-J, Seo M-K, Ma T-J, Lee D-R (2002) Effect of chemical treatment of Kevlar® fibers on mechanical interfacial properties of composites. J Colloid Interface Sci 252:249–255
5. Valenca SL, Griza S, De Oliveira VG, Sussuchi EM, De Cunha FGC (2015) Evaluation of the mechanical behavior of epoxy composite reinforced with Kevlar® plain fabric and glass/Kevlar® hybrid fabric. Compos Part B 70:1–8
6. Liang, Pearson RA (2010) The toughening mechanism in hybrid epoxy-silica- rubber nanocomposites (HESRNs). Polymer (Guildf) 51(21):4880–4890
7. Prakash VRA, Jaisingh SJ (2018) Mechanical strength behaviour of Silane treated E-glass fibre/Al 6061 & SS-304 wire mesh reinforced epoxy resin hybrid composite. Silicon 10:2279–2286
8. Dinesh T, Kadirvel A, Arunprakash (2018) Effect of Silane modified E-glass fibre/iron(III)oxide reinforcements on UP blended epoxy resin hybrid composite, silicon 10(3):1–12
9. Ramesh C, Manickam C, Maridurai T, Arun Prakash VR (2017) Dry sliding wear characteristics of heat treated and surface modified hematite particles-epoxy particulate composite. Romanian journal of materials 47(3):401–405
10. Arunprakash VR, Rajadurai A (2016) Mechanical, thermal and dielectric characterization of iron(III)oxide reinforced epoxy hybrid composite. Digest Journal of Nanomaterials and Biostructures 11:373–380
11. Peng CB, Akil HM, Affendy MG, Khan A, Nasir RBM (2014) Comparative study of wear performance of particulate and fiberreinforced nano-ZnO/ultra-high molecular weight polyethylene hybrid composites using response surface methodology. Material Design 63:805–819
12. Pontefisso A, Zappalorto M, Quaresimin M (2013) Influence of interphase and filler distribution on the elastic properties of nanoparticle filled polymers. Mech Res Commun 52:92–94
13. Hua Y, Gu L, Premaraj S, Zhang X (2015) Role of interface in the mechanical behaviour of silica/epoxy resin nanocomposites. Materials 8(6):3519–3531. https://doi.org/10.3390/ma8063519
14. Tsai JL, Huang BH, Cheng YL (2011) Enhancing fracture toughness of glass/epoxy composites for wind blades using silica nanoparticles and rubber particles. Procedia Engineering 14:1982–1987
15. Sobrinho LL, Calado VMA, Bastian FL (2011) Effects of rubber addition to an epoxy resin and its Fiber glass-reinforced composite. Polym Compos 33(2):295–305. https://doi.org/10.1002/pc.21265
16. Sokolova OA, Kuhn M, Palkowski H (2012) Deep drawing properties of light weight steel/polymer/steel sandwich composites. Archives of Civil and Mechanical Engineering 12:105–112
17. Silva H, Ferreira JA, Costa JD, Capela C (2013) A study of mixed mode inter-laminar fracture on nano clay enhanced epoxy/glass fiber composites. Ciencia & Tecnologia dos Materiais 25:92–97
18. Rathnakar G, Shivanand H (2013) Fibre orientation and its influence on the flexural strength of glass fibre and Graphite fibre reinforced polymer composites. International Journal of Innovative Research in Science Engineering and Technology 2(3):548–552Xxx
19. Arun Prakash VR, Rajadurai A (2017) Inter laminar shear strength behavior of acid, base and silane treated E-glass fibre epoxy resin composites on drilling process. Defence Technology 13:40–46
20. Selver E, Potluri P, Hogg P, Soutis C (2016) Impact damage tolerance of thermoset composites reinforced with hybrid commingled yarns. Compos Part B Eng 91(15):522–538
21. Domun N, Hadavinia H, Zhang T, Sainsbury T, Liaghat GH, Vahid S (2015) Improving the fracture toughness and the strength of epoxy using nanomaterials – a review of the current status. Nanoscale 7:10294–10329
22. Sathish KG, Siddeswarappa B, Kaleemulla KM (2010) Characterisation of in-plane mechanical properties of laminated hybrid composites. Journal of Minerals and Materials Characterization Engineering 9(2):105–114
23. Manikandan V, Jappes JTW, Kumar SMS, Amuthakkannan P (2012) Investigation of the effect of surface modifications on the mechanical properties of basalt fibre reinforced polymer composites. Compos Part B 43:812–818