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RESEARCH ARTICLE

Mechanical, thermal and interfacial properties of Carbon-Kevlar reinforced epoxy composite

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Abstract: Twill woven Carbon-Kevlar (CK) fabric was reinforced in epoxy matrix by conventional hand lay-up process. The fabric weight fraction in the composites was kept around 58% and stacking sequence was varied from single to five plies. Tensile test was performed and the fracture surface after tensile test was evaluated by scanning electron microscope (SEM). The test result revealed that the tensile properties are strongly dependent on the number of plies. Three point flexural test of the composite was also carried and an increasing trend was observed. Maximum impact energy was recorded for CK3 sample by 202.7 KJ/m^2. Thermal stability of the composite was studied via the thermo gravimetric analysis (TGA) and Fourier transform infrared spectroscopy (FT-IR) result show interaction between fiber and matrix material. Finally, CK fabric reinforced epoxy-based composites showed balanced and tailor-able mechanical properties by varying the number of plies, suitable for desired applications in many areas including building, construction, marine, automotive *etc*.

Keywords: Carbon-Kevlar fabric, epoxy, polymer composites, mechanical properties, thermal properties

1 Introduction

In the beginning of composite research, natural fiber reinforced polymer composite was the main concern[1]. Natural fibers are not uniform in most characteristics and they are hydrophilic in nature[2,3]. This nature makes them incompatible with hydrophobic polymer matrix materials and reduces the interfacial interaction between reinforcement and matrix thus negatively affects the mechanical properties of composite materials. As a result, synthetic fibers gain popularity as reinforcing materials in high strength applications[4]. Nature of fiber contents in the composite materials plays a vital role. The mechanical properties of composites are controlled by the strength and elastic properties of the fibers, the matrix and bond between the reinforcement and matrix materials which governs the stress transfer. Mechanical properties of composite materials could be improved by specially oriented fiber materials such as glass fiber, aramid fiber etc.[5].

Monolithic composite of different synthetic and natural fibers have been explored rigorously[6–11]. But mechanical properties of the monolithic composite especially strength and elastic modulus reduce significantly since the reinforcement direction moves away from the direction of load[12,13]. So, various researches are being carried out to find different novel properties by hybridization[14,15]. Different fibers are woven together one type in vertical direction called warp and another in horizontal direction called weft to produce the new type of hybrid woven fabrics thus combine the wonderful characteristics of both fiber in a single composite materials[16,17]. Fiber hybridization is now more attractive to current researchers. Two or more different types of fibers are combined together to get synergistic response from each of the individual fibers are termed as hybrid. Hybrid composite shows exceptional properties that can be used to meet the versatile and competing design requirements in a more cost effective way than conventional composites[18]. Balanced strength and stiffness, balanced thermal distortion ability, reduced weight and/or cost, improved fatigue resistance, reduced notch sensitivity, improved fracture toughness and impact re-

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sistance are some advantages of hybrid composites[19] . Muhi *et al.* reported that hybrid E-glass/Kevlar 29 reinforced polyester composite is superior in absorbing impact energy than the single glass composite[20] . In another study, S2 glass fiber was hybridized with carbon fiber and result presented that the hybrid composite show better impact properties than monolithic carbon composite under low impact velocity[21] .

The constituents of composite such as matrix, reinforcement and interface between them directly influence the mechanical behavior of composite materials[22] . In addition, stacking sequence also affects the performance of hybrid composite[23] . Different researcher have reported the effect of stacking sequence on the mechanical properties in hybrid composite and found that composite properties vary greatly with the variation of stacking sequences[24–27] . Pegoretti *et al.* reported that impact strength of intraply composite is higher than that of intraply and homogenous composite of the same reinforcement[28] . In another work, Kim *et al.* reported that stacking sequence directly influence the mechanical properties of the composites and symmetric stacking sequence perform poor than asymmetric stacking sequence[29] . In searching for new type of composite materials, this experiment aims to develop a distinct type of preforms of the reinforcing fabric by using Kevlar-29 and carbon in weft and warp direction respectively. In this study, a 2 up and 2 down twill structure was used where the ratio of carbon and Kevlar was 50:50. This special type of preform structures was not yet reported in literature. Five composites were fabricated by varying the plies from single to five and their impacts on different mechanical properties were evaluated. Surface fracture of the composite was evaluated by SEM and bonding between the fiber and matrix was investigated by FT-IR. Thermal stability of the composite was studied by TGA.

2 Materials and methods

2.1 Materials

CK fabric was collected from CHN Carbon Fiber Technology Co., Ltd., China. Carbon and Kevlar used in this experiment were T 300 (3K) and K 29 (1500D) respectively. The linear area density of the fabric was 195 gm/m^2 and weave structure of the fabric was 2/2 twill using carbon in warp and Kevlar in weft as shown in the Figure 1(b). In this weave structure a warp and weft were interlaced in in two upper and two lower alternating positions mutually perpendicular so a bi-directional orientation was established. Warp and weft density were the same and 5 filaments per 10 mm. Epoxy (Bisphenol A Di-glycidyl Ether) and epoxy hardener used in this

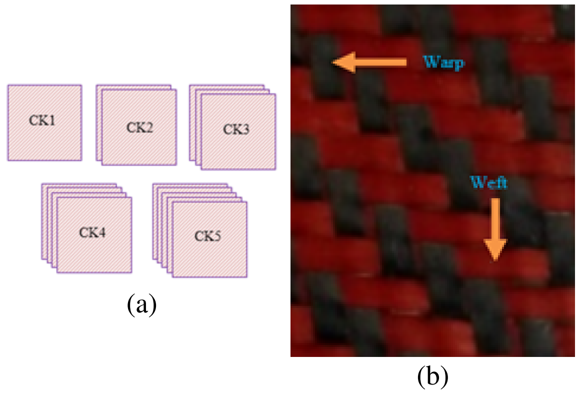

Figure 1. (a) Different stacking sequence of CK composite; (b) 2/2 twill weaves construction indicating carbon in warp direction and Kevlar in weft direction

experiment were supplied by Polyolefin Co. Ltd, Singapore.

2.2 Methods

2.2.1 Composite fabrication

The composite samples were fabricated by conventional hand lay-up technique. The low temperature curing epoxy resin and corresponding hardener are mixed by weight as recommended. Five different types of composites have been fabricated with different layers. For composite fabrication, the cast of each composite is cured under a load of about 20 kg for 24 hours before it removed from the mould. Then this cast is post cured in the air for another 24 hours after removing out of the mould. CK weight fraction for plies was kept around 58%. Number of plies variation in the composite and their arrangement is shown in the Figure 1(a).

2.2.2 Mechanical testing of the composite

Tensile and bending properties of the composite were determined. Five specimens were tested and average values were recorded for each test and type of composites. Tensile tests were conducted according to ASTM D 638-01 using a Universal Testing Machine (Hounsfield series, model: INSTRON 1011, UK) with a cross-head speed of 10 mm/min. The dimensions of the test specimen were (ISO 14125): 60 mm × 15 mm × 2 mm. Three point bending test of the composite was carried out according to ASTM D 7264 using the same machine as mentioned above at a cross head speed of 5mm/min. Impact test for different fabricated composites were carried out according to ASTM D-256.

2.2.3 Water uptake percentage

For water uptake test composite samples (20 × 10 × 2 mm^2) were immersed in a static water bath at 25 °C for different time periods (up to 60 min). Before immersion in water, the specimens were dried in an oven at 105 °C, cooled in a desiccators using silica gel and weighed. After certain periods of time, samples were taken out from the bath and wiped using tissue paper, then weighed. Water uptake was determined according to ASTM D 570 by using the following formula as shown in Equation 1.

$$\text{Water absorption } \% = \frac{W_a - W_b}{W_b} \times 100 \qquad (1)$$

Where W_a is weight after water immersion and W_b is weight before immersion.

2.2.4 Surface morphology, thermal stability and absorption spectra analysis

Surface morphology of the produced composite was carried out using scanning electron microscopy (JEOL JSM 6490 LA). Sample was taken from the fractured region by abrasive disc cutting. An acceleration voltage of 20 kV, a working distance of 11 mm was used for this experiment. Thermal gravimetric analysis (TGA) was carried out using TGA 50 thermogravimetric analyzer (Shimadzu, Japan) under nitrogen atmosphere with a flow rate of 10 mL/min and a scan rate of 10°C/min over a temperature range of 20°C to 600°C. A test sample of 10-13 mg was used for each run. The weight loss was obtained with respect to temperature. Infrared spectra of the composite were recorded by 8400S Shimadzu Fourier transform spectroscopy (FTIR). Potassium bromide window-KBr micro pellets with a sample to KBr weight ratio of 0.005 were produced for the powder measurements in the mid-IR region. FT-IR powder spectra from 4000 to 400 cm^{-1} were recorded. Samples spectra were obtained from 40 scans each with a nominal resolution of 1 cm^{-1}.

3 Results and discussion

Woven CK fabric was reinforced in thermoset epoxy matrix by hand lay-up process with fabric percentage of 58. The mechanical properties such as tensile strength (TS), tensile modulus (TM), elongation at break (Eb%), bending strength (BS), bending modulus (BM) were evaluated. Five samples of different fiber ply such as CK1 for 1 ply, CK2 for 2 ply, CK3 for 3 ply, and so on were fabricated for this experiment.

3.1 Evaluation of mechanical properties

Tensile properties in terms of tensile strength (TS) and flexural strength (FS) of CK-Epoxy composite is presented in Figure 2 as a function of number of plies respectively. From the Figure 2, it is found that TS of the composite varies significantly with number of plies. As indicated in Figure 2, CK3 composite has the highest TS of 311.80 MPa among the tested specimens. This is about 83% higher than the 5 plies composite sample which had the lowest TS. Number of plies did not have significant influences for single layer and 2 layers composites showing almost the same tensile strength (TS). Four layers sample show 25.66% decrease in tensile strength from the highest value. The reason for highest tensile strength in 3 plies sample may be due to the better interfacial adhesion between reinforcement and matrix material. It is known that fiber-matrix adhesion and the stress transfer efficiency of the interface play an important role in determining the strength of a composite[30,31] . When load is applied, then the fiber tries to align them in the direction of load which makes it more effective to withstand applied load. Poor fiber matrix interaction initiates the formation of micro crack in composite materials as a result tensile strength decrease. Flexural strength (FS) of composite determines the capability of the materials to withstand the bending load before reaching the breaking point. Figure 2 shows that CK5 sample is stronger and rigid than others samples. A gradual increasing trend is observed in flexural strength of the composites i.e. with increasing the plies flexural strength increases. Lowest flexural strength is found for single ply composite of 34.55 MPa and this increase dramatically by almost 2653% and reaches the peak at 5 CK sample. In case of flexural strength the extreme layer play the vital role. Carbon is very tough as well as Kevlar; hence increasing number of fabric plies shows very high flexural strength.

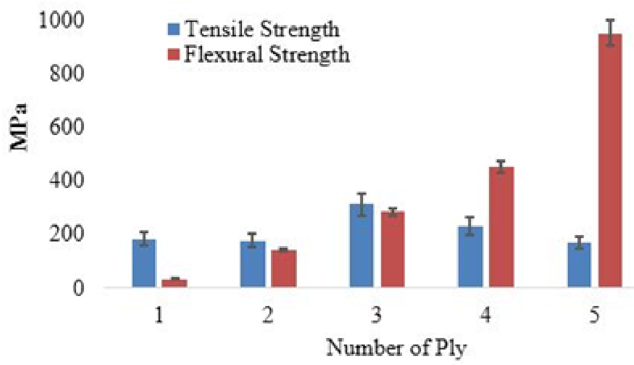

Figure 2. Tensile and flexural strength of CK-Epoxy composite

Figure 3 illustrates the tensile modulus (TM) and flexural modulus (FM) of CK-epoxy composites in different formulations. The composite prepared using 2 plies of CK showed the highest tensile modulus (7.6 GPa) amongst the composite evaluated. Likewise tensile strength, CK5 sample produced the least modulus. This is about 88% lower than the highest modulus. A decreasing trend is evident from CK2 sample to CK5 sample. This reduction in modulus with the increase of plies may be attributed to the ductile properties of Kevlar fiber. Although, it was expected that 3 plies composite will show the highest value of modulus as like as tensile strength but it shows the lower tensile modulus. The result of this variation may be due to the presence of more void content resulted by air entrapment during the fabrication of composite. Void affects the tensile properties adversely reported by the researcher[32] . The higher void content results in micro cracks in the composite which shows poor modulus. As in Figure 3, it can be seen that 5 plies composite shows the maximum flexural modulus of 47.95 GPa as expected. Flexural modulus showed the similar trend of flexural strength discussed earlier. It is interesting to note that single ply sample did not produce any flexural modulus. Flexural modulus increased about 369% from CK2 sample to 5 plies sample. An insignificant change in flexural modulus is found between 2 and 3 plies samples. The increase in flexural properties with the number of plies can be attributed to the blending of carbon and Kevlar fibers. Composite failure is dominated by the fiber buckling of Kevlar but incorporation of stiff carbon resist the buckling of Kevlar. On the contrary, tendency of breakage of carbon fiber is restricted by ductile Kevlar fiber and thus CK composite yield higher flexural properties.

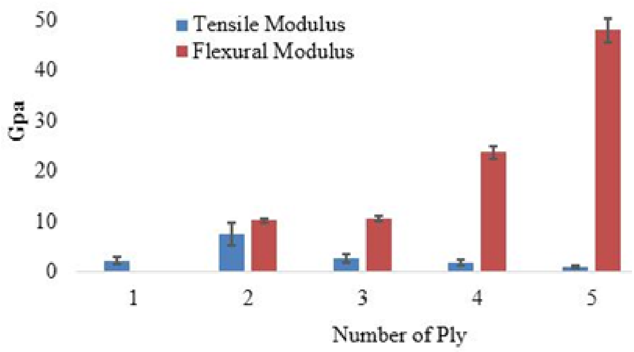

Figure 3. Tensile and flexural modulus of CK-Epoxy composite

Izod impact test was carried out to analyze the effect of twill woven carbon Kevlar fabric plies on the energy absorbing capacity of the hybrid composite. The impact property of the CK-Epoxy composite is shown in the Figure 4. The impact energy of the composite is affected by the interlaminar and interfacial parameters and the reinforcing materials play a vital role as they directly influence the crack formation in the composite[33] . Regarding number of CK plies, it is found that single ply composite shows no impact strength. On the other hand, CK3 sample shows maximum impact strength whereas 5 plies CK composite shows least impact strength of 114.7 kJ/m^2. This can be attributed to the improper interaction between fiber and matrix. This may be due to weak interfacial bonding between CK and epoxy. In general, impact energy is extended through plastic deformation of matrix; fiber breakage and fiber pull out. Plastic deformation of the composite is shown in the Figure 6 which explains the reason for higher impact strength of CK composite. In addition, presence of more carbon fiber in CK5 sample was likely to restrict the extent of the plastic deformation of the Kevlar fiber, which caused lower impact strength.

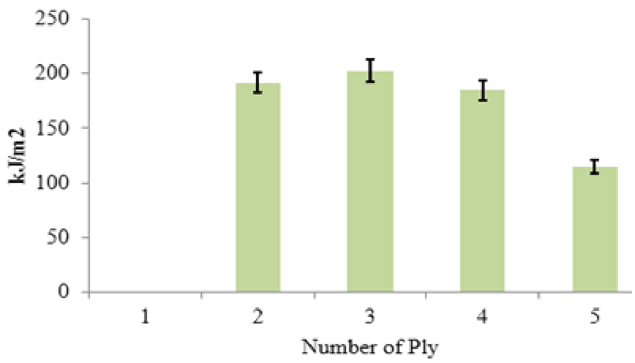

Figure 4. Impact strength of CK-Epoxy composite

3.2 Water uptake percentage

Figure 5 depicts the water uptake (changes in weight in mg) of the composite against soaking time. It was found that CK composite showed very rapid absorption of water up to 20 min and absorb 2.34% of water. The organic group present in the epoxy backbone favors the composite to interact with water[34] . Further immersion of the composite in water shows very little absorption of water by 1.14% from 20 min to 40 min. A very small drops in water absorption is recorded from 20 to 30 min by 0.114%. Then the composite reabsorb water and highest amount of 0.073 mg is absorbed at 65 min and became static. It is worth noticing that for short immersion time amount of water absorbed was not in equilibrium condition. The higher absorbency and diffusivity of water molecules during re-absorption is an anomalous diffusion behavior. This can be explained by the relaxation phenomena as well as reverse osmosis. Formation of micro-voids during the mechanical test facilitates the water passage into the composite and research to the saturation. Afterwards, due to reverse osmosis, some amount of water diffuse back to the source. In addition, capillarity would create an ideal passage for water molecules to enter into the composite materials. The absorbed water molecules may cause swelling of fiber and re-orient the fiber architectures. So, after diffusion back of water molecules, the polymer structure is different from the original one because of the swelled segmental conformation and thus more water absorption takes place during re-absorption[35] . Prolonged immersion time may finally make the samples saturated.

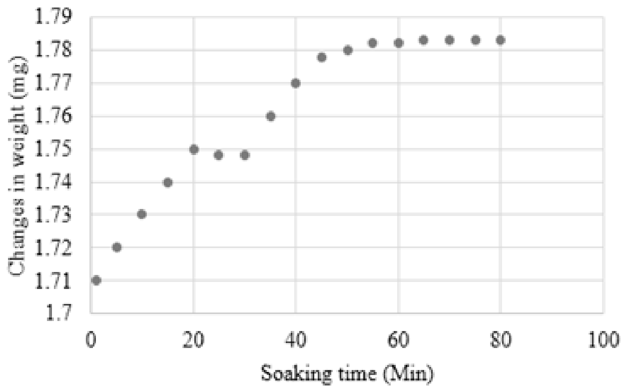

Figure 5. Water uptake percentage of CK-Epoxy composite

3.3 Surface failure analysis

Generally, it is well known that fiber matrix interface play crucial role in determining mechanical properties of CK composite. The composite materials requires strong interfacial bond between the reinforcing materials and matrix to transfer the stress effectively[36] . To investigate the failure mechanism of the CK reinforced epoxy composite, the tensile fracture surface was evaluated by SEM image as shown in the Figure 6. It can be seen from that fibers pull out from the matrix take place resulting crack and void. This means the weak interfacial bonding between fiber and matrix which cannot withstand the force applied on it or transfer the load efficiently. Thus flaws, microcracks and void generate and reduce the composite mechanical properties. Displacement of CK layers from the epoxy is also visible in the fractogrpah which causes delamination. This may be due to the lower strength of thin layer of epoxy matrix. So, it can be concluded that the composite properties are not homogeneous.

3.4 Thermal stability analysis

The thermal stability of CK/epoxy composite as a function of temperature was analyzed by thermo-gravimetric analyzer. The TGA curves of composite and epoxy resin is shown in the Figure 7. It is observed that CK composite shows good thermal stability up to 600 °C. More than 40% residual mass of CK composite was left. On the other hand, epoxy resin shows more thermal degradation than the composite. Epoxy start to degrade before 200 °C and touch the lowest point at 600 °C where only 12% of epoxy was left. So TGA curves indicates that, incorporation of CK in epoxy enhance the thermal stability of epoxy. For pure epoxy the onset temperature was 200 °C whereas for composite it increases to around 300°C. The composite shows higher residual mass than the epoxy at 600°C indicated in the TGA curve. Thus addition of CK fabric in epoxy increases the thermal stability and makes the composite suitable for the applications in area of higher temperature resistant materials.

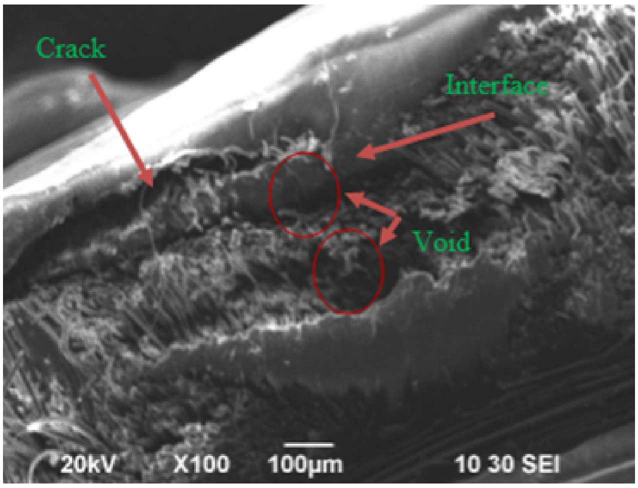

Figure 6. Fracture micrograph of CK-epoxy composite after tensile test

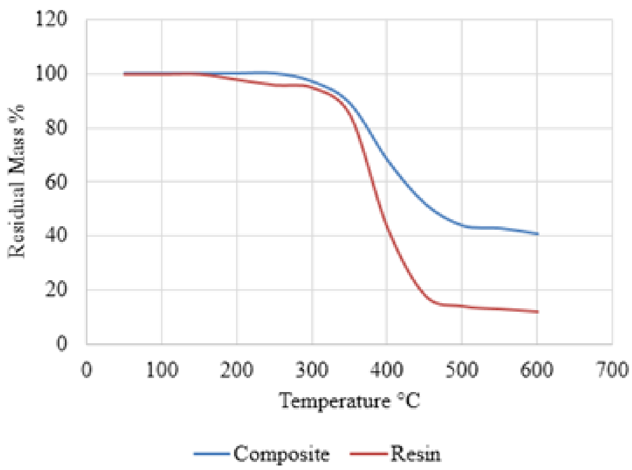

Figure 7. Thermograph of CK-epoxy composite

3.5 Absorption spectral analysis

The FTIR spectrum of CK-epoxy is presented in Figure 8. The composite sample had multiple absorption bands in the range of 3400 - 3600 cm^{-1} indicate the N-H stretching band (Hydrogen bonded), O-H stretching (Hydrogen bonded), O-H stretching also probably due to the terminal –OH groups (or from traces of water molecules entrapped into the composite matrix) for Kevlar moiety. The absorption band appears at 2841, 2873, 2923, 2960 and 2730 cm^{-1} shows the aliphatic CH and CH_2 stretching vibrations. Another multiple bands appear in the range of 1473.5 cm^{-1} for C=C in the benzene. A C-N stretching band appears at about 1400 cm^{-1} for primary amides. The primary amides give N-H bending vibration bands in the range from 1640 to 1620 cm^{-1}. They often nearly overlap the C=O stretching absorption bands. Primary amides give other bending bands at about 1125 cm^{-1} and a very broad band in the range from 750 to 600 cm^{-1}. The absorption bands at 1550 cm^{-1} are attributed to a combination of a C-N stretching band and an N-H bending bands. All the assigned peaks are strongly supporting the weak interactions between the Carbon, Kevlar and Epoxy in the composite matrix.

Figure 8. FTIR absorption spectra of CK-epoxy composite

4 Conclusion

Five samples with ply 1 to 5 were developed by hand layup process for this experiment. In this study the effect of ply variation on tensile strength, bending strength, tensile modulus, bending modulus and impact strength were analyzed. Specimen CK3 shows the maximum tensile strength for all type of composite used in this experiment whereas CK2 shows the highest tensile modulus. Flexural properties show an increasing trend with the increase in number of plies. Based on the results single ply sample shows zero impact strength while three plies sample produce the highest result. Water uptake test exhibit a rapid absorption initially and decrease slowly before reaching the saturation point. TGA test indicates the stability of composite materials against temperature and significant improvement is observed in thermal stability of composite materials. So from the above studies it can be infer that by varying the number of plies, different mechanical properties of CK reinforced epoxy composites can be tailored and could find potential applications as high-performance engineering materials.

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