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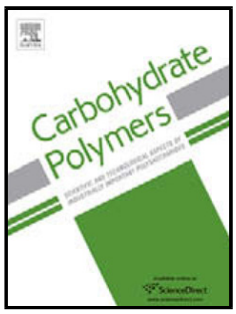

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Development of flax/carbon fibre hybrid composites for enhanced properties

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Abstract

Uni-directional (UD) and cross-ply (CP) cellulosic flax fibre epoxy composites were produced by hybridising UD carbon fibre prepreg onto flax system. A compression moulding technique was used to produce both flax and carbon/flax hybridised laminates. The effect of carbon fibre hybridisation on the water absorption behaviour, thermal and mechanical properties of both UD and CP flax specimens were investigated by means of water absorption, tensile, thermogravemetric analysis and flexural testing. The results showed that water absorption behaviour of hybrid samples are markedly improved compared to those without hybridisation. Similarly, the thermal stability, tensile and flexural properties of the hybrid composites are significantly improved in comparison with UD and CP flax composites without hybridisation. The experimental results suggest that cellulosic flax fibre reinforcement contributed to improve the toughness properties by promoting crack propagation whereas the carbon fibre contributed in improving thermal stability, water absorption behaviour and the overall strength and the stiffness of the hybrid composites.

***Keywords*:**

Hybrid composites; Cellulosic fibres; Mechanical properties; Compression moulding

1. Introduction

Environmental legislation as well as consumers pressure for the adaptation of a "cradle to the cradle" concept for material use throughout the world has triggered a paradigm shift towards using natural materials as a substitute for non renewable synthetic fibres like glass and carbon (Bledzki & Gassan, 1999; Bledzki, Reihmane, & Gassan, 1996; Dhakal, Zhang, & Richardson, 2009).

Review on international research into cellulosic fibres and composites (Eichhorn, Baillie, Zafeiropoulos, Maikambo, Ansell, Dufresne, Entwistle, Herrera-Franco, Escamilla, Groom, Hughes, Hill, Rials, & Wild, 2001), summarised a number of international research projects being undertaken to understand the mechanical properties of natural cellulose fibres and composite materials. A study on the applications of thermoset and thermoplastic matrices relative to natural cellulosic fibre based products is supported by number of publications and reviews (Joseph, Joseph, & Thomas, 1999; Mohanty, Misra, & Drzal, 2001; Faruk, Bledzki, Fink & Sain, 2012). Thus, it is well documented that natural cellulosic fibre reinforced composites is an emerging alternative to synthetic fibres as a reinforcement in composite materials (De Rosa, Dhakal, Santulli, Sarasini, & Zhang, 2012; Dhakal, Zhang, Bennett, & Reis, 2012a).

Because of their unlimited availability, much higher specific strength than conventional fibres as presented in Table 1 (Jayaramudu, Maity, Sadiku, Guduri, Rajulu, Ramana, & Li, 2011), lower density and problem-free disposal make natural fibres attractive reinforcements for polymer matrix composites (Dhakal, Zhang, & Richardson, 2007b; Khan, Hassan, & Drzal, 2005; Joseph & Thomas, 1996; Richardson, Santana, & Hague, 1998), cellulosic fibres (hemp, flax and jute) composites have been successfully used for light-weight and low cost applications in recent years. However, significant barriers for structural applications of these composites still exist. These barriers include the lack of

confidence in the use and performance of natural plant fibres and their composites, their incompatibility with the hydrophobic polymer matrix, limited understanding of diffusion behaviour, and lack of established manufacturing process and poor resistance to moisture (Dhakal, Zhang, Richardson, & Errajhi, 2007a; Khan, Ganster, & Fink, 2009; Mwaikambo & Ansell, 2002).

Hybrid fibre composite materials are a combination of more than one type of fibre in the same matrix. Though it is possible to combine multiple types of fibre into a hybrid material, a combination of two types of fibre is the most beneficial (John & Thomas, 2008). Cellulosic/synthetic hybrid composite exploits the synergy between cellulosic natural fibres in glass/carbon polymer composites with improved performance while reducing environmental impact has been an important topic from research and industrial point of view (Abdullah-Al-Kafi, Abedin, Beg, Pickering, & Khan, 2006; Dhakal et al., 2012a; Khalil, Hanida, Kang, & Fuaad, 2007; Hariharan & Khalil, 2005). A promising compromise between performance and environmental sustainability can be achieved by replacing part of petroleum based non-renewable reinforcement by renewable natural reinforcement in polymer composites (Dhakal, Zhang, Reis, Surip, & Bennett, 2012b; Sreekala, George, Kumaran, & Thomas, 2002).

Hybrid composites are one of the emerging areas in polymer composites. Over the last few years, polymer based hybrid materials reinforced with natural cellulosic fibres with synthetic fibres have received great attention. A comprehensive review conducted by (Dhakal, Zhang, & Bennett, 2012c; Jawaid & Khalil, 2011) has outlined the use of hybrid composites fabricated by combining cellulosic and synthetic reinforcements. According to the study, the use of cellulosic fibre as reinforcement can reduce the material cost and at the same time yield high strength-to-weight ratios. The study has further outlined that cellulosic fibres offer several advantages compared with synthetic fibres such as glass and carbon. They however, also pointed out that the cellulosic fibre structure is influenced by several

conditions which cause variation in the fibre quality, is one of the major disadvantages of natural cellulosic plant fibres. The study concluded that several cellulosic fibre composites hybridised with synthetic fibres are cost effective, environmentally friendly and can reach the performance of glass fibre composites; it not only can be used by automotive industries but can be explored its application in other areas such as aircraft components, building industry, rural areas and biomedical. Imperfect impregnation especially in natural fibre composites leads to dry fibres and entrapped air, leaving voids in final product and affecting their mechanical and thermal properties. Prepregs are especially designed to overcome the manufacturing difficulty of impregnation of reinforcement with the resin. Although carbon fibre and glass fibre prepregs have been in use for a number of years, a prepregs made of natural cellulosic fibres such as flax and hemp were not commercially available until recently. It has, therefore, not reported yet how the use of natural fibre based polymer prepregs and its hybridisation with synthetic would influence on the mechanical and environmental properties of composites.

Cellulosic flax fibres (*Linum usitatissimum L*) are one of the strongest natural reinforcements. So, flax based epoxy has a potential to achieve high specific strength than conventional reinforcements (Summerscales et al., 2010; Bos et al., 2002). In the present study, a novel cellulosic flax epoxy prepregs composites (uni-directional and cross-ply oriented) are hybridised with commercially available synthetic carbon fibre epoxy prepreg system by using compression moulding technique and their water absorption behaviour, thermal stability and mechanical properties are investigated.

2. Experimental

2.1 Materials and methods

The unidirectional carbon fibre prepreg used to hybridise flax prepregs samples with epoxy resin content 37 wt.% was supplied by Gurit (U.K.) Ltd. The flax prepregs, unidirectional and cross ply, nominal resin content 55 wt.% each, were supplied by Lineo,

Belgium. An adhesive Teflon film used as a mould release agent was purchased from Aerovac. The details of prepregs used are presented in Table 1.

2.2 Fabrication of hybrid samples

The prepreg materials were taken out of the deep freezer 24 hours prior to moulding to allow defrosting sufficiently at room temperature. Each sample was comprised of 6 ply of prepreg material. Each ply was cut by scissors into rectangles and was laid up directly on top of each other to form a single laminate in a balanced lay-up of orientation. Rolling was employed to eliminate trapped air. Flat steel plates were used as moulds. A Teflon sheet separated the laminate sample from the mould plates. An additional plastic sheet was placed between the bottom mould and the compression moulding machine platen to stop excessive resin from leaking and contaminating the machine.

All of the laminates were performed on a Bypel Compression Moulding machine (Figure 1). The materials, placed between steel mould plates, were heated at maximum 130°C. A uniform moulding pressure of 0.5 MPa was applied to each 6 layer laminate for duration of 45 minutes. These parameters were stated as the optimum curing parameters for the carbon fibre prepreg, and followed similar recommendations for the flax prepregs. A total of five different specimens as were fabricated and were referred to as:

1. 6 ply flax fibre cross-ply orientation- FlaxCP
2. 4 ply unidirectional carbon fibre and 2 ply flax fibre- FlaxCP-Carbon
3. 6 ply unidirectional carbon fibre- Carbon
4. 6 ply unidirectional flax fibre- FlaxUD
5. 4 ply unidirectional carbon fibre and 2 ply flax fibre- FlaxUD-Carbon

2.3 Water absorption test

The effect of water absorption on flax and carbon fibre hybridised composites were investigated in accordance with BS EN ISO 62:1999. The samples for tensile and flexural tests were cut to a size of 150x20x3 mm^3 and 60x15x3 mm^3, respectively. Water absorption

tests were conducted by immersing the composite specimens in a de-ionised water bath at 25 ^{o}C; until the samples reached near saturation. After immersion for 24 hours, the specimens were taken out from the water and all surface water was removed with a clean dry cloth and the specimens wee weighed. This process was repeated regularly at 24, 48, 98, 196, and up to 648 hours exposure. The percentage of water absorption in the composites was calculated by weight difference between the samples immersed in water and the dry samples. The percentage weight gain of the samples was measured at different time intervals and the moisture content versus square root of time was plotted.

2.4 Flexural testing

The flax and carbon fibre hybridised epoxy prepreg composites were tested for determining flexural stress and modulus under three point bending in a Zwik/Roell Z030 machine in accordance BS EN 2746:1998 test method. The size of the flexural sample used was 60 mm x 15 mm. A total of five specimens were tested for each type of prepreg composites. The crosshead speed chosen was 2 mm/min. The span- depth ratio for flexural testing was 16:1.

2.5 Tensile testing

The tensile strength and modulus of the flax and flax/carbon fibre hybridised composites were measured in a universal testing machine. A total of five specimens were tested for each type of prepreg system with a crosshead speed of 10 mm/min. Test specimens were individually cut using water jet cutting into rectangular beams from the laminate slabs.

2.6 Thermal stability

In order to study the effect of carbon fibre hybridisation on the thermal stability of flax composites, thermogravemetric analysis (TGA) was performed using a TGA Q 50 V 6.1 module from TA Instruments. The samples were placed in a platinum crucible, and heated in a nitrogen filled environment at the heating rate of 20 ^{0}C/min from ambient temperature to 550 ^{0}C. The initial weights of the samples were approximately 5-8 mg. The data from the test

is displayed as TG (weight loss as a function of temperature) and as DTG (derivative thermal gravimetry, weight loss rate as a function of temperature).

2.7 Scanning Electron Microscopy (SEM)

The morphologies of fractured surfaces of the composites were examined using a SEM JSM 6100 at room temperature.

3. Results and discussion

3.1 Water absorption behaviour

Figure 2 shows percentage of weight gain as a function of square root of time for Flax and flax/carbon hybridised samples immersed in de-ionised water at room temperature (23 ^{o}C). The maximum percentage weight gain for Flax UD and CP specimens immersed at room temperature for 648 hours is approximately 13 and 23%, respectively. The maximum percentage weight gain for carbon fibre hybridised specimens (FlaxUD/carbon and FlaxCP/carbon) immersed at room temperature for 648 hours is approximately 2 and 8%, respectively, showing a big drop as a result of carbon fibre hybridisation. Although carbon fibres are insensitive to the effects of water absorption, flax fibres and epoxy resin are both susceptible. Water is absorbed along the fibre-resin interface, flowing through the composite, where it can cause hydrolytic breakdown of any chemical bonding between the fibre and resin as well as swelling of the resin (Dhakal et al 2007b). With this in mind it can be said that the increased number of interfaces between the FlaxCP fibres and the resin is greatly increased when compared to FlaxUD. For FlaxCP sample, the moisture has less resistance and more directions in which it can flow, leading to an increase in moisture uptake (as seen in Figure 2). Mechanical and water absorption properties of jute/glass fibre reinforced epoxy hybrid composites studied (Koradiya, Patel, & Parsania, 2010) indicated that hybrid composites showed improvement in water absorption behaviour and mechanical properties.

The results in Figure 2 show that the hybridisation of carbon significantly reduces the amount of water absorbed. It should also be noted that the FlaxUD-Carbon sample absorbed

moisture significantly lower than FlaxUD alone. Similarly, FlaxCP carbon samples absorb moisture lot less than FlaxCP alone. The decrease of water uptake in these hybrid composites is attributed to the how the carbon fibre was incorporated. The carbon fibre was reinforced in the periphery and the flax fibre was at the core which seems giving the maximum resistance to water absorption.

3.2 Flexural properties

A typical load-deformation curves obtained from 3 point-bending testing is shown in Figure 3. The flexural strength and modulus obtained via calculation involving the failure load and test dimensions of flax prepregs (flax cross-ply and flax uni-directional) and carbon fibre hybridised flax epoxy prepreg composites are summarised in Table 2.

Figure 3 compares the flexural properties of the hybrid composites with those of the flax UD-CP and carbon prepreg composites. The load deformation curve for carbon fibre sample is linear with a small non-linear region at the end of the test and a sudden drop of the load after a peak load and a small portion of prolonged curve before it finally broke. For both flax samples, FlaxCP and FlaxUD, without hybridisation, the load/deformation curves show a non linear behaviour with a prolonged load deformation curve.

The load/deformation curves are indicative of load history, which has a link with damage initiation and propagation. The overall curves for both flax samples can be approximately divided into two parts at the peak load. The first part is related to damage initiation where there is a linear increase of load against the deformation and at this state there would be no visible damage indicating elastic response of the samples. The second part is mainly associated with the damage propagation phase where the load decreases incrementally suggesting final failure of the specimens. As for carbon sample, the second part of the curve, which is damage propagation, seems a lot less than that of flax samples. With the hybridisation of flax with carbon prepreg, the load deformation curve changes from linear to more prolonged non-linear. As can be seen from Table 2, carbon fibre prepregs sample

displayed the highest flexural strength of approximately 1660 MPa. The flexural strength noted for FlaxCP and FlaxUD without hybridisation is approximately 140 and 314 MPa, respectively. The flexural strength recorded for FlaxCP-Carbon and FlaxUD-Carbon is approximately 145 and 319 MPa, respectively. With the hybridisation of carbon fibre with the flax fibre prepregs samples, FlaxCP and FlaxUD, there is a slight increase in the flexural strength.

The flexural modulus of carbon fibre prepreg sample displayed the highest modulus of approximately 127 GPa. The modulus value for flax cross-ply and uni-directional samples was recorded approximately 7 and 20 GPa, respectively. With the hybridisation of carbon on both flax samples, the modulus was increased to approximately 10 and 29 GPa, (an increase of 43 and 45%), respectively. This increase in modulus for flax samples with the introduction of carbon prepreg is significant. It is evident from this result that in flexural results, the hybridisation of carbon with flax is advantageous or a stiffness or modulus but not so beneficial for flexural strength.

The average deformation at peak load recorded for FlaxCP and FlaxUD samples is 5.96 and 4.41 mm, respectively. For carbon fibre prepreg sample, the deformation at peak load is 3.50 mm, which is approximately 70% lower than that of FlaxCP. With the hybridisation of flax into carbon prepreg, the deformation at peak load is increased by approximately 40%. It is clear evidence that the deformation at peak load of flax prepreg samples under flexural testing increases compared to carbon fibre prepreg sample. Moreover, the deformation of flax samples both UD and CP showed highest deformation, indicating greater elongation at break than carbon samples. With flax hybridisation, FlaxUD-Carbon, the elongation at break of carbon fibre has been increased significantly. The load deformation curve for this sample shows a prolonged deformation beyond its maximum flexural strength which can be related to the fracture behaviour of flax fibre. The load-deformation curves for FlaxCP-carbon composite, a couple of step-like load drops are recorded. Although

glass/carbon fibre reinforced polymer composites have become increasingly popular in variety of applications, they are still weak in toughness.

3.2.1 Effect of hybridisation on flexural properties

The flexural properties data listed in Table 2 and shown in Figure 3 revealed that, flax/ carbon fibre hybridised composites exhibited improvement in elongation at break compared to carbon prepreg alone. The improvement in this property was accompanied by decrease in flexural strength for carbon composites. Similarly, both flexural strength and the modulus of the flax samples were enhanced with the hybridisation of carbon fibre but with reduction in elongation at break. It is apparent from the values obtained for the carbon sample that this decrease in flexural strength was caused by the presence of flax fibres which inherently have lower strength than those of carbon fibres but better elongation properties. Traces of flexural load vs. deformation curves (Fig. 3) showed that carbon hybridised flax composites samples have higher flexural strength compared to that of flax composites without hybridisation. The flexural strength and modulus of both flax composite samples have increased with the carbon fibre hybridisation. In carbon fibre prepreg flax composites, unfortunately, this increase in flexural strength comes at the expense of substantial reduction in deformation or extension (Table 2). With the hybridisation of flax with carbon composites, the elongation has been increased accompanied by trade-offs, such as reduced strength. These results clearly demonstrate that the hybridisation of flax with carbon has beneficial effect on flexural strength, modulus and elongation. The compatibility between two hybridising materials is very important when developing hybrid composites (John & Thomas, 2008).

The enhancement properties in hybrid composites are largely governed by fibre volume fraction, fibre orientation and the intermingling of the fibres and the interfacial adhesion between the reinforcement and the matrix (Sreekala et al., 2002). The flexural properties of hybrid composites in this study show dependence on how the reinforcements are placed geometrically. The flax prepregs are placed between carbon fibre prepregs and placed

in the middle. The different behaviours exhibited by the various samples can therefore be attributed to the geometrical effect of reinforcements and the properties of reinforcements. Flexural strength and modulus are significantly influenced by the properties of reinforcement closest to the top and the bottom surfaces of the specimens. The top surface experiences the compression force and the bottom surface tension force. The middle part of the specimen experiences shear force. The total bending deflection in a flexural test is a combination of a bending deflection and shear deflection. The improved flexural strength, improved stiffness and enhanced elongation at break properties obtained for hybridised composite systems can be related to load distribution mechanism as discussed above in three-point bending test mode.

The elongation properties of carbon fibre samples exhibit a lot lower than that of flax composites (sudden drop in load when it fails). One way of improving the elongation at break behaviour of carbon fibre composites is to hybridise tough materials with the carbon composites, such as ductile cellulose natural fibres; namely flax (Bessadok, Langevin, Gouanve, Chappey, Roudesli, & Marais, 2009). Similarly, the strength of flax composites can be enhanced by hybridising carbon with flax composites. As a result, it can be combined the good properties of carbon/glass, i.e. high stiffness and good properties of flax, i.e. good toughness and elongation at break. Despite their low flexural strength, flax fibre and flax hybridised composites demonstrate better toughness properties by showing higher elongation compared to carbon fibre composites. This could be related to the high strain to failure of flax fibre epoxy prepreg composites.

3.2.2 Failure mechanisms

Figure 4 shows an SEM micrograph of fractured surfaces in the flexural test for different samples. The failure mechanisms involved in carbon fibre composites is matrix cracking, fibre fracture in brittle fashion. For carbon fibre hybridised samples, in the case of FlaxCP and FlaxUD, there is a considerable amount matrix cracking and fibre bending. For FlaxCP-

Carbon and FlaxUD-Carbon samples, there is an indication of matrix cracking and fibre pullout. Fibre pullout occurs when the interfacial stresses at the fibre matrix interface exceeds the interfacial strength, causing the fibre to debond from the matrix. SEM micrograph of fractured surface in flexural test shown in Figure 4 further clarifies that the delamination, fibre tearing and breakage for carbon hybridised flax samples.

3.3 Tensile test results

The tensile strength and the modulus curves taken for the degradation of flax, carbon and carbon flax based epoxy prepregs and hybridised flax-carbon based epoxy prepreg composites are shown in Figure 5 and are summarised in Table 3. Figure 5 displays the strength that carbon fibre offers when compared to natural fibres, especially since this was a hybrid sample. The hybridisation of carbon fibre has provided the hybrid material much stiffer, stronger properties over its natural fibre counter-parts, showing that the hybridisation of carbon and flax can result in a material with significantly improved mechanical properties. FlaxCP-Carbon exhibited a 47% decrease in percentage to strain failure, as well as a 282% increase in tensile strength. A similar trend of increased in mechanical properties for hybrid composites were observed by other researchers. Effect of glass fibre hybridisation with natural fibres for application in the piping industry (Cicala, Cristaldi, Recca, Ziegmann, El-Sabbagh, & Dickert, 2009) and glass kenaf hybrid composites developed (Davoodi, Sapuan, Ahmad, Ali, Khalina, & Jonoobi, 2010) for application in passenger car bumper beam indicated that hybrid composites possess better mechanical properties than un-hybridised composites.

3.4 Effect of structure on the mechanical properties

Looking back at Tables 2 and 3, it is apparent in this experiment that the variation in flexural and tensile results between individual samples (CV% and Standard Deviation values) is remarkably good. During flexural testing, the natural fibre and hybrid samples competed evenly with Carbon (in terms of standard deviation and coefficient of variance), with FlaxUD

outperforming Carbon. This suggests that repeatability is possible; an important factor when considering mass production. Figures 6 and 7 show microscopic images of carbon and carbon flax hybridised samples. Carbon has the most uniform cross-section; each ply lying flat and in a uniform manner, with each ply distinctly identifiable from each other. FlaxUD and FlaxCP are completely different. With each layer being cross-ply, FlaxCP looks like a single structure. FlaxUD is not much different, probably due to the increased size of the fibres intermingling with each other.

3.5 Thermal behaviour

For flax composites and hybrid composites to be used in load bearing applications, the understanding of thermal stability is very important. It is evidenced from the TGA results that carbon fibre hybridisation can significantly influence the thermal stability of flax composites. The thermogravemetric (TG) and the differential thermogravemetric (DTG) curves taken for the degradation of flax, carbon and carbon flax based epoxy prepregs and hybridised flax-carbon based epoxy prepreg composites are shown in Figure 8 (a). The TG and DTG curves have been used to obtain the onset of decomposition temperature, temperature at the decomposition peak, decomposition rate at the peak as well as the fraction of material that is not volatile at 550°C, denoted as char, are summarised in Table 4. The characteristics of the TG and DTG curves are: the onset temperatures of the start of degradation (onset of decomposition temperature, the intersections of the extrapolated base lines with tangents drawn in the inflection points of the TG curve), the temperatures at the maximum rate of degradation in the first degradation step, temperature at the main decomposition peak, and the decomposition rate. Carbon fibre sample showed the onset of decomposition temperature at 365 °C.

The onset of decomposition temperature for flax samples (FlaxCP and FlaxUD) is recorded 327 and 320 °C, respectively. The decomposition temperature for carbon fibre hybridised flax composite samples (FlaxCP-Carbon and FlaxUD-Carbon) is recorded approximately 339 and 322 °C, respectively. This shows a slight increase on onset of decomposition temperature upon the introduction of carbon fibre onto flax prepregs. The final residual char yields of the various samples are listed in Table 4, showing significantly difference for various samples. Flax samples (FlaxCP and FlaxUD) showed char yield of approximately 14 and 15%, respectively. Upon the introduction of carbon prepreg onto flax, the residual char yield left at 550°C for both flax samples increased considerably from 14 and 15% to approximately 35 and 38%, respectively. The shift of char yield to higher percentage indicates an increase of thermal stability of composites upon the hybridisation of carbon fibre

onto flax epoxy composites. As expected, the carbon fibre composites showed a charring structure leaving a char yield of 68% indicating highest thermal stability amongst the studied samples. This is attributed to resistance of carbon fibre to high temperature and better fibre matrix compatibility.

The DTG curves for different samples are shown in Figure 8 (b). The degradation pattern for flax, carbon and flax carbon hybridised systems are distinct. The DTG weight loss vs. temperature plot for flax cross-ply prepreg composites exhibit a two stage degradation process with a initial weight loss that starts just above room temperature, a very weak peak, corresponds to the vaporisation of absorbed water in the flax fibre (DTG peak at around 50 °C) and second main degradation peak at around 364 °C, whereas the degradation temperature for flax cross-ply-carbon hybridised sample shows a three-stage degradation process. The first related to water vaporisation at around 50 °C, the second stage degradation process at around 368 °C with a weight loss of approximately 67% and the third stage degradation is at around 434 °C with a weight loss of approximately 42%. The second shoulder in the peak could be related to the degradation of the cellulose and hemi-cellulose. The third could be related to the degradation of carbon fibre chain. This initial weight loss of water vaporisation was not observed for carbon based sample as these samples hardly absorb moisture. The temperatures at the maximum rate of degradation (represented by peaks on the DTG curves) in Flax-carbon shifted to lower temperatures compared with that of flax prepregs.

From DTG curves, it can be observed that the flax composite samples (FlaxCP and FlaxUD), the peak developed at about 364 and 358 ^{o}C, showing its maximum rate of decomposition 1.47 and 1.30%/^{o}C, respectively. The carbon fibre hybridised samples (FlaxCP-Carbon and FlaxUD-Carbon) indicate two step degradation processes. The first peak

for these samples occurred at around 364 and 358 ^{o}C, which is related to the degradation of the cellulose and hemi-cellulose (Singleton et al., 2003).

4. Conclusions

The present study concerning flax based epoxy pre-impregnated composites and the hybridisation of carbon fibre pre-impregnated epoxy composites and their effect on water absorption, thermal stability, flexural and tensile behaviour has led the following conclusions:

- Natural fibre hybrid composites are cost effective and possess better mechanical and thermal stability have potential to replace or reduce the utilisation of synthetic fibres as reinforcements in polymeric composites. The results from this study proved that hybridisation of carbon fibre with natural fibre such as flax is possible, using relatively simple equipment to manufacture samples which returned significantly improved environmental, thermal and mechanical performance.
- The environmental testing yielded excellent results; carbon fairing the best (absorbing the least amount of water) and FlaxCP performing inferior to that of FlaxUD. The hybrid samples sat between these extremes, the best result coming from FlaxUD-Carbon; exhibiting behaviours competitive to that of pure carbon composite.
- The maximum flexural and tensile properties were increased by the hybridisation of carbon prepregs. Similarly, the elongation at break was greater for both FlaxUD and FlaxCP samples compared to carbon alone.
- The thermal degradation behaviour of carbon/flax hybrid composites showed that the rates of weight losses were decreased with the carbon fibre hybridisation on flax prepreg composites. The residual char yield of the carbon hybridised composites was found to be higher than that of flax prepregs composites without carbon fibre hybridisation.

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Table 1: The detail properties of prepreg used

Reinforcement	Arial weight (g/m^2)	Ply thickness (mm)	Weave
FlaxCP	315	0.300	Twill 2/2
FlaxUD	190	0.165	Ribs 4/4 - unidirectional
Carbon fibre	476	0.281	unidirectional

Table 2: Flexural properties of different specimens

Sample	Average Max Load (N)	Cv (%)	Average Flexural Strength (MPa)	Cv (%)	Average Flexural Modulus (GPa)	Cv (%)	Average Deformation at Peak Load (mm)	Cv (%)
FlaxCP	138.24	0.11	140.40	0.11	6.69	0.28	5.96	0.06
FlaxCP-Carbon	80.31	0.18	145.00	0.18	9.71	0.34	3.80	0.80
Carbon	159.62	0.05	1660.01	0.05	126.74	0.13	3.50	0.09
FlaxUD	97.71	0.02	313.65	0.02	20.18	0.05	4.41	0.15
FlaxUD-Carbon	60.09	0.22	318.83	0.22	28.83	0.29	5.04	0.65

Table 3: Tensile properties of different specimens

Sample	Average Max Load (N)	Cv%	% strain to failure	Cv (%)	Tensile strength (MPa)	Cv (%)	Tensile modulus (GPa)	Cv (%)
FlaxUD	9158.7	0.09	4.07	0.22	126.30	0.09	2.9	0.13
FlaxCP	8324.6	0.02	4.56	0.30	100.9	0.03	4.40	0.03
FlaxCP-Carbon	24211.0	0.01	2.59	0.02	284.8	0.02	11.9	0.01

Table 4: Summarised thermal analysis data for various specimens

Specimens	Onset decomposition temp. (^{o}C)	Temperature at the main decomposition peak (^{o}C)	Decomposition rate at the peak (%/^{o}C)	Residual Char yield (%)
FlaxCP	327.00	363.95	1.47	14.06
FlaxCP- Carbon	339.00	367.00	0.83	35.18
Carbon	365.00	418.44	0.38	68.02
Flax-UD	320.47	358.00	1.30	15.16
FlaxUD-Carbon	321.65	357.00	0.70	37.63

Figure captions:

Figure 1: Mould and compression moulding schematics

Figure 2: Water absorption curves for flax and flax/carbon hybridised samples

Figure 3: Load deformation curves for different specimens

Figure 4: SEM micrographs of (a) FlaxCP (b) FlaxCP-Carbon (c) Carbon (d) FlaxUD (e) FlaxUD-Carbon

Figure 5: Load extension curves for different samples in tensile testing

Figure 6: Cross-sections of: (a) Carbon UD, (b) FlaxUD, (c) FlaxCP

Figure 7: Cross-sections of: (a) FlaxUD carbon, (b) FlaxCP carbon

Figure 8: (a) Thermogravemetric traces for different samples, (b) DTG traces for different samples

Research highlights

- A cost effective process of hybridisation is developed.
- Water absorption reduced, mechanical properties were improved due to hybridisation.
- Hybridised flax/carbon composites can be used as load bearing materials.

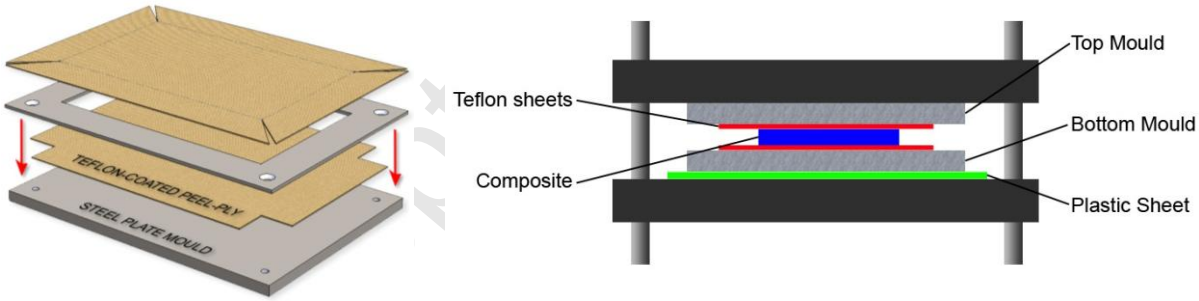

Figure 1: Mould and compression moulding schematics

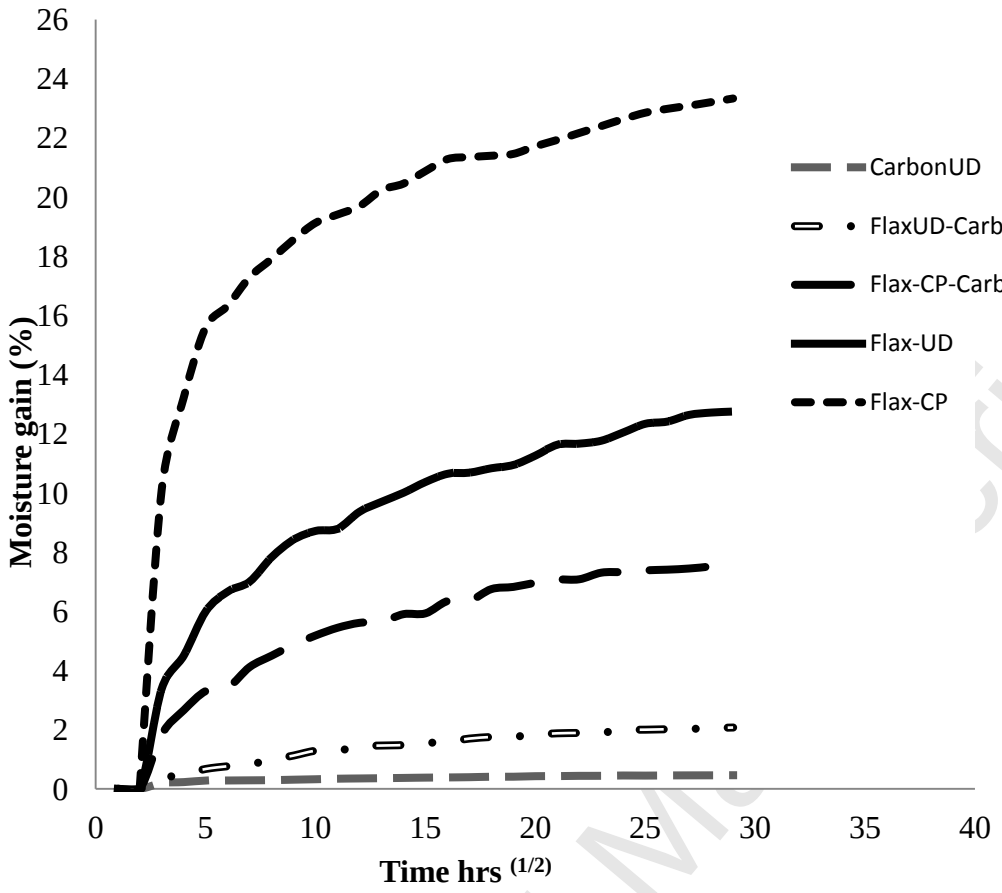

Figure 2: Water absorption curves for flax and flax/carbon hybridised samples

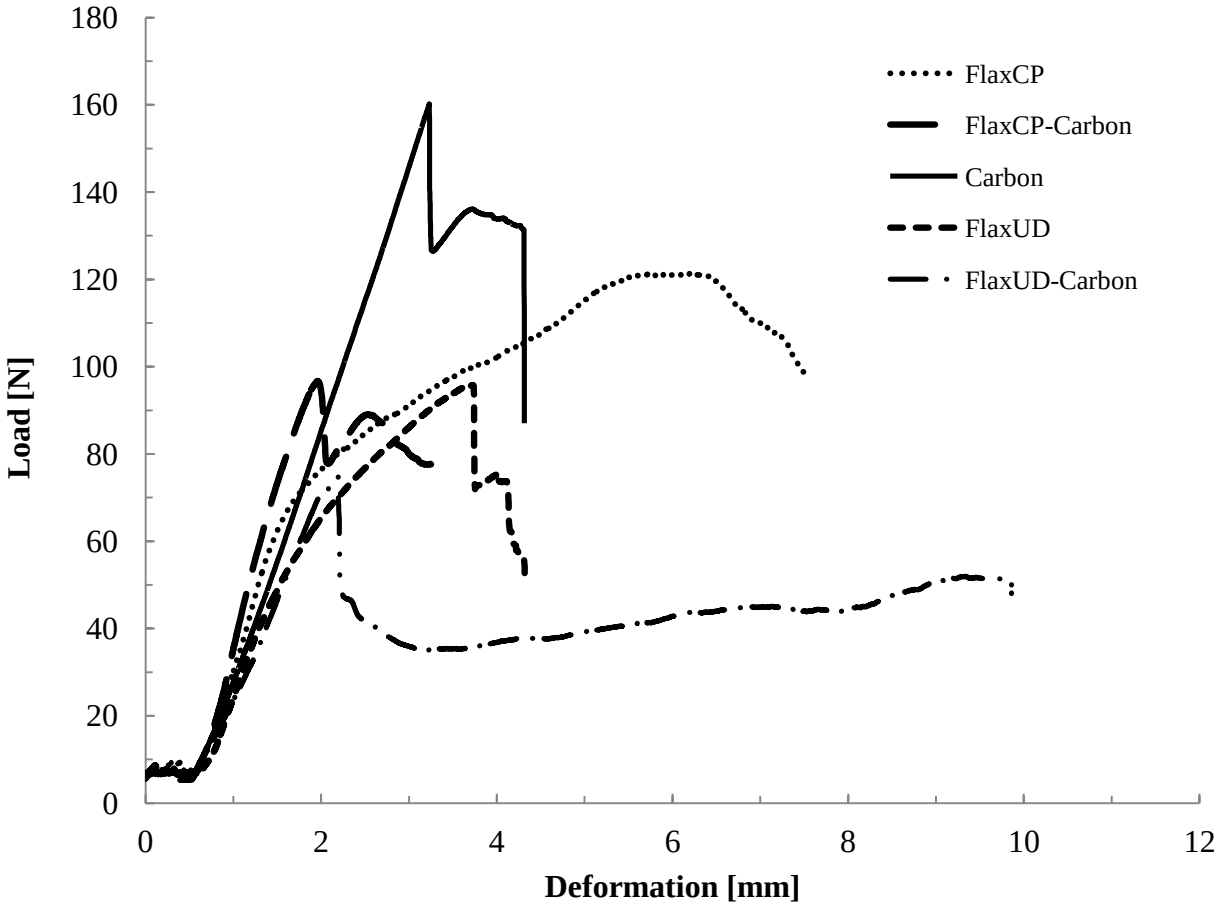

Figure 3: Load deformation curves for different specimens

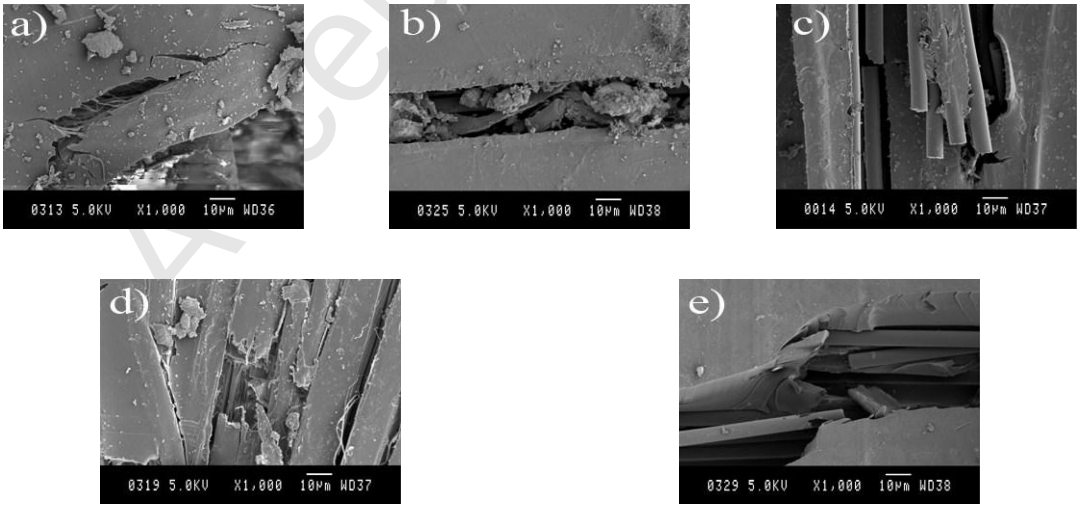

Figure 4: SEM micrographs of (a) FlaxCP (b) FLaxCP-Carbon (c) Carbon (d) FlaxUD (e) FlaxUD-Carbon

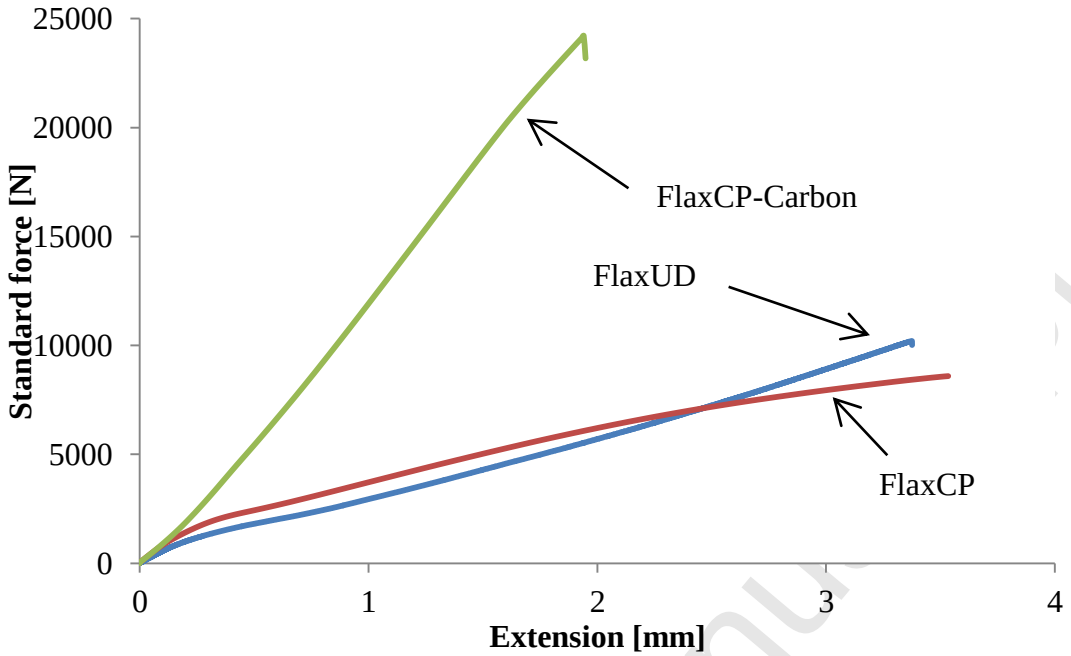

Figure 5: Load extension curves for different samples in tensile testing

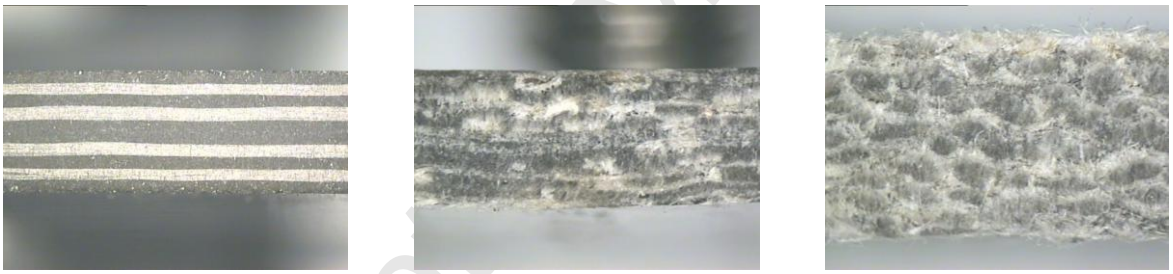

Figure 6: Cross-sections of: (a) Carbon UD, (b) FlaxUD, (c) FlaxCP

Figure 7: Cross-sections of : (a) FlaxUD carbon, (b) FlaxCP carbon

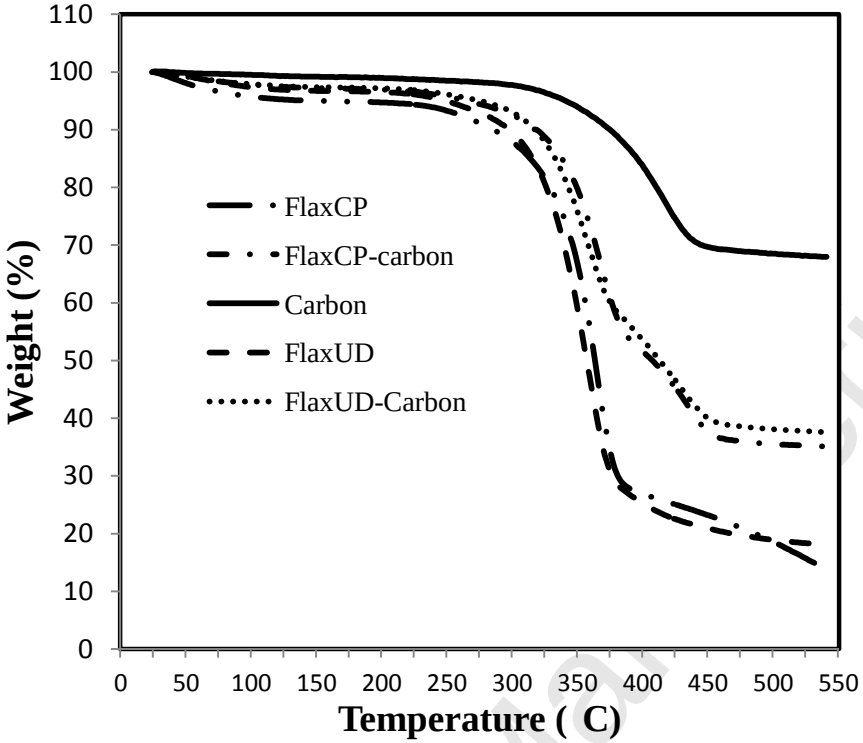

Figure 8a: Thermogravemetric traces for different samples

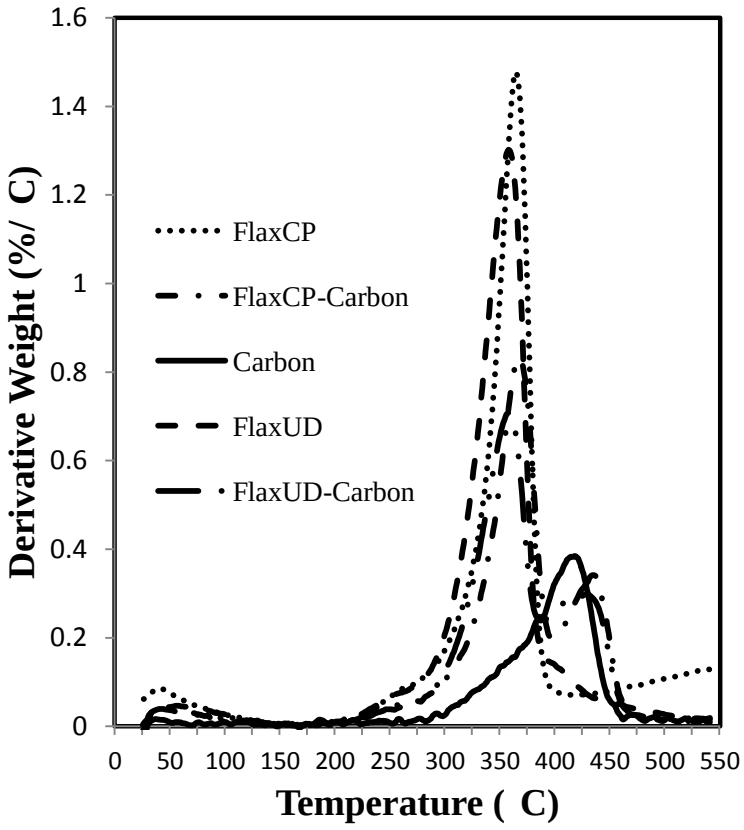

Figure 8b: DTG traces for different samples