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Mechanical Properties of Boron and Kevlar-49 Reinforced Thermosetting Composites and Economic Implications

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Abstract: *A wider adoption of emerging thermosetting composite materials using Boron and Kevlar-49 fibres will be facilitated by establishing their mechanical properties and production costs. This study aims to characterise these reinforced composites on the basis of performance and economic considerations that can be readily used by manufacturers and designers. Composites with polyimide and polyester thermosetting plastics were prepared and tested in tension, compression and bending. The results are compared with those predicted by several micromechanics models and their limitations have been identified. The developed composites are ranked on a cost-performance basis that can be used for different applications.*

Keywords: Thermosetting composites, characterisation of composites, boron fibres, kevlar fibres, mechanical properties

1. INTRODUCTION

Continuous fibre reinforced thermosetting composites are being used in large-scale structures such as aerospace, marine, automotive and so on. Characterisation of the tensile, flexural and compressive properties as well as the anisotropic nature of composites is more complicated compared to conventional materials.[1] There are a limited number of studies on properties of Boron and Kevlar-49 thermosetting composite laminates which exhibit excellent mechanical properties.[2] Boron fibres are not only strong in tension but also facilitate strong compression in composites. Kevlar-49 reinforcement has been seldom used in high-performance structural applications but its good mechanical properties combined with low density need further exploration. Polyimide is used in the composite and microelectronics industries[3] and its composites possess high mechanical strength, acceptable wear resistance, good thermal stability, good anti-radiation and good solvent resistance.[4] Low Modulus (LM) unsaturated polyester resin is the most important resin system commercially, accounting for around 80% of the relevant market. A comparative cost analysis is necessary to assess the potential deployment of composites in an economical way.

2. EXPERIMENTAL

2.1 Materials

In this study, continuous fibres of Boron 5521 (from Specialty Materials Inc.[5]) and unidirectional Kevlar-49 aramid fibre monofilament (from Dupont™ de Numours) were selected as reinforcements. Thermosetting materials used as matrix were: (i) polyimide resin PMR-15 (Kapton HN® DuPont Nemour) which required an elevated temperature of 315°C for curing; and (ii) unsaturated polyester resin (Scott Bader® Crystic™ 196E) which is a low modulus thermosetting matrix that can be cured at 35°C after preparing the composite. The basic physical and mechanical properties of fibres and matrix materials used in this study are listed in Table 1 and 2. Notations for the prepared composites are as follows:

Composite 1:	F1S1 – fibre F1 (Boron) with thermosetting plastic S1 (Polyimide)
Composite 2:	F1S2 – fibre F1 (Boron) with thermosetting plastic S2 (LM Polyester)
Composite 3:	F2S1 – fibre F2 (Kevlar) with thermosetting plastic S1 (Polyimide)
Composite 4:	F2S2 – fibre F2 (Kevlar) with thermosetting plastic S2 (LM Polyester)

Table 1: Properties of Boron and Kevlar-49 fibres.

1	2	3	4	5	6	7	8	9	10
F1#	Boron	140	2630	399.9	399.9	166.9	0.20	4136.85	4826.33
F2*	Kevlar-49	12	1467	151.7	4.1	2.9	0.35	2757.90	517.12

#as provided by the manufacturer, Specialty Materials Inc.
**as provided by the manufacturer, Dupont Inc. USA*

Notes: Column headings are as follows: (1) Fibre notation; (2) Fibre type; (3) Fibre diameter, d_f *(μm); (4) Density,* ρ_f *(kg* m^{-3}*); (5) Longitudinal Modulus,* E_{f1} *(GPa); (6) Transverse Modulus,* E_{f2} *(GPa); (7) Longitudinal Shear Modulus,* G_{f1} *(GPa); (8) Longitudinal Possion's Ratio,* v_{f1}*; (9) Longitudinal Tensile Strength,* σ_{fT} *(MPa); and (10) Longitudinal Compressive Strength,* σ_{fC} *(MPa).*

Table 2: Properties of the thermosetting plastics used as matrices.

1	2	3	4	5	6	7	8
S1	Polyimide	1218	3.45	1.28	103.4	206.8	89.6
S2	LM Polyester	1163	2.21	1.11	55.2	103.4	55.2

Notes: Column headings are as follows: (1) Matrix notation; (2) Matrix material; (3) Density, ρ_m *(kg* m^{-3}*); (4) Modulus,* E_m *(GPa); (5) Shear Modulus,* G_m *(GPa); (6) Tensile Strength,* σ_{mT} *(MPa); (7) Compressive Strength,* σ_{mC} *(MPa); and (8) Shear Strength,* τ_m *(MPa).*

The architecture, manufacturing and quality control in preparing the test specimens had followed the established recommendations.[6] The composites were manufactured and post-cured for 16 h in air. The volume fraction of Boron and Kevlar-49 fibres used in the preparation of the two sets of composites was maintained at 61% of the composite volume. As Kevlar-49 fibres have poor interfacial adhesion with the thermosetting matrix resin due to low surface energy and chemically inert surface of the fibre, following the improvements reported,[7,8] a chemical treatment of Kevlar-49 fibres was done using 10 wt% phosphoric acid (H_2PO_4) solution on a laboratory scale apparatus. Prior to using them in the manufacture of composite, the residual chemicals were removed by boiling with acetone at 80°C for 2 h followed by washing with distilled water and drying in a vacuum oven at 80°C for 24 h.

All the composites were prepared in a sheet form of 5 mm thickness (+10%) by pultrusion using RDXLL-5000 (Shanghai D&G Instruments Co., Ltd) injection moulding machine according to GB 1040-79 (China). Melt and mold temperature of 260°C and 80°C, respectively, have been used. A schematic of the matrix injection pultrusion process used for producing the thermosetting composites is shown in Figure 1. The manufactured composites were cured for 16 h in air at 315°C for polyimide case, followed by cooling at the rate of 1.3°C min^{-1}. In the case of polyester resin, the composite is allowed to cure at near ambient conditions after emerging from pultrusion machine.

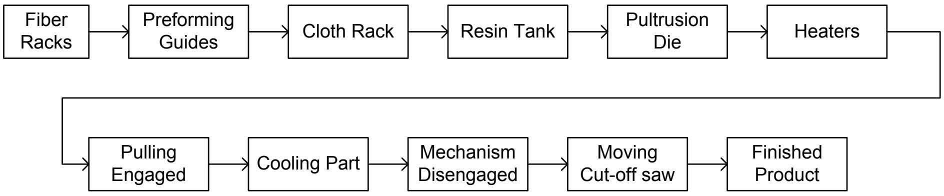


Figure 1: Schematic of the matrix injection pultrusion process used for the preparation of thermosetting composites.

2.2 Mechanical Testing of Composites

Specimens for different mechanical tests were cut from the 5 mm thick sheets of the four types of composites produced using pultrusion process. The specimens were stored in desiccators before testing on a computer controlled 30 kN MTS Alliance RT/30 testing machine equipped with a digital controller and computer data acquisition.

2.2.1 Uniaxial tensile test

Dog-bone shape specimens having 10 mm width and 60 mm gage length were tested following BS 2792 Part 3 Method 321:1994 at ambient conditions using an extension rate of 1 mm min^{-1}. The elastic modulus and the tensile strength were calculated from the maximum load and the actual cross-sectional area of the specimen.

2.2.2 Compression test

Specimens with gage length of 10 mm and width of 10 mm were used following BS 2792 Part 3 Method 345A:1993 standard. From the data recorded during the test, the compressive modulus and the compressive strength corresponding to the maximum load at failure could be determined.

2.2.3 Three-point flexural test

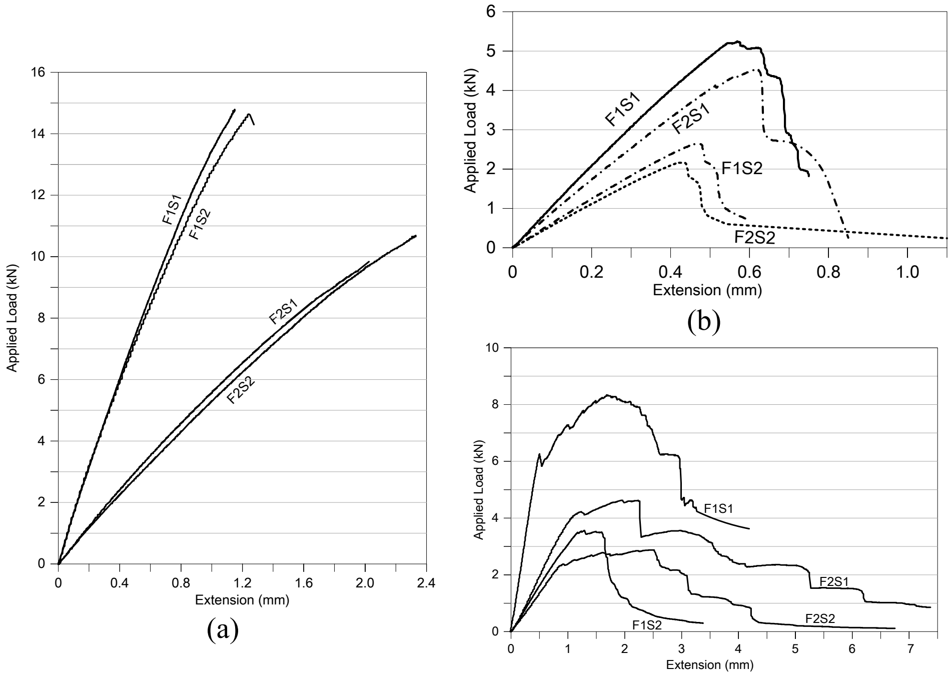
Rectangular specimens of 10 mm width and a span length of 40 mm (span length to thickness ratio was 8:1) were used. The radius of the loading roller tip was 5 mm. The flexural strength and modulus were calculated following BS 2782 Part 3 Method 335A:1993 using the measured load–crosshead displacement curve.

More details about the specimen dimensions and tests are given in an earlier publication.[9]

3. RESULTS AND DISCUSSIONS

3.1 Longitudinal Tensile Properties

Figure 2(a) illustrates the load-displacement responses of Boron and Kevlar-49 fibre reinforced samples. F1S1 and F1S2 samples showed higher peak loads than those of F2S1 and F2S2. All the four composites exhibited some non-linear response. High strength of Boron fibre leads to higher levels of strength compared to those of Kevlar-49 composites. The extension/elongation of Boron based composites is less than those exhibited by Kevlar-49 based ones. Though the mechanical properties of the two chosen matrices, especially in tensile strength, are significantly different (Table 2), the mechanical properties of the respective composites in tension are almost identical, indicating the critical contribution and limiting role of the fibres in the performance of the composites.



(a) (b) (c)

Figure 2: The load-displacement curves obtained from (a) uniaxial tension tests, (b) compression tests, and (c) flexural tests of the four prepared composites.

Boron and Kevlar-49 thermosetting composites exhibited either elastic non-linear or plastic behaviour after a certain elongation. Occasionally, during pultrusion process, unpredicted fibre curvatures or misalignments happened that resulted in a non-linear tension stress-strain curve having a slope that decreased with rising stress. Resin flow during wetting of fibres is another major factor which led to fibre curvatures. It is observed that higher non-linearity responses of Kevlar-49 based thermosetting composites was found when compared to Boron based composites. It is also because the fibre diameter of Kevlar-49 fibres is about 10 times less than Boron fibres. The small radii of Kevlar-49 fibres would easily cause fibre curvature and those fibres would bend around another fibre leading to development of slip bands by shear plastic deformation of the polymer.

3.2 Longitudinal Compressive Properties

The compressive load versus displacement responses of the tested composites loaded along the in-plane direction is shown in Figure 2(b). The curve slopes indicate that the compressive moduli of composites manufactured by

Polyimide matrix are generally higher than the LM polyester composites. It is observed that the load-displacement behaviour of all the tested specimens show nearly linear elasticity up to the yield point. There is a sudden drop of the stress after the maximum yield stress and failure occurred rapidity indicating the loss of composite integrity for both types of composites. Prior to yield point, F1S1 exhibited approximately twice the compression strength of F1S2. Kevlar-49 based thermosetting composites reached the yield strength with small compressive deformation compared to Boron-based ones.

In addition, compression strengths of the prepared unidirectional thermosetting composites are significantly lower than their tensile strengths. The failure of composites in compression is usually triggered by fibre microbuckling, when individual fibres buckle inside the matrix. The buckling process is controlled by fibre misalignment.

For Kevlar-49 based composites, the fibre fails plastically in compression at a stress of only a fifth of their respective tensile breaking stress. The fineness of the fibres can also present a problem as the contraction of the resin which occurs during curing and cooling can cause the fibres to buckle. Such buckled fibres may not be able to withstand applied compression loads. This effect does not arise with large diameter fibres, like Boron fibres which have diameters of 140 µm compared with 12 µm for Kevlar-49 fibres. This correlates well with the comparatively small values of compressive properties of Kevlar-49 based thermosetting composites absorb much less energy, which means that they have great tenacity for brittle fibres when they are broken in comparison with Boron fibres. This is because the fibre can deform plastically in compression.

An elastic fibre can be bent to a minimum radius of curvature at which the tensile stresses in the convex surface attain the breakage stress of the Kevlar-49 based composites. The oscillating nature of the load-displacement curves immediately after yielding and continuous dropping load up to failure is the common feature for all the tested composites. The misaligned fibres begin to buckle when the matrix is yielding. The matrix surrounding the fibres harden after yielding occurs. This failure process repeats itself and this mechanism is responsible for the oscillating nature of the load-displacement curve.

3.3 Transverse Flexural Properties

Figure 2(c) shows the experimentally obtained stress-strain curves from the three-point bending tests for the four thermosetting composites under normal orientation. They showed that the tested composites failed gradually and strains at maximum stress remained nearly the same. F1S1 exhibits highest strength and flexural modulus, followed by F1S2, F2S1 and F2S2. Kevlar-49 based composites generally failed gradually at comparatively larger deflections. Its composites generally fail gradually at larger strains when compared to that of fibre glass reinforced plastics, indicating increasing energy absorption and better damage tolerance. When the loading was in normal orientation, strains at maximum stress remained constant with strain increases. F1S1 and F1S2 exhibit highest strength and flexural modulus, followed by F2S1 and F2S2.

3.4 Cost Analysis

The manufacturing cost can be estimated with a rigorous consideration of the process-performance-cost interrelations based on the fundamental data. The total manufacturing cost of a part is obtained[10] by summing the costs incurred during each operation of the manufacturing sequence, and the following equation can be used:

$$\begin{aligned}
C_{MANUF} &= \sum_{h=1}^{m} Q_h P_h (1 + F_{scrap,h}) + \sum_{i=1}^{n} \big[(1 + F_{ovh}) \times \\
&\left(\sum_{j=1}^{o_i} \frac{S_{w,j}}{Z_i} t_{setup,i} + \sum_{k=1}^{p_i} F_{pres,k} S_{w,k} t_{run,i} (1 + F_{rew,i}) + \sum_{l=1}^{q_i} \frac{S_{w,l}}{M_i} t_{move,i} \right) + \\
&I_R V_{i-1} \frac{t_{queue,i}}{H_Y} + I_R V_i \frac{t_{wait,i}}{H_Y} + \sum_{s=1}^{r_i} \left(\frac{2}{N_{is} + 1} (E_{0,is} - F_{sal} E_{0,is}) + F_{mtn} E_{0,is} \right. \\
&\left. + I_R E_{0,is} + U_{E,is} \frac{H_{EQ,is}}{t_{run,is}} \right) \frac{t_{run,is}}{H_{EQ,is}} \left(1 + F_{rew,i} \right) \big]
\end{aligned} \tag{1}$$

When some of the manufacturing operations are not performed in house, the expression in square brackets for the relevant operations is replaced by the cost of subcontracting the relevant operation(s). The explanation of the relevant symbols can be found in Table 3.

The composites produced for this study had a C-channel configuration with a girth of 320 mm and in lengths of 6000 mm, and 6 pieces were produced at a time. Quantities of fibres and matrix used for the estimation of total manufacturing cost are given in Table 3. All input parameters for the calculation of total manufacturing cost for Boron and Kevlar-49 thermosetting composites are also shown in the table.

Table 3: Model input data for the manufacturing cost estimation of Boron and Kevlar-49 selected thermosetting composites by pultrusion.

Model Input Data	Symbol	Unit	F1S1	F1S2	F2S1	F2S2
Quantity of material	Q	kg	17.97	17.78	11.84	11.65
Material purchase price	P	USD kg^{-1}	11.72	11.61	8.03	7.69
Scrap factor	F_{scrap}	%	2	2	3	3
Equipment purchase price	E_0	USD	120k	120k	120k	120k
Equipment lifetime	N	yr	15	15	15	15
Equipment salvage factor	F_{sal}	%	20	20	20	20
Equipment maintenance factor	F_{mtn}	%	1	1	1	1
Equipment utilities	U_g	USD	0	0	0	0
No. of workers	o,p	Manday	2	2	2	2
Worker's wages	S_w	USD hr^{-1}	15	15	15	15
Worker's presence factor	F_{pres}	%	100	100	100	100
Run time	t_{run}	Min	0.78	0.78	0.67	0.67
Rework factor	F_{rew}	%	0	0	0	0
Interest rate	I_R	%	8	8	8	8
Overhead factor	F_{ovh}	%	75	75	75	75

The quantity of material is the total weight of constituents per cubic mm while material purchasing price shows the total material cost of constituents including additives in USD per kg. This cost evaluation procedure is relatively simple and applicable to a wide range of manufacturing processes. The model considers the manufacturing cost as the sum of the material cost, the labour cost and the overhead cost, and the estimated values are shown in Table 4. The economic potential of the composites can be derived on the basis of cost per unit property (strength or modulus), and the results are shown in Table 5. A comparison of the results obtained in this study indicates that the best results are obtained with F1S2 (followed by F1S1, F2S2 and F2S1) for tensile properties, F1S1 (followed by F1S2, F2S1 and F2S2) for flexural properties and F1S1 (followed by F2S1, F1S2 and F2S2) for compressive properties. The results can assist a designer to choose the most suitable composites during preliminary engineering design stage itself.

Table 4: Results of cost for manufacturing of the Boron and Kevlar-49 selected thermosetting composites.

Composite Cost in USD	Notation	F1S1	F1S2	F2S1	F2S2
Total manufacturing cost per 6 m length	x	399.79	372.70	250.70	216.83
Unit cost for the chosen section (per meter)	$y = x/6$	66.63	62.12	41.78	36.14
Unit cost for 1 m × 1 m × 5 mm thickness sheet	$Z = y /0.32$	208.23	194.12	130.58	112.93
Cost per m^3	$z/0.005$	41,645	38,823	26,115	22,587
Cost per kg	–	22.21	20.99	21.15	18.59

Reference price of constituents (USD):

Cost per m^3 of fibre	–	34,072	34,072	13,467	13,467
Cost per kg of fibre	–	12.96	12.96	9.18	9.18
Cost per m^3 of matrix	–	6,293	4,385	6,293	4,385
Cost per kg of matrix	–	5.17	3.77	5.17	3.77

Table 5: Cost comparison on the basis of tensile, compressive and flexural properties of the tested composites.

Property	Composite	1	2	3	4	5	6
Tensile	F1S1	22.21	236.9	0.094	22.94	0.968	2
	F1S2	20.99	234.7	0.089	22.58	0.930	1
	F2S1	21.15	161.8	0.131	8.87	2.384	4
	F2S2	18.59	159.4	0.117	8.75	2.125	3
Compressive	F1S1	22.21	105.6	0.210	10.80	2.056	1
	F1S2	20.99	51.3	0.409	4.76	4.409	3
	F2S1	21.15	85.4	0.248	6.13	3.450	2
	F2S2	18.59	40.9	0.454	2.94	6.323	4

(*continued on next page*)

Table 4: (*continued)*

Property	Composite	1	2	3	4	5	6
Flexural	F1S1	22.21	315.9	0.0703	7.45	2.981	1
	F1S2	20.99	204.9	0.102	4.82	4.355	2
	F2S1	21.15	134.6	0.157	3.17	6.672	3
	F2S2	18.59	94.9	0.196	2.23	8.336	4

Notes: Column headings are as follows: (1) Cost per kg (USD); (2) Strength (MPa): (3) Cost to Strength Ratio (USD/MPa); (4) Modulus (GPa); (5) Cost to Modulus Ratio (USD/GPa); and (6) Order of Preference in Cost Ratio (per unit cost).

4. CONCLUSION

The mechanical properties of uniaxial thermosetting composites with Boron and Kevlar-49 fibres reinforced in polyimide and low modulus polyester matrix were investigated. It was found that the Boron based reinforced thermosetting composites had higher strength and elastic modulus than those obtained for Kevlar-49 composites, especially compressive strength and moduli. The consolidated results indicate that tensile strength values are similar to respective fibre composites since they are fibre dominated. The compressive strengths are lower and appear to be matrix dependent. From the cost analysis, Boron-polyester composite provides the best performance in terms of cost per unit tensile properties whereas Boron-polyimide composite provides the best performance in terms of cost per unit compressive and flexural properties. The results can serve as ready reference to designers to choose the most suitable composites during preliminary engineering design stage.

5. ACKNOWLEDGEMENT

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