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INFUSION OF NATURAL *vs.* SYNTHETIC FIBRE COMPOSITES WITH SIMILAR REINFORCEMENT ARCHITECTURE IN THE CONTEXT OF A LCA

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SUMMARY: In the context of a comparative and Quantitative Life Cycle Assessment (QLCA) of natural fibre relative to glass fibre when used as the reinforcement in composites, experiments have been conducted to study the differences in their processability and performance. Composites were manufactured from plain weave reinforcement fabrics by resin infusion under flexible tooling (RIFT). It proved difficult to get truly comparable reinforcement fabrics, but the indications are that mould filling times will be longer for natural fibres at comparable fibre volume fractions. The mechanical properties were measured in flexure and indicate that comparable panel stiffnesses are possible at equal weight.

KEYWORDS: Flax fibre, glass fibre, life cycle assessment (LCA), resin infusion under flexible tooling (RIFT)

INTRODUCTION

In an environmental comparison of china reed fibre as a substitute for glass fibre in plastic transport pallets, Corbière-Nicollier et al [1] suggested that such natural fibres are less environmentally damaging than glass fibres for seven of the eight environmental impact classification factors (Table 1). The exception was eutrophication. The plants which are currently attracting most interest as sources of reinforcement are flax and hemp (in temperate climates) or jute and kenaf (in tropical climates).

Life cycle assessment (LCA) is an environmental assessment method, which "considers the entire life cycle of the product from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end-of-life treatment and final disposal" [2]. An LCA study as defined by the ISO 14040 series of standards has four phases:

- The goal and scope definition

- Life Cycle Inventory analysis (LCI)
- Life Cycle Impact Assessment (LCIA)
- Life Cycle Interpretation

The methodology for LCA is defined by the international standards for Environmental Management Systems [3]. ISO 14047 [4] defines eight environmental impacts which closely mirror the environmental impact classification factors (EICF) used by Azapagic [5, 6] shown in Table 1.

Table 1 Environmental Impact Classification Factors (EICF)

ISO/TR 14047:2003(4)	**Azapagic et al (5,6)**
Acidification	Acidification Potential (AP)
Ecotoxicity	Aquatic Toxicity Potential (ATP)
Eutrophication/Nitrification	Eutrophication Potential (EP)
Climate change	Global Warming Potential (GWP)
Human toxicity	Human Toxicity Potential (HTP)
Depletion of abiotic/biotic resources	Non-Renewable/Abiotic Resource Depletion (NRADP)
Stratospheric ozone depletion	Ozone Depletion Potential (ODP)
Photo-oxidant formation	Photochemical Oxidants Creation Potential (POCP)

The study reported here is part of a project which aims to carry out a comparative and Quantitative Life Cycle Assessment (QLCA) of natural fibre relative to glass fibre when used as the reinforcement in composites. Flax is the chosen fibre in this study as it is the most agro-chemical intensive of the above bast fibres. If the study demonstrates that flax is the better option, then the other bast fibres should be even more environmentally friendly than glass fibres. So far for this study, the goal and scope have been defined [7, 8, 9] and we are currently progressing towards completion of the LCI and LCIA.

The aim of this paper is to compare the processing and properties of two composite systems with similar reinforcement architecture. Producing a natural fibre laminate with identical reinforcement architecture to a glass laminate is challenging as the fibre diameters differ, hence also the surface area per tow. Typical values of (fibre modulus in GPa / fibre density in Mgm^{-3}) are ~ 42/1.5 for flax and ~70/2.5 for glass, *i.e.* 28 in both cases. For the comparison, reinforcement fabrics with areal weights pro rata to density were sought.

EXPERIMENT

Plain weave fabrics of flax fibre (areal weight = 0.25 kgm^{-2}) and glass fibre (areal weight = 0.4 kgm^{-2}) were identified. The provenance of the flax fabric (linen textile) is unknown, but was made of spun short fibre. The glass fibre mat was supplied by Carr Reinforcements Ltd, Cheshire, UK. The fabric characteristics are shown in Table 2. Laminates of similar thickness were produced, so that the span/depth ratio in bending and hence the respective contributions of flexural and shear distortion of the test beams were similar.

Table 2 Characteristics of the reinforcement fabrics

	Areal weight – kgm^{-2}	**Warp - tows/m**	**Weft –tows/m**
Flax	0.25	~ 900	~ 1200
Glass	0.4	~ 600	~ 600

Two sets of experiments were carried out (with both reinforcements enclosed by the same bag on each occasion) for woven flax and woven glass. For the first experiment, the target was a plate of at least 2 mm thickness, as required by the mechanical test standards (details below). The following equation was used with an assumed fibre volume fraction for a woven reinforcement of 0.5 for both cases to determine that seven layers of each fabric should be used.

$$n = V_f \rho_f t / A_F$$

where n = the number of layers, V_f = volume fraction of the fibres, ρ_f = density of the fibre, t = the thickness of the laminate and A_F = the areal weight of the fabric,

Resin infusion under flexible tooling (RIFT) at ambient temperature was used to manufacture good quality composite products. Dry fibre mats were laid onto a glass plate and then covered by a peel ply and porous release film. Flow medium/transport mesh was laid over the first half of the reinforcement with a 2 cm gap from the edge (Fig. 1). The whole stack was enclosed by a flexible plastic sheet (bag). The bag was sealed and put under vacuum. The resin was drawn into the mould by this vacuum to impregnate the fibre mats.

The resin used in the experiment was Sicomin SR 8100 epoxy with 22 phr (parts per hundred by weight of resin) of SD 8824 hardener. The mixed resin system has an initial viscosity of 165 mPa.s at 20ºC according to the manufacturers data sheet. The filling times (Table 3 – times to complete initial wetting of the whole reinforcement) were similar in both flax and glass laminates. Note that the range of filling times is only -15 % to +9 % of the average values for all experiments. The plates were cured for 24 hours at ambient temperature and then post-cured in the oven with the temperature increased from 20ºC to 60ºC over four hours, at a constant 60ºC for a further eight hours then a gradual decrease in temperature from 60ºC to 20ºC over one hour.

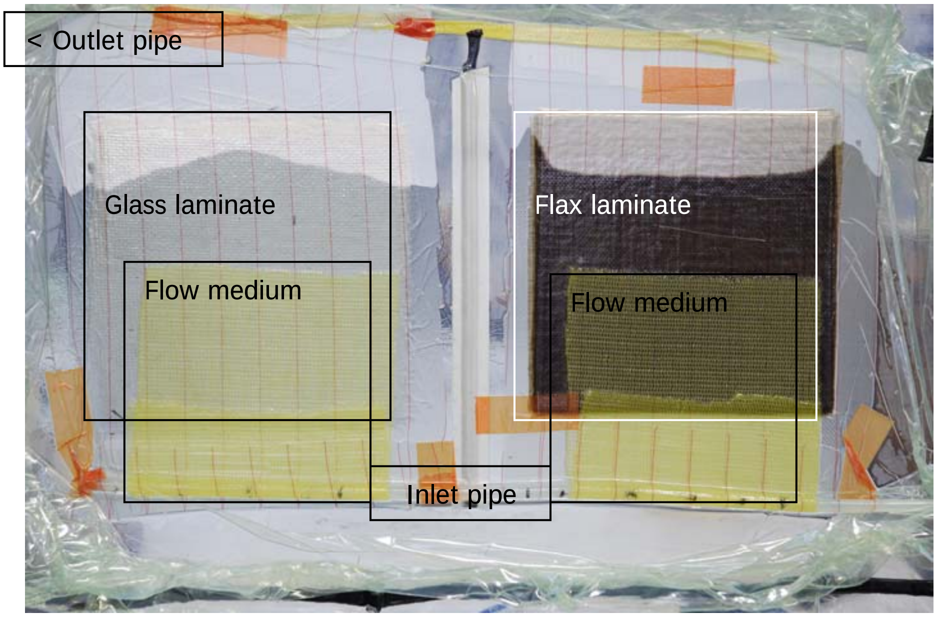

Fig. 1 Photograph of experiment set up (each laminate is 200 mm square).

Table 3 Laminate filling times

Laminate	No of Layers	Bag Pressure	Filling time
First Experiment - Flax	7	1019 mbar	2min 20 sec
First Experiment - Glass	7	1019 mbar	2min 20 sec
Second Experiment - Flax	7	1012 mbar	2min 30sec
Second Experiment - Glass	11	1012 mbar	2min 42sec
		Mean:	2min 25sec

The glass composite in this first experiment was only 1.7 mm thick, while the flax composite was 2.8mm thick. The second experiment was carried out with 7 layers of flax fabric and 11 layers of glass to achieve composites of similar thickness.

RESULTS

Seven samples of 20mm × 150mm were machined from each second experiment composite panel for the three point flexural test. Samples were tested in accordance with the ISO 14125 (adapted from CRAG 200) standard using a span of 100 mm. A 500N load cell was used in the Instron 5582 machine with a cross-head speed of 5 mm/min. The individual load *vs*. deflection curves for each specimen are shown in Fig. 2. The flexural moduli and strengths are summarised in Table 4 and the relative magnitudes of Young's moduli are shown in Fig. 3 for all the tested samples (note that the axes have different scales).

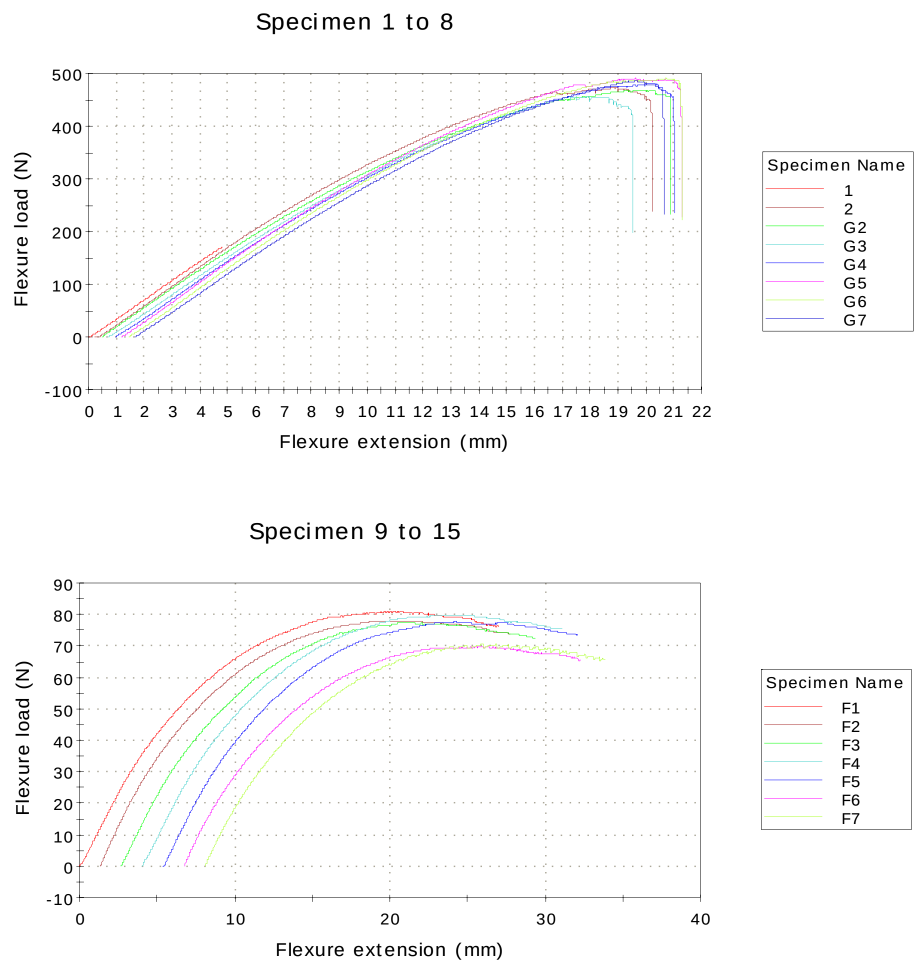

Fig. 2 Load vs. deflection curves for glass fibre reinforced composite samples (specimens 1 to 8) and for flax fibre reinforced composite samples (specimens 9-15).

Table 4 Flexural testing results for glass and flax composite samples

		Thickness (mm)	Width (mm)	Volume Fraction	Flexural Modulus (GPa)	Flexural Strength* (MPa)	Flexural Strength** (MPa)
Glass	Mean	2.8	20.7	0.63	18.5	440	291
	Std Dev	0	0.1	0	0.64	12.9	5.31
Flax	Mean	2.8	20.6	0.42	4.84	74.6	59.4
	Std Dev	0.08	0.1	0.01	0.46	7.92	5.88

* Flexural strength calculated using CRAG method 200.
** Flexural strength calculated using BS EN ISO 14125:1998 with the large deflection correction equation [10]
Flexural strength for flax is calculated from the peak load as no failure was observed.

DISCUSSION

In comparing flax and glass fibre, the fibres have similar cross-sectional dimensions although the flax fibre cross section is not round and hence the fibre "diameter" is only indicative of the fibre dimensions. The short flax fibres are spun to produce a yarn for weaving hence they have lower fibre length distribution factor (glass fibres are continuous fibres) and a lower fibre orientation distribution factor (both fibres have crimp but the flax also has helical fibre orientation within the bundle due to the spinning). An ideal pair of woven fabrics for comparison would have similar number of fibres within each tow and similar tow counts in both warp and weft directions. In practice it was not possible to obtain a perfect glass fibre equivalent of the flax fabric.

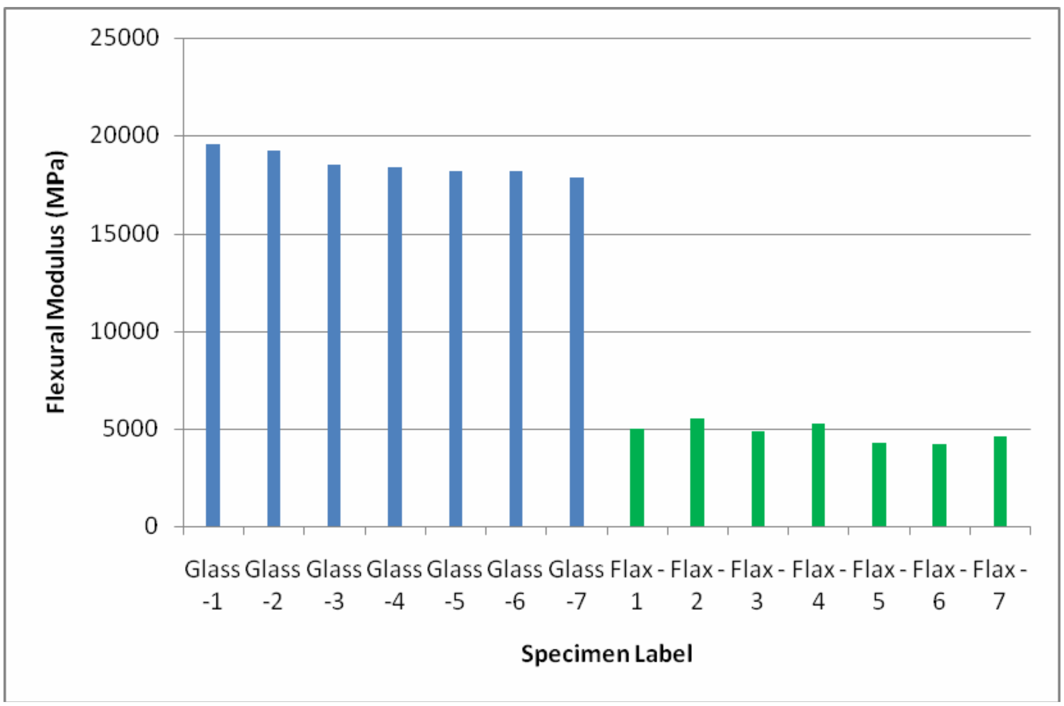

Fig. 3 Comparison of flexural moduli for all glass- and flax-reinforced composites.

The results indicate that for reinforcement fibres of equivalent (compensated for fibre density) areal weight, the glass fibre fabric will fill more rapidly at similar fibre volume fractions. The natural fibre composite achieves a lower fibre volume fraction, lower modulus and lower flexural strengths. Using the Kozeny-Carman-Blake analysis, the permeability, K, is a function of the porosity (ε) [11] and is proportional to either $(1-V_f)^3/(V_f)^2$ or to $\varepsilon^3/(1-\varepsilon)^2$. The permeability of flax fibre composite at a fibre volume fraction of 0.63 will thus be only 11% of a similar flax fibre composite at a fibre volume fraction of 0.42 and hence will take much longer to infuse.

Comparisons of specific modulus (E/ρ), beam stiffness ($E^{1/2}/\rho$) and panel stiffness ($E^{1/3}/\rho$) [12] are given in Table 5. The E value for the higher fibre volume fraction in flax reinforced composite was obtained using $E = \eta_o V_f E_f + V_m E_m$ when flax fibre has E_f =14.6 GPa (for the textile fabric obtained for this study) and the resin system has E_m = 2.85 GPa (manufacturers data sheet).

Densities of the respective composites have been calculated using rule of mixtures with the specific gravities of 1.11 (resin), 1.5 (flax) and 2.5 (glass). The density of the resin has been calculated at 1.11 Mgm^{-3} using rule of mixtures with 27 phr by volume of hardener and densities of 1.158 and 0.942 respectively for the resin and hardener (from manufacturers data sheet) and assuming no shrinkage during cure.

Table 5 Calculations of the composite properties

		V_f %	*E/GPa*	ρ/Mgm^{-3}	E/ρ	$E^{1/2}/\rho$	$E^{1/3}/\rho$
Flax	Measured	42	4.8	1.274	3.77	1.72	1.32
Flax	Calculated	63	5.7	1.356	4.20	1.76	1.32
Glass	Measured	63	18.5	1.986	9.32	2.17	1.33

When comparing the mechanical performance of the materials, the three parameters (E/ρ, $E^{1/2}/\rho$ and $E^{1/3}/\rho$) are all lower for flax than for glass composites. For panels, the composites are effectively equivalent if judged using $E^{1/3}/\rho$. For panels in flexure, no weight saving is achieved by increasing the fibre content (values of $E^{1/3}/\rho$ are virtually independent of V_f). In respect of the LCA, a panel of equivalent stiffness could be produced if a fibre volume fraction of 63 % can be achieved at the same thickness, or at the same weight for a fibre volume fraction of 42 %. In the latter case, there will be a significant increase in the polymer content (which is the component with the higher embodied energy). If the higher fibre volume fraction route is followed, then the process times will be extended.

CONCLUSION

These preliminary experiments suggest that panels of equivalent stiffness can be produced at identical weight with broadly similar process times. However, the experiments conducted here indicate that, at the same fibre volume fraction, a flax laminate will have a lower permeability and hence it will be significantly slower to fill. A thicker beam (for flax) will require more resin and this component of the composite is environmentally less desirable as it is of higher embodied energy.

The authors would be most grateful to know of any results for studies similar to the one reported here that might inform the ongoing LCA.

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