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CONTINUOUS FIBRE COMPOSITES OF DIFFERENT SUSTAINABILITY LEVELS

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Different continuous fibre composites were manufactured from two woven flax fibre fabrics using an epoxy resin, two liquid thermoplastic resins and a compostable thermoplastic film. Two manufacturing processes were probed: liquid infusion and hot compression lamination. Dry fabric behaviour was probed including in-plane shear, in-plane tension, transverse compaction, bending stiffness and bending spring-back. Manufacturing trials were conducted for flat plates. Structural performance was probed though quasi-static tensile and bending tests, impact tests and dynamic bending analysis. Observations were made in terms of consolidation, performance, current limitations and potential. Early conclusions were reached about the relationship between sustainability, ease of manufacturing and level of mechanical performance, for the materials and processes selected in this work. Avenues for future improvement were identified.

1 INTRODUCTION

Structural flax fibres offer good specific structural properties and strong sustainability advantages as they are cultivable, with variability remaining a major challenge in the development of flax fibre reinforced structural polymer matrix composites (PMCs) [1, 2].

With strong industrial, consumer and societal drive towards sustainable practices, the primary objective of this work is to investigate the manufacturing and performance characteristics of flax fibre reinforcements for structural composites offering different avenues and levels of sustainability. The processing and performance of flax-based 1) compostable and mechanically recyclable PMCs featuring compostable PLA film of biological origin, 2) mechanically and chemically recyclable PMCs featuring curable thermoplastics, and 3) ground re-purposable non-recyclable PMCs featuring a thermosetting resin, were assessed. The distinction between compostable, mechanically recyclable, chemically recyclable and ground repurposed materials holds pivotal significance in the pursuit of sustainability. Recyclable thermoplastic PMCs that undergo chopping, separation, melting or de-polymerization followed by another cycle of moulding and service are limited by compromises inherent to their recycling journey. Biodegradable materials, on the other hand, have the ability to break down into substances that may reintegrate an ecosystem cycle through biological processes over time. Compostable PMCs can undergo complete biodegradation when subjected to industrial composting conditions [3]. With the hope of going beyond the confines of recyclability, aspirations extend towards harnessing the potential of compostability for structural PMCs. This project is also based on a vision promoting local material sourcing, local economic activity and local technology development.

2 MATERIALS, PROCESSES AND CHARACTERIZATION METHODS

2.1 Materials

Two reinforcement fabrics were used for manufacturing PMC plates. Fabric #1 was TEXONIC TF-05-T, a 195 g/m^2 2x2 twill weave flax fibre fabric with balanced 50% - 50% volume and weight distribution along the warp and weft. Fabric #2 was EcoTechnilin FLAXDRY BL200, a 220 g/m^2 2x2 twill woven flax fibre fabric with balanced 50% - 50% volume and weight distribution along the warp and weft directions. Whilst those descriptions are largely similar, the fabrics are very different in appearance with visibly different yarn section aspect ratios and fabric cover factors as shown in Figure 1. Different methods were used for characterizing dry fabrics processability as detailed in Section 2.3. Vastly different results were anticipated given the different appearances of the fabrics, but characterization work painted a more nuanced picture as discussed below.

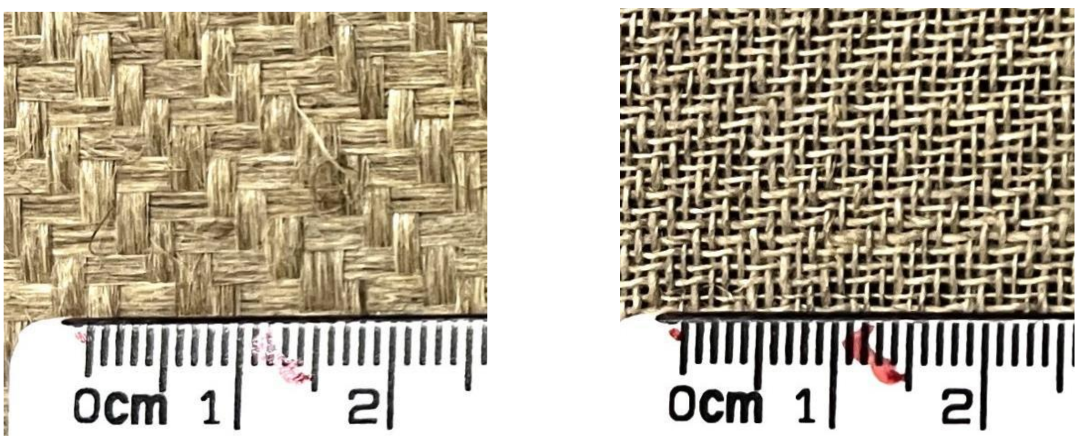

Figure 1. Flax fibre reinforcement fabrics. Left: TEXONIC TF-05-T; right: EcoTechnilin FLAXDRY BL200.

Resin #1 was room temperature cure thermosetting two-part epoxy resin system PRO-SET INF-114 INF-211, used primarily for reference purposes. The resin has moderate cure speed with 100 minutes approximate working time followed by 10 hours vacuum off time. Resin #2 was curable thermoplastic resin Arkema Elium™ 188 O designed for room-temperature vacuum infusion. Elium™ 188 O is a two-part resin which was catalysed using Luperox® peroxide in this work. Resin #3 was curable thermoplastic resin Arkema Elium™ 151 XO/SA designed for vacuum infusion with low viscosity, low exothermy and long open times. Arkema Elium™ 151 XO/SA is a two-part resin which was used with MEKP peroxide initiator in this work. Elium™ resins may be reheated and thermoformed or recycled chemically through de-polymerization. Resin #4 was EVLON™ clear compostable thermoplastic PLA film manufactured from a corn base for packaging and overwrap applications. Thickness of the film used in this work was 0.015 mm. Seal initiation temperature for the original intended application is 60˚C. General melting temperature and density for PLA are circa 150°C and 1.24 g/cm^3.

2.2 Processes

A typical vacuum infusion process was used for making plates with liquid resins #1, #2 and #3, followed by post-cure in all cases. Vacuum was set to 1 atm and a resin trap was used at mould outlet. Vacuum was maintained for minimally 10 minutes prior to infusion for all resins. The resin trap was monitored attentively when infusing to prevent off-gassing of any diluted volatile organic compounds (VOCs). Optional post-cure was performed with all three liquid resins as specified in technical data sheets (TDSs) to hasten completion of polymerization, using a Carbolite™ PF convection laboratory oven with Eurotherm 3216 temperature controller validated using a REED ST-9610B thermocouple reader. Post-cure times and temperatures were 8 hours at 49°C for Resin #1 and 2 hours at 80°C for Resins #2 and #3. All plates made using Resins #1, #2 and #3 featured 5 layers of Fabric #1 or Fabric #2.

Plates were made from Resin #4 using hot compression lamination. EVLON™ PLA film layers were interleaved between plies of flax reinforcement fabrics. Impregnation was driven by platen pressure, with resin viscosity reduced by heat. Similarly to above, plates made from Resin #4 featured 5 layers of Fabric #1 or Fabric #2, with numbers of film layers adjusted to a target 50% v_f, which generally corresponds to typical v_f targets for liquid resin vacuum infusion. Stacks of flax reinforcement and PLA film were compressed between silicone membranes, steel plates and Instron steel platens using an Instron universal testing frame 68FM-100 series equipped with a convection oven as shown in Figure 2. Different levels of pressure, temperature and time were trialed.

Figure 2. Hot compression lamination. Left: stack with top silicone and metal sheets removed for clarity; centre: stack on lower platen in Instron oven; right: stack compressed between platens with oven rolled back for clarity.

2.3 Characterization methods for dry fabrics

The following tests were conducted on dry reinforcement fabrics, with the goals of understanding fabric structures and assessing manufacturability: cover factor, Peirce bending test, convex spring back [4], concave spring back [4], tensile stiffness and strength, transverse compaction, in-plane shear tests, and informal double-curvature draping on hemispheres [5]. Complete results appear in [6, 7]; selected salient results and conclusions are presented here.

Average cover factors for Fabrics #1 and #2 were 1.0 and 0.5 respectively. These expectedly different values did not lead to markedly higher shear locking angles for Fabric #2 or to lower shear locking angles for Fabric #1 as seen in the top part of Figure 3. Fabric #1 was also observed to perform equally well in informal draping tests conducted on hemispheres with radii 40mm and 75mm. Fabric #1 was observed to compact transversely to higher dry v_f values. Fabric #1 showed higher bending stiffness but bending spring back behaviours were comparable for both fabrics as seen in the lower part of Figure 3. To conclude, in terms of manufacturability both fabrics shared in-plane in a similarly easily manner, both in a flat configuration and upon draping hemispheres. Fabric #1 required somewhat more effort to form to shape but maintained its deformed shape better.

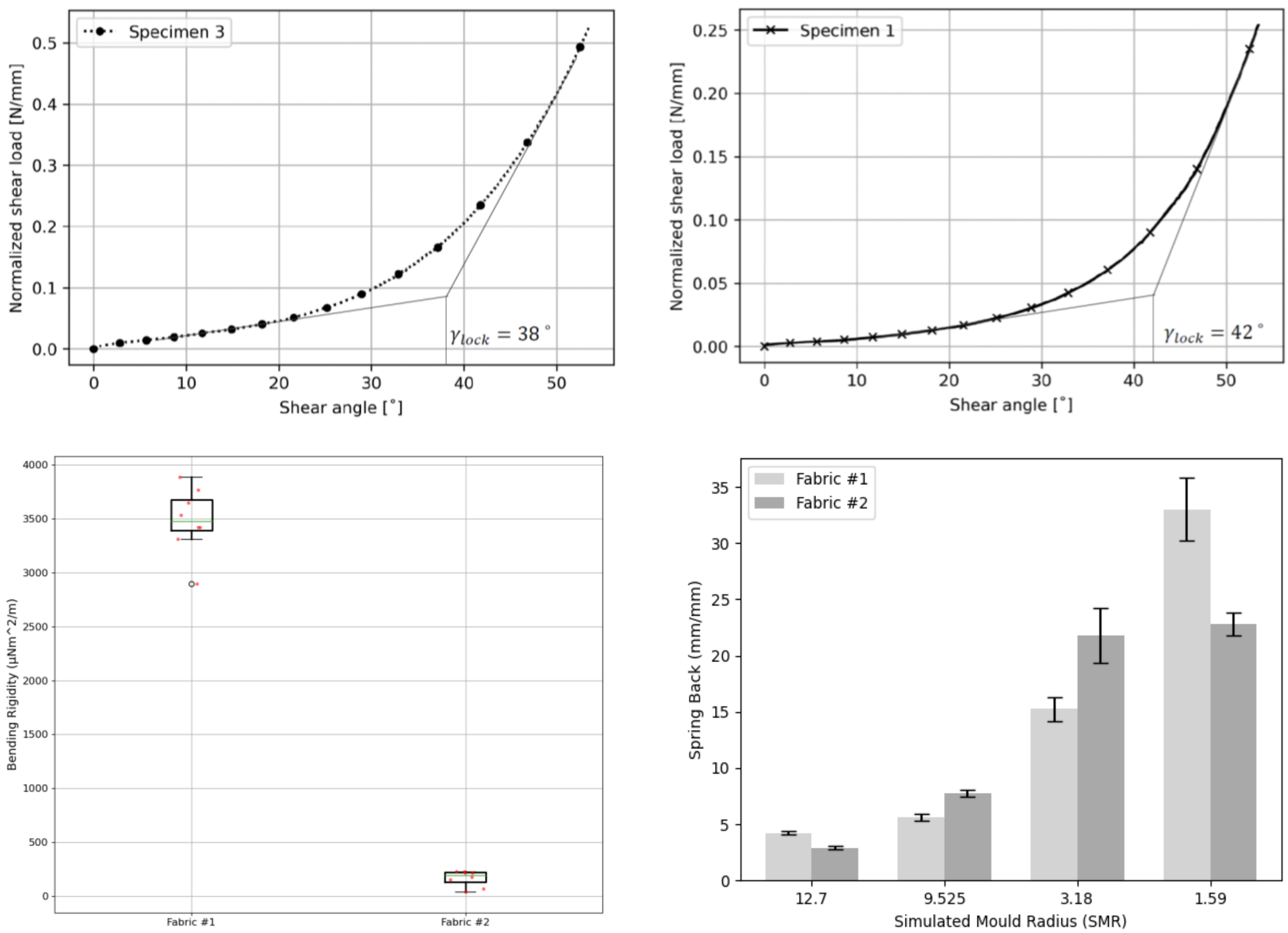

Figure 3. Select dry fabrics characterization results. Top left: in-plane shear curve, Fabric #1; top-right, in-plane shear curve, Fabric #2; lower left: bending stiffness, both fabrics; lower right: spring back ratio, both fabrics.

2.4 Characterization methods for composite plates

The following tests were conducted on coupons extracted from composite plates: quasi-static tensile tests, quasi-static three-point bending tests, Charpy impact tests and dynamic mechanical analysis performed in bending. Sample amounts, sample dimensions and test configurations detailed in [6, 7] reflect relevant ASTM standards as much as possible in light of limited manufactured plate dimensions. Complete results appear in [6, 7]; selected salient results and conclusions are presented here.

Results for failure strength in tension and in bending presented in the top part of Figure 4 compared well with similar results obtained from literature for generally comparable glass fibre PMCs with comparable v_f . Results from Charpy impact tests presented in the lower part of Figure 4 also compared well with similar results obtained from the literature for glass fibre PMCs, and were of the same order of magnitude as results obtained for carbon-epoxy PMCs. The authors acknowledge that these comparisons are anecdotal; nevertheless, results related to failure were

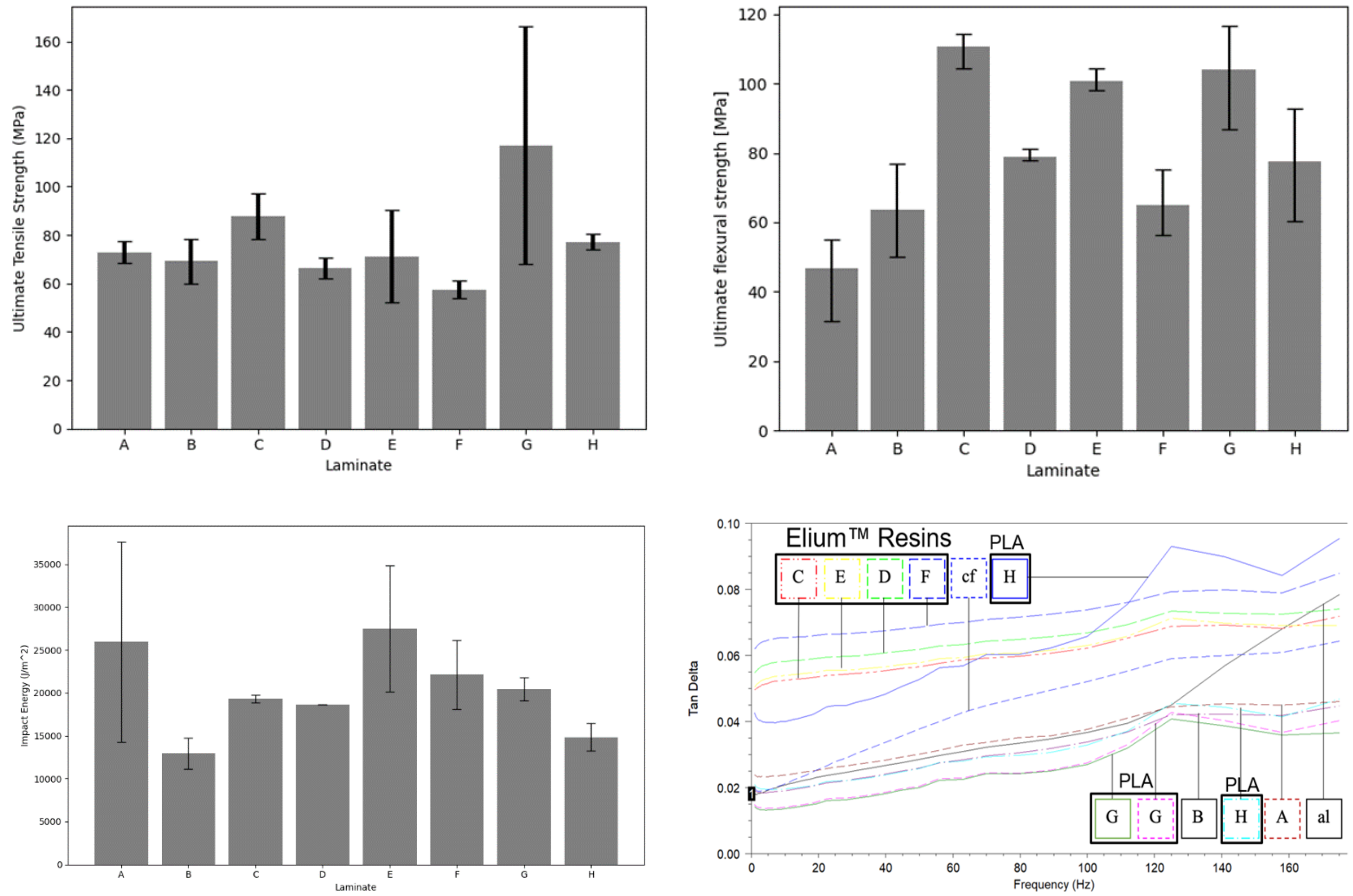

Figure 4. Select composites characterization results. Top left: tensile strength; top right: flexural strength; lower left: impact strength; lower right: DMA results. A – Resin #1 & Fabric #1; B – Resin #1 & Fabric #2; C – Resin #2 & Fabric #1; D – Resin #2 & Fabric #2; E – Resin #3 & Fabric #1; F – Resin #3 & Fabric #2; G – Resin #4 & Fabric #1; H – Resin #4 & Fabric #2.

encouraging. Damping behaviour of the laminates was generally regarded as encouraging as seen in the lower right part of Figure 4 when compared with a carbon epoxy composite and an aluminium allow tested in the same conditions, shown as curves cf and al respectively. Damping was higher than for the carbon fibre composite tested for all laminates made from Elium™ resins, and it was lower for all other laminates made from epoxy resin and EVLON™ film bar for one curve which was considered wayward. Here again, the authors acknowledge that comparisons are encouraging but anecdotal.

Whilst data is not reported here, it must be mentioned that stiffness results were significantly lower than hoped for all PMCs; this aspect of material performance will require further investigation.

3 CONCLUSION

Flax-fibre PMC materials with varying levels of sustainability were manufactured and characterized. Bending stiffness and bending spring back were characterized for two fabrics, establishing the suitability of the materials for moulding complex geometries. Mechanical properties of the PMC materials were characterized through various quasi-static testing methods. Damping properties of each laminate were measured through DMA testing. Optical cross-section microscopy was conducted to determine interlaminar consolidation. Bending stiffness assessments revealed that this property was predominantly influenced by roving and yarn geometry rather than fibre properties, with Fabric #1 exhibiting higher bending stiffness. Comparison of bending spring back ratios suggested potential difficulties and lack of reproducibility in this aspect of draping, especially over tight radii, with natural fibre fabrics showing greater spring back compared to common glass and carbon fibre reinforcements.

PMC laminates demonstrated potential for strength-based designs and applications. Analysis of mechanical test results indicated that moduli did not meet expectations. This may possibly be attributed, in part, to moisture content in the resin which is thought to compromise interlaminar interfaces. Mitigation strategies such as fibre surface coating prior to infusion and control of humidity during processing should be investigated. Impact testing results and comparisons with literature values suggests potential for manufacturing impact-resistant natural fibre PMC materials.

Laminates made from corn-derived PLA thermoplastic film showed encouraging potential towards manufacturing compostable structural PMC materials. Reproducible manufacturing presents challenges and the process will be the subject of further development.

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4 REFERENCES

[1] L. Yan, N. Chouw and K. Jayaraman. "Flax fibre and its composites – A review". *Compos. Part B Eng.*, Vol. 56, pp 296-317, 2014.

[2] M. Ramesh. "Flax (Linum usitatissimum L.) fibre reinforced polymer composite materials : A review of preparation, properties and prospects". *Prog. Mater. Sci.*, Vol 102, pp 109-166, 2019.

[3] M.F. Cosate de Andrade, P.M.S. Souza, O. Cavalett and A.R. Morales. "Life cycle assessment of poly (lactic acid) (PLA): comparison between chemical recycling, mechanical recycling and compositing". J. Polym. Environ., Vol. 24, No. 4, pp 372 -384, 2016.

[4] P. Kanz, F. Robitaille. "Concave and convex small radius bending behavior of single and multiple layers reinforcement fabrics". *Tex. Res J.*, Accepted in final form, 2024.

[5] P. Kanz. "*Characterization of textile draping behaviours for composite manufacturing processes*". MAsc thesis, University of Ottawa,2021.

[6] R. Bernstein. "*Manufacturing and performance analysis of sustainable structural composites: investigating their feasibility for the design and construction of eco-friendly bicycles*". Undergraduate thesis in Mechanical Engineering, University of Ottawa, 2024.

[7] C.-A. Roy. "*Manufacturing and performance analysis of sustainable structural composites: PLA film and curable thermoplastic 151 XO/SA reinforced with flax fibre fabrics*". Undergraduate thesis in Mechanical Engineering, University of Ottawa, 2024.