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Development of a Recyclable Flax Fiber Reinforced Polymer Composite

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ABSTRACT

This study compared the mechanical properties of a recyclable flax fiber reinforced polymer composite (FFRP) with a covalent adaptable network (CAN) matrix to an FFRP composite with a conventional (unrecyclable) epoxy resin matrix. The results indicated that composites fabricated via vacuum-assisted resin transfer molding (VARTM) exhibited up to 19% higher tensile modulus and strength compared to those fabricated via hand layup, attributed to reduced air void content and more uniform fiber alignment. Microscopy evidence supported by mechanical property tests revealed superior adhesion of the CAN matrix to flax fibers compared to conventional epoxy resin. Additionally, a solvent-based method was demonstrated for separating fibers from the CAN matrix, facilitating reuse or upcycling.

KEYWORDS
Recyclable, Flax, FFRP, VARTM, Epoxy, Covalent Adaptable Networks, Vitrimer

INTRODUCTION
In infrastructure, fiber reinforced polymer (FRP) composites are used in bridge girders and decks, wind turbine blades, utility pipelines, to strengthen and repair civil structures, as internal reinforcement in reinforced and prestressed concrete members, etc. The aging infrastructure provides a large market that could accelerate the growth of composites use in infrastructure projects. While FRP composites offer significant advantages over concrete and steel—such as higher strength-to-weight ratio, improved durability, and accelerated construction—these materials typically comprise glass or carbon fibers originating from non-renewable feedstocks with a substantial carbon footprint. In addition, matrix materials in FRP composites are thermosets, polymers with permanent covalent crosslinks between polymeric chains. Crosslinks contribute exceptional mechanical properties and chemical stability to thermosets. However, the downside of crosslinks is their irreversible and permanent nature which makes thermosets intrinsically unrecyclable. Consequently, FRP composites integrating thermosets cannot be recycled and are commonly disposed in landfills or incinerated at the end of their usable service life (Controy et al. 2006), contributing to environmental pollution.

This study developed novel FRP composite materials manufactured from renewable and carbon-negative flax fibers. In addition, the project integrated covalent adaptable networks (CANs) (Kloxin and Bowman 2013) in the matrix of the composite to enable a composite matrix that retains the beneficial properties of thermosets while also imparting recyclability, self-healing and weldability to the composite.

BACKGROUND SECTION
In recent years, biobased composites have drawn considerable attention because the demand for sustainable materials has increased considerably over the past few decades. Flax fibers have emerged as one of the most promising alternatives to synthetic fibers. They were selected for this project because they are abundant and renewable, carbon-negative (the plant absorbs 1.39 kg CO_2/kg of fiber from the atmosphere) and have mechanical properties that are superior to other natural fibers (Barth and Carus

2015). For comparison, flax fibers that were utilized in this study have an elastic modulus—a material property generally governing composite design—of 60 GPa or approximately 85% of the modulus of E-glass fibers (70 GPa). However, flax fibers' specific modulus (i.e., elastic modulus-to-density ratio) is approximately 50% higher than E-glass, making them structurally and economically a viable alternative for E-glass (Shah 2013). In terms of composite properties, FFRP with a fiber volume fraction (FVF) of 53% fabricated via VARTM was shown to achieve elastic modulus in excess of 34 GPa and tensile strength of over 275 MPa (Bcomp 2020), exceeding the minimum requirements for pultruded members (ASCE 2010).

Flax fiber adhesion to polymer resins can be a challenge. Chemical surface treatments were found to improve the mechanical properties of the bio-composites and the adhesion between the fiber and the resin. For example, Van de Weyenberg et. al (2006) studied the effect of alkali treatment on the flexural properties of UD flax fiber. The results showed that the tensile strength of treated flax-epoxy composites using 3% of NaOH solution improved the tensile strength and elastic modulus from 218 to 283 MPa and 18 to 22 GPa, respectively. This result showed that a chemical treatment is an effective way to enhance the fiber and epoxy matrix bonding and, eventually, to improve the tensile properties of the composite. Alkali treatment cleans the fiber surface, modifies the chemistry on the surface, lowers the moisture uptake, and increases the surface roughness (Yan et al., 2013).

Thermosets, such as epoxy or vinyl ester, are commonly used matrix materials in composites for construction due to the ease of processing, chemical stability, and mechanical properties. As a result of the permanent covalent bonds in their structure, thermosets cannot be recycled, reshaped, remolded, or dissolved. Therefore, while natural fiber composites provide significant environmental benefits on a cradle-to-gate basis, inability to recycle or reprocess these composites is a significant barrier that diminishes their environmental benefits (Zhao et al. 2022). Moreover, the susceptibility of natural fibers to moisture absorption was found to cause matrix cracking (due to swelling stresses) which can lead to inferior long-term performance of these composites (Selvan and Athijayamani 2016), particularly when subjected to fatigue loading.

In this study, covalent adaptable networks (CANs) were incorporated into a traditional epoxy matrix to address the challenges of matrix recyclability and composite durability. By introducing CANs, the resin can be reprocessed, enabling composite recycling and self-healing. Underlying CANs reprocessability are chemical bonds that can undergo bond shuffling and rearrangement in response to external triggers like chemicals, light, or heat, allowing CANs to repair damage from small molecular-level defects to larger cracks. The use of CANs has shown promising results in extending the lifespan of infrastructure plastics, reducing maintenance requirements, and significantly decreasing overall gate-to-grave emissions (Milev et al. 2023).

In this work, we integrated disulfide bonds (capable of undergoing bond exchange) in a traditional epoxy matrix to impart recyclability and self-healing properties. Our prior work has demonstrated the exceptional ability of disulfide bonds to enable spontaneous self-healing (Milev et al. 2023); therefore, the primary objectives of this study were to: (a) address processing and manufacturing challenges associated with integration of CAN matrix with flax fibers; (b) contrast properties of FFRP with CAN matrix against an FFRP with a conventional epoxy matrix; and (c) demonstrate a solvation-based method for separation of fibers and CAN matrix.

EXPERIMENTAL PROGRAM

The experimental program involved testing the tensile properties of FFRP samples prepared according to Table 1. The control group was made using VARTM with a resin commonly used for VARTM composite manufacturing. Recyclable composites were also prepared using both VARTM and hand layup methods.

The CAN resin used in the recyclable composites contains a solid cross-linker that must be melted to ensure proper mixing with the base resin. Since VARTM is typically conducted at room temperature,

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processing the CAN resin through VARTM poses several challenges, which were addressed in this study.

In addition to the standard composites with untreated fibers, an alternative composite was prepared using alkali-treated flax fibers and CAN resin in an attempt to improve the adhesion between the fibers and the matrix. Typically, hand layup results in composites with lower quality properties compared to VARTM, so this composite was included to explore potential enhancements. To evaluate the effect of fiber surface treatment, thermogravimetric analysis (TGA) and tensile tests on single flax yarns were performed. These tests aimed to assess any changes in the properties of the yarn resulting from the surface treatment of the fibers.

Table 1. Overview of test groups.

Group	Fiber treatment	Epoxy Resin	Hardener	Manufacturing technique
Control	Untreated	Araldite LY1564	XB 3404	VARTM
CAN-NT-HL	Untreated	EPON 826	2-APD	Hand layup
CAN-NT-VARTM	Untreated	EPON 826	2-APD	VARTM
CAN-ST-HL	5% NaOH solution for 15 min.*	EPON 826	2-APD	Hand layup

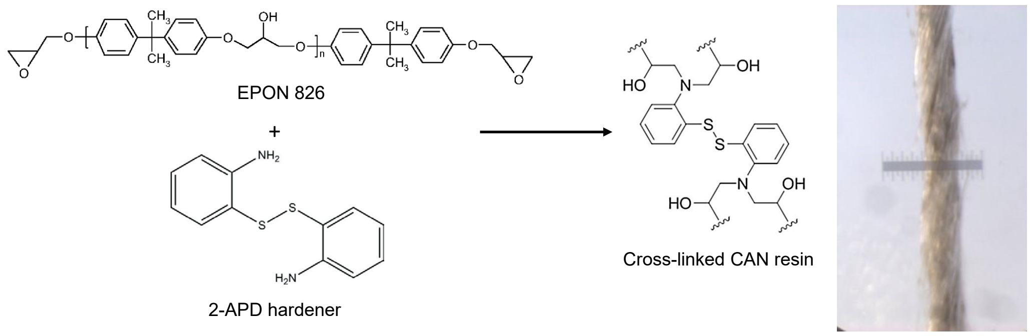
*selected based on Aly et al. (2012)

MATERIALS AND METHODS

Materials

A unidirectional (UD) flax fabric and EPON 826 resin, utilized in this study, were supplied by Bcomp® and Hexion, respectively. The recyclable FFRP composite was manufactured by using flax fabric and CAN resin. The CAN matrix consisted for a mixture of EPON 826 monomer and 2-Aminophenyl Disulfide (2-APD) cross-linker in a weight ratio of 100:34, corresponding to the stoichiometric ratio of 1.0 between epoxide functional groups and amine hydrogens. The chemical structure of EPON 826 resin, 2-APD hardener, and the resulting CAN resin structure are depicted in the Figure 1. Under external heat, disulfide bonds within the crosslinks can undergo disulfide metathesis exchange reaction which alters the topology of the polymer network while maintaining the same cross-linking density. This property enables CAN resin reprocessing and self-healing.

The mechanical properties of recyclable FFRP composite with CAN matrix were compared to the conventional epoxy-based flax fabric composite. The conventional epoxy was made by combining Araldite LY1564 resin and XB 3404 hardener, representative of resins typically used for VARTM process. The monomer and hardener were mixed in weight ratio of 100:36, as specified by the manufacturer.



(a) (b)

Figure 1 Composite constituents: (a) chemical structures of EPON 826 resin, 2-APD hardener, and the resulting cross-linked network; and (b) singe flax yarn (scale bar represents 1 mm).

Conventional and recyclable FFRP composite panels were manufactured using 7 plies of 275 g/m^2 unidirectional (UD) flax fiber fabric. The fabric consisted of tex spun flax fiber yarns (Figure 1b). The hydrophilic properties of flax fibers make them susceptible to varying moisture content depending on the relative humidity of the environment. Therefore, to maintain the consistent hygric state between the test groups, the fabric was dried in the oven for 15 minutes at 115 °C prior to infusing the resin.

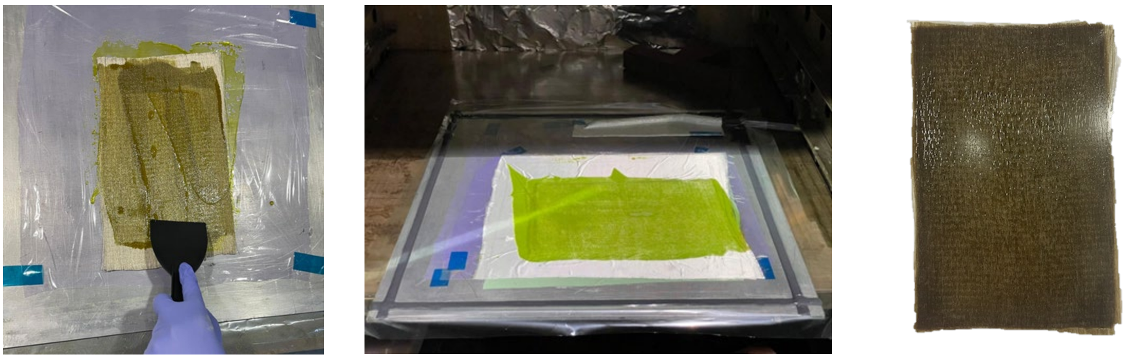
Composite Fabrication

Hand layup and VARTM were employed for manufacturing composite laminates. For the infusion process, CAN resin was prepared by dissolving 2-APD in the monomer at 80 °C. In the hand layup technique (Figure 2), the process involved stacking seven flax fabric plies followed by saturating them with resin using a plastic spatula. To minimize excess resin and reduce voids, vacuum bagging consolidation was employed, as depicted in Figure 2b. Additional layers including three peel plies and E-glass fabric were added on top to absorb excess resin and ensure safe removal of the cured composite without causing damage.

The VARTM process, as shown in Figure 3, utilized distribution media to enhance the flow of resin. However, the CAN resin used in this study becomes excessively viscous at room temperature when prepared by mixing the monomer and 2-APD at 80 °C. To address this issue, the temperature of the CAN resin was maintained at 80 °C throughout the infusion process. Simultaneously, the preform was kept in an oven at 80 °C for the entire duration of the infusion. This ensured that the resin remained at an optimal viscosity for the VARTM process. On the other hand, the VARTM process for the control group was conducted at room temperature without any temperature adjustments.

After resin infusion, preforms were subjected to staged cure cycle in the oven, while maintaining constant vacuum pressure, for both the control and CAN resin FFRP composites. The cure cycle for recyclable composite consisted of 5 hours at 125 °C, followed by 1 hour of post-curing at 150 °C. The curing cycle for the conventional epoxy-based FFRP composite consisted of 2 hours at 80 °C and 2 hours of post-curing at 150 °C.

Another recyclable FFRP composite panel was also prepared by hand layup technique utilizing the surface treated flax fabric and CAN resin. The surface treatment was applied by submerging the flax fabric in a 5% NaOH (alkaline) solution for 15 minutes at room temperature. This was followed by rinsing with deionized water and pat drying. To remove the NaOH residue, the fabrics were submerged in an acetic acid solution (pH=3) for 1 minute and then rinsed with deionized water and pat dried. The fabric was then dried in the oven for 8 hours at 80 °C.



(a) Applying resin using plastic scraper | (b) Vacuum bagging of the preform | (c) Cured panel

Figure 2. Flax composite manufacturing using hand layup technique.

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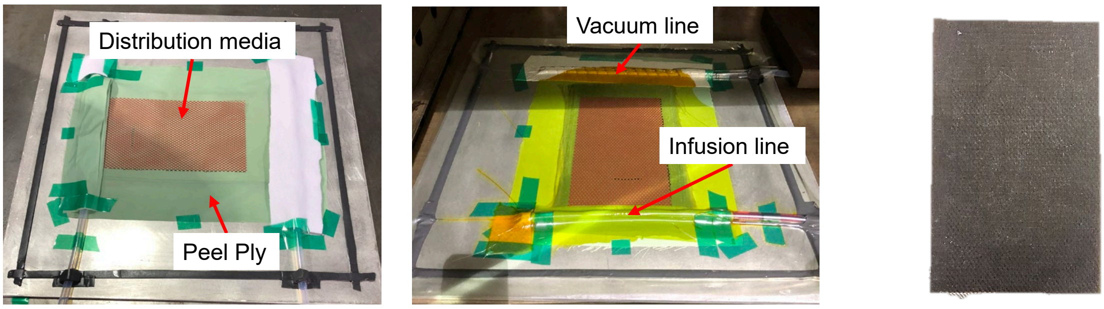


(a) VARTM setup (b) Resin infusion using VARTM setup (c) Cured panel

Figure 3 Flax composite manufacturing using VARTM process.

Experimental Methods

Flax Yarn Characterization—Tensile testing was conducted on single flax yarns (Figure 1b) in an MTS Exceed E42 universal testing machine equipped with a 50 N load cell. The yarn gauge length was kept at 25 mm. Yarns were tested in displacement control mode at 2mm/min displacement rate. An optical microscope was used to measure the effective cross-sectional area of yarns assuming a circular cross-section (Figure 3). Yarn diameter was measured at six locations along the length to calculate the average diameter.

Thermogravimetric analysis (TGA) measurements were conducted on Discovery TGA to evaluate the effect of alkali surface treatment on the flax fiber thermal decomposition properties. Flax samples measuring at least 7 mg were heated at a constant rate of 10 C/min over the temperature range from 30 to 500 °C.

Tensile Testing of FFRP Composites—FFRP laminates were cut into 254 x 178 mm panels with a wet saw, and then tabbed with 38-mm wide tapered G10 fiberglass/epoxy laminate using an epoxy adhesive (LOCTITE® EA 9309.NA™ AERO). The FFRP panels were then cut into 12.7-mm wide coupons using a diamond saw (AGS-1020AHD). The overall length of the tensile coupons was 254 mm. Each sample was measured at the top, bottom, and middle of for thickness and width. The specimen dimensions conformed with ASTM D3039 (ASTM 2017).

Tensile testing was performed in an Instron 5985 universal testing machine at a constant displacement rate of 1.27 mm/min according to ASTM D3039. Eight samples were tested for each type of FFRP composites. Tensile coupons were instrumented with 350-Ohm biaxial strain gauges sensors with 10.7 x 11.4 mm grid dimensions. Tensile strength, tensile modulus, and Poisson's ratio were computed from stress-strain data. Primary tensile modulus (E_1) and Poisson's ratio were calculated within the strain range of 1,000 to 3,000 microstrain. Secondary tensile modulus (E_2) was computed for the strain range of 5,000 to 7,000 microstrain.

Microscopy—The microstructure of polished FFRP composite cross-sections was examined using a Keyence VK laser confocal microscope. Fractured surfaces were analyzed using a VHX-1000 digital optical microscope. High-magnification images of the fiber surface were captured using a FIB Auriga 60 scanning electron microscope (SEM) in secondary electron mode to assess the fiber-matrix adhesion qualitatively.

RESULTS AND DISCUSSION

Flax Yarn Characterization

TGA experiments revealed a negligible difference between untreated and alkali-treated flax fibers, indicating that the adopted fiber surface treatment did not affect thermal decomposition properties of the fibers (Figure 4a). However, single yarn tensile tests indicated a stark difference between the untreated and treated group (Figure 4b)—on average, untreated yarns had 142% higher elastic modulus and 48% higher strength compared to alkali-treated yarns. The alkali treatment, intended to enhance fiber-matrix adhesion, led to the formation of additional voids and fiber fibrillation due to the removal of pectin and lignin from the flax fibers. This process resulted in increased roughness of the fibers. While this improves the adhesion between the fibers and the matrix, our data clearly demonstrates that it also diminishes the mechanical properties of the yarn.

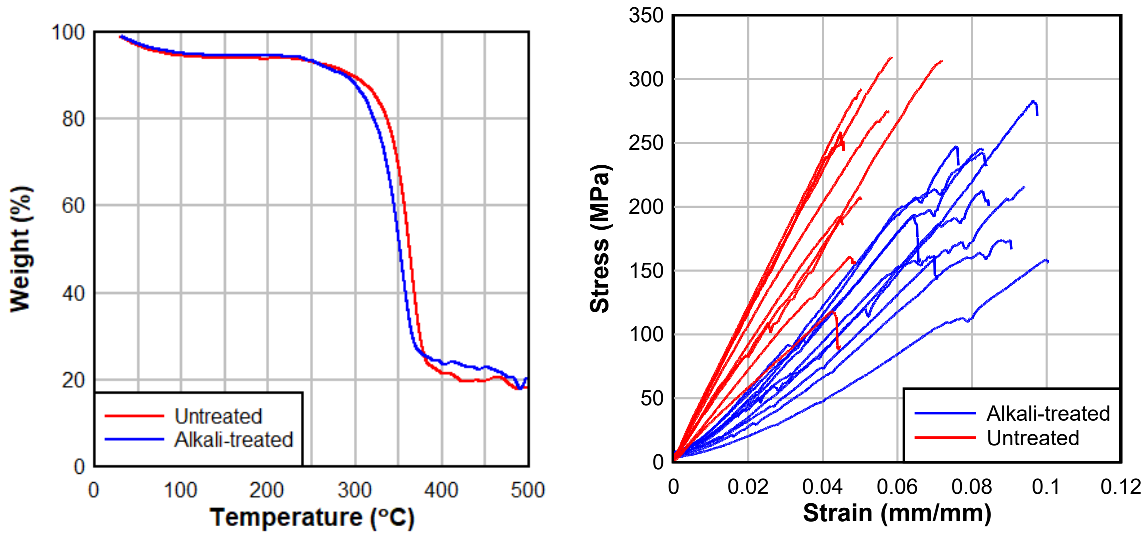
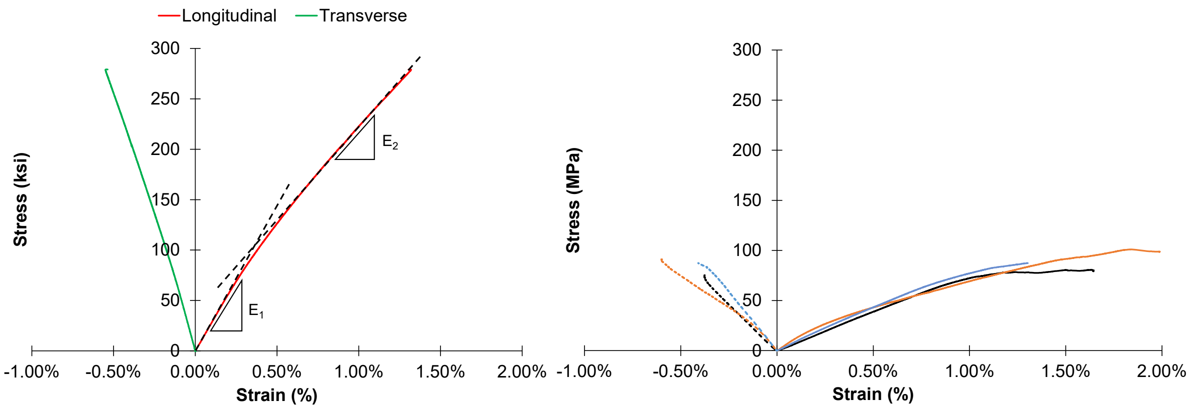


Figure 4. Flax fiber characterization: (a) TGA curves for untreated and alkali-treated fibers; and (b) single flax yarn stress vs. strain plots.

Mechanical Behavior of FFRP

The typical stress-strain behavior of FFRP composites without fiber surface treatment is depicted in Figure 5a. These composites displayed a characteristic bilinear stress-strain curve, characterized by the presence of primary and secondary moduli. However, FFRP composites incorporating alkali-treated flax fibers exhibited a distinct behavior. Figure 5b illustrates that the stress-strain curves of these composites varied among the samples and displayed a non-linear behavior that is atypical for composites.



(a) (b)

Figure 5. (a) Typical stress-strain curve for the FFRP composites without alkali surface treatment; and (b) longitudinal and transverse stress-strain plots of FFRP composites with alkali-treated fibers.

Mechanical properties of the tested composites are presented in Table 2 and graphically illustrated in Figure 6. The average laminate thickness of all four groups ranged from 2.5 to 3.6 mm. The lowest thickness was achieved for CAN resin FFRP fabricated via VARTM, indicating superior performance of the resin for VARTM applications. Hand-layup method produced composites with the highest thickness, likely due to air entrapment typical for hand layup. The Poisson's ratio for all the composites was within the 0.40 to 0.46 range.

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The choice of composite manufacturing process significantly influences the mechanical behavior of FFRP. Comparing the CAN resin FFRP composite produced through VARTM with the laminate manufactured via hand layup, the VARTM composite exhibited 19% higher tensile strength and primary modulus. This discrepancy may be attributed to the uneven resin distribution on the fabric and the introduction of fiber misalignment during the hand layup process. Additionally, matrix voids can become trapped within the preform during hand layup and prove challenging to eliminate, even with vacuum bagging. In contrast, the conventional epoxy FFRP composites manufactured using VARTM demonstrated 7.7% lower tensile strength and 7.1% lower primary modulus compared to the CAN resin FFRP composite produced through VARTM.

The modulus retention, defined as the ratio of secondary to primary modulus, provides valuable insight into the impact of the manufacturing method on the composite properties. Notably, hand layup displayed the lowest modulus retention among the tested methods, indicating a relatively weaker fiber-matrix interface. In contrast, CAN resin FFRP manufactured through VARTM demonstrated the highest modulus retention, suggesting a stronger adhesion between the fibers and the resin. The modulus retention serves as an indirect measure of the fiber-matrix interface adhesion, and the higher value exhibited by the CAN resin FFRP indicates enhanced bonding between the fibers and the resin matrix.

Table 2. Mechanical Properties of the FFRP composites

Test Group	Thickness (mm)	Strength (MPa)	E_1 (GPa)	E_2 (GPa)	Modulus Retention (E_2/E_1)	Poisson's Ratio
Control	3.05 ± 0.05	257.9 ± 11.7	24.1 ± 2.3	15.5 ± 0.7	64%	0.46 ± 0.04
CAN-NT-HL	3.30 ± 0.05	235.1 ± 10.3	21.8 ± 1.3	12.2 ± 0.6	56%	0.42 ± 0.04
CAN-NT-VARTM	2.54 ± 0.05	279.2 ± 6.2	25.9 ± 1.4	19.5 ± 0.7	75%	0.40 ± 0.04
CAN-ST-HL	3.56 ± 0.05	91.0 ± 13.1	7.7 ± 2.0	N/A	N/A	0.43 ± 0.06

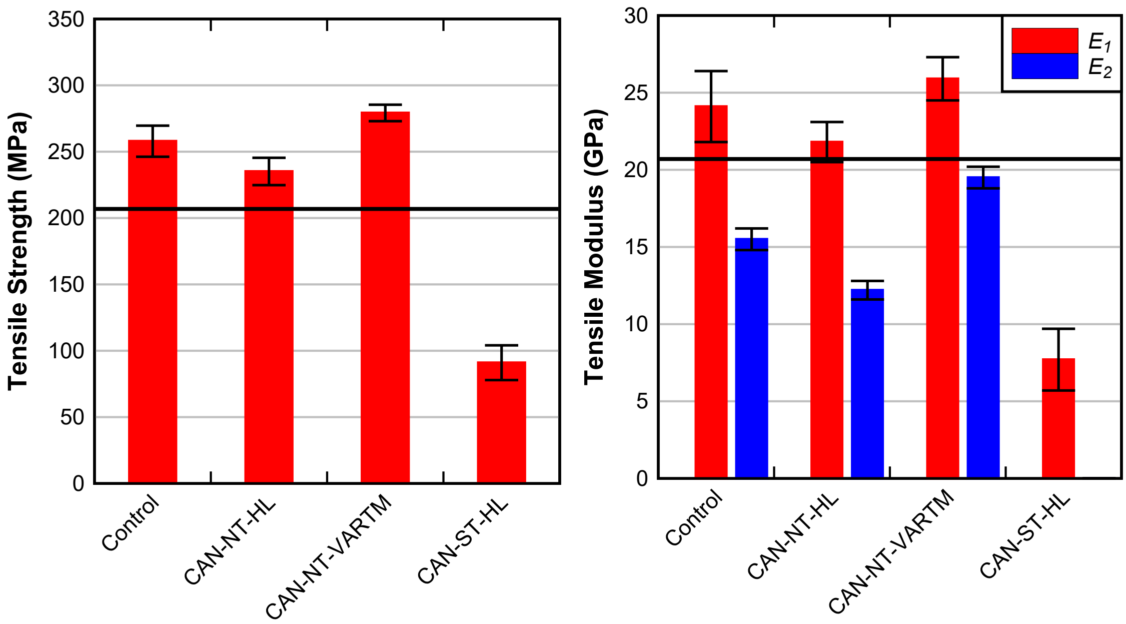
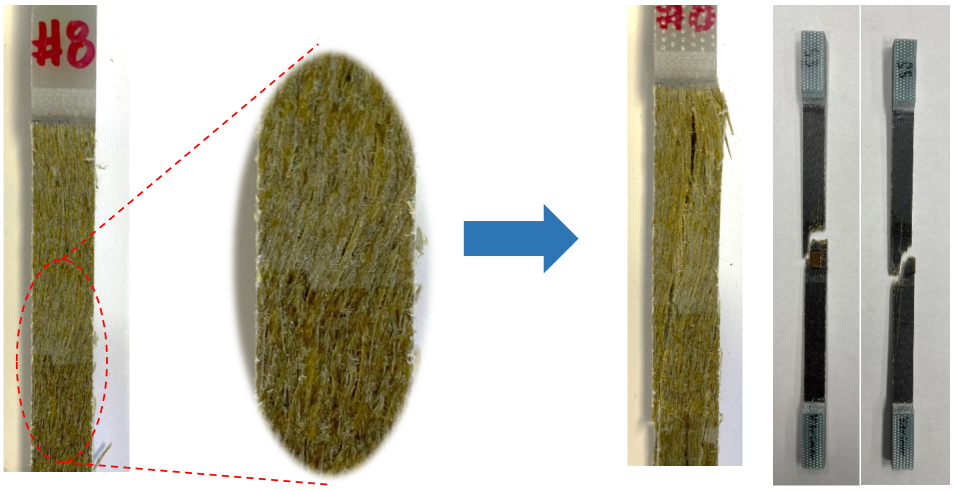


Figure 6. Summary of tensile properties of FFRP composites. Error bars indicate one standard deviation. Solid reference lines indicate minimum property requirements for composites used in pultruded structures (ASCE 2010).

The FFRP composite incorporating alkali-treated flax fibers demonstrated the lowest mechanical performance compared to the other groups. This can be attributed to two factors: the reduction in mechanical properties of the flax yarns, as evidenced in Figure 4b, and the fiber wrinkling effect caused by alkali treatment. Figure 4b clearly shows that the alkali treatment resulted in a decrease in the mechanical properties of the flax yarns. This reduction in strength and modulus of the individual yarns translates to diminished overall performance of the FFRP composite. Furthermore, the alkali treatment introduced fiber wrinkling. This wrinkling effect caused waviness and misalignment of the fibers (Figure 7a), leading to delamination failure mode and a subsequent decline in the mechanical performance of the FFRP composites incorporating alkali-treated fibers. The common failure mode in other groups was rupture within the gauge length, as shown in Figure 7b.

The end goal of the project is to develop FFRP composites appropriate for pultrusion applications. The measured properties were, therefore, compared to the minimum requirements specified for glass FRP pultruded members (ASCE 2010). All the untreated flax fabric-based composites met the minimum requirements for longitudinal tensile strength (207 MPa) and longitudinal tensile modulus (20.7 GPa) (Figure 6). The CAN resin FFRP composite manufactured using the VARTM process surpassed the specified requirements, exceeding them by 35% for tensile strength and 25% for modulus. However, the FFRP composite with alkali-treated flax fabric did not meet the specified requirements for pultrusion applications.

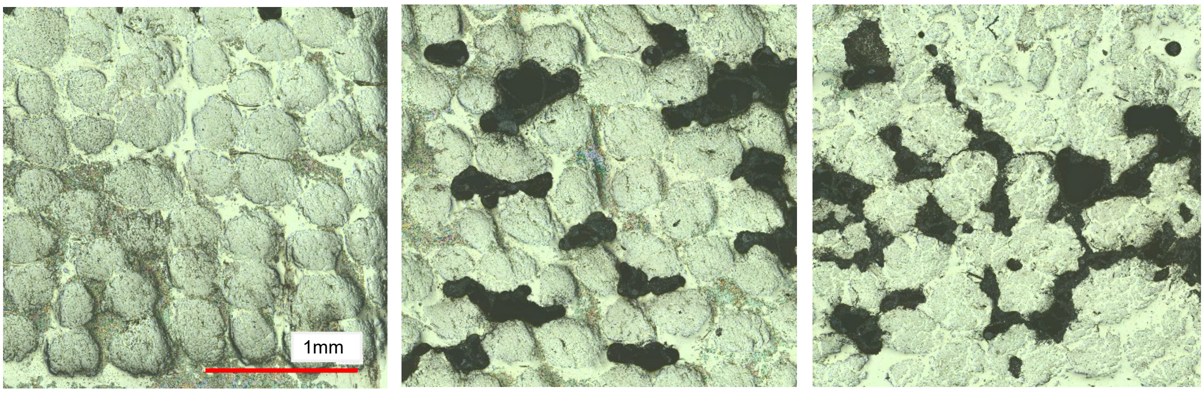


(a) (b)

Figure 7. Typical failure modes of FFRP composites with: (a) alkali-treated fibers; and (b) untreated fibers.

Microscopy

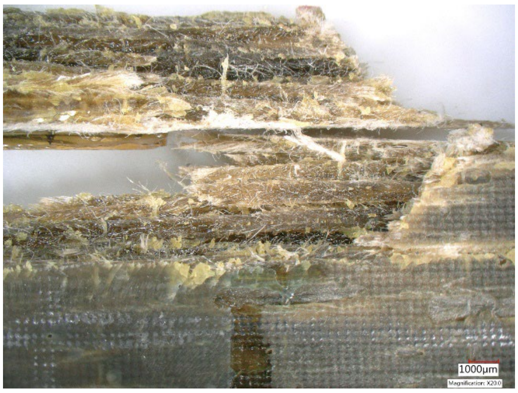
Figure 8 displays laser confocal microscope images of polished cross-sections of FFRP samples. The images clearly indicate that the VARTM manufacturing process minimizes porosity and maximizes the fiber volume fraction. In contrast, both hand-layup groups exhibit significant porosity, which contributes to their inferior mechanical properties. Comparing the alkali-treated to the untreated fiber group, it is evident that the air void interconnectivity is more pronounced in the alkali-treated samples. Furthermore, a notable difference is observed in the shape of the yarns. Untreated yarns maintain a compact elliptical shape, while the alkali-treated group shows signs of yarn disintegration and fraying. These findings provide additional evidence that supports the observed poor performance of the composite with alkali-treated fiber.



(a) VARTM (b) Hand-Layup (c) Hand-Layup (alkali treated)

Figure 8. Confocal laser microscope images of cross-sections.

Fractured surfaces were examined using a digital optical microscope to investigate how the test variables influenced the failure mode. In the hand-layup group with untreated fibers, the primary mode of failure was fiber rupture (Figure 9a). However, there was also evidence of local delamination. This can be attributed to the presence of microcracks that nucleated and spread from the entrapped air voids (Figure 8b). As a result, a combination of interlaminar failure and fiber rupture was observed in this group. The effect was even more significant in the alkali-treated group, likely due to the observed fiber misalignment shown in Figure 7a, as well as the interconnectivity of pores (Figure 8c). The fractured surfaces displayed a mixture of interlaminar failure and fiber rupture, indicating the influence of both factors on the overall failure behavior. In contrast, FFRP fabricated using the VARTM process did not exhibit interlaminar failure. The failure plane clearly indicated that fiber rupture was the dominant mode of failure. This suggests that the VARTM process, with its reduced porosity and improved fiber alignment, contributed to enhanced resistance against interlaminar damage.



(a)

(b)

(c)

Figure 9. Digital optical microscope photographs of typical failed surfaces for: (a) hand-layup FFRP (no alkali treatment); (b) VARTM FFRP; (c) hand-layup (alkali-treated fibers).

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High-magnification scanning electron microscopy (SEM) images were used to analyze the failed surfaces of the samples and assess the fiber-matrix adhesion qualitatively (Figure 10). The results showed that the control FFRP sample had no visible resin residue, while the CAN resin composites exhibited a coating of CAN matrix on the fibers. This SEM evidence supports the notion of improved fiber-matrix adhesion achieved with CAN resin. Additionally, the lower Poisson's ratio and significantly improved modulus retention observed in CAN VARTM composites compared to the control further indicate enhanced adhesion. The authors hypothesize that the presence of disulfide linkages in the CAN resin contributes to this improved adhesion. Under specific conditions, including negative vacuum pressure, high temperature during curing, and the presence of water molecules at the fiber-matrix interface, the disulfide bonds may undergo hydrolytic cleavage, forming thiol (-SH) and sulfenic acid (RSOH) intermediates. The thiol groups may then react with carbonyl groups (C=O), predominantly found in lignin. This possible thiol addition to the carbonyl group could explain the observed superior adhesive properties of the CAN resin. This is a topic of ongoing investigation.

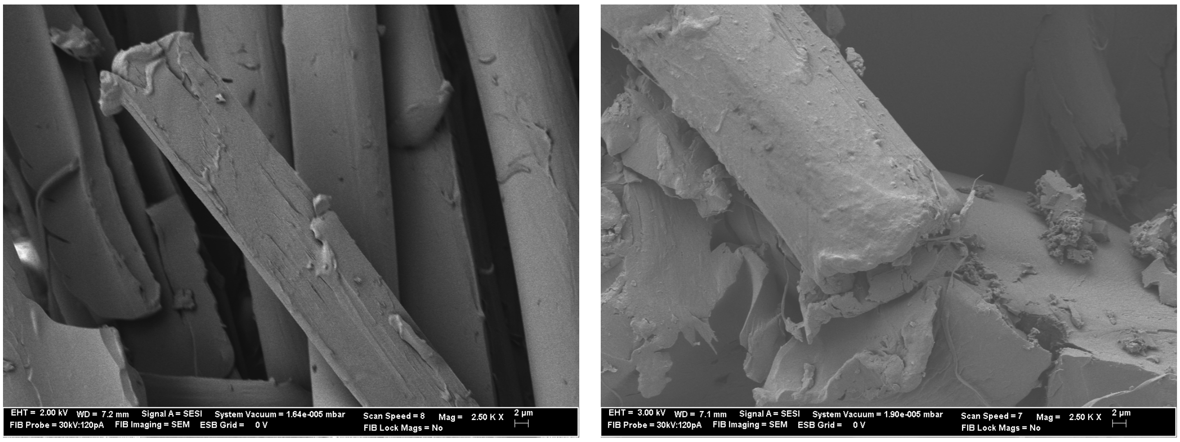

Figure 10. SEM images of typical fiber surfaces of: (a) control FFRP composite; and (b) CAN resin composite.

RECYCLABILITY

A proof-of-concept experiment was conducted to assess the recyclability of CAN-based FFRP composites. A recyclable composite sample was submerged in a solution of 2-mercaptoethanol and dimethylformamide (DMF) for 24 hours. During this time, the resin completely dissolved due to the reversible nature of disulfide crosslinks. The solvent works by cleaving the disulfide bonds through thiol-disulfide exchange. In this process, the thiol group (-SH) in 2-mercaptoethanol reacts with the disulfide bond (-S-S-) to form a new thiol group (-SH) and a new disulfide bond (-S-S-). This reaction occurs when the thiol group attacks one of the sulfur atoms in the disulfide bond, resulting in the bond being cleaved. The presence of dimethylformamide as a solvent aids in dissolving the reactants and creating a suitable environment for the thiol-disulfide exchange reaction. As a result, the flax fabric could be extracted from the composite without any residual resin, as shown in Figure 11. The dissolution of the resin is reversible, and the authors are currently working on methods to extract the resin from the solvent for reuse or upcycling purposes.

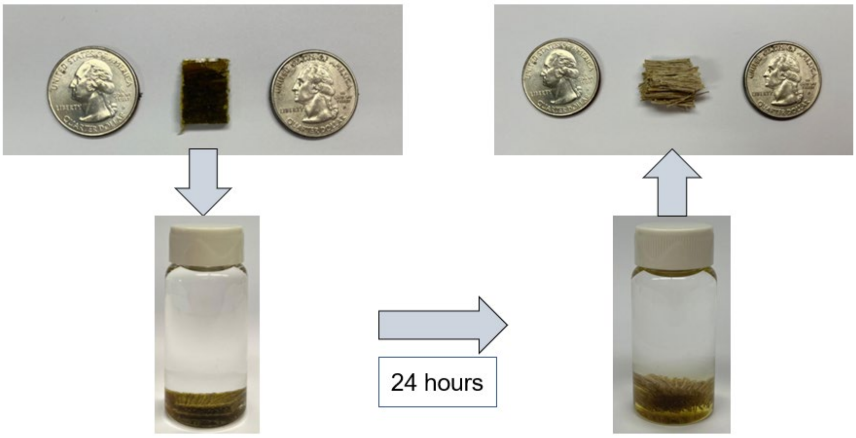

Figure 11. Process of dissolving recyclable resin

CONCLUSION

The study evaluated the feasibility of using a reprocessable CAN resin to manufacture FFRP composites. Tensile tests were conducted on FFRP composites to evaluate the effect of manufacturing method (hand layup vs. VARTM) and alkali fiber surface treatment on the mechanical behavior of recyclable FFRP composites. TGA and single flax yarn tensile tests were conducted to characterize the effect of alkali treatment on fiber thermal and mechanical properties, respectively. Composites' microstructure was evaluated via laser confocal microscopy, optical microscopy, and SEM to evaluate the effect of studied variables on the microstructure, failure mode and fiber-matrix adhesion, respectively. The following conclusions were made based on the presented experimental evidence:

- Untreated flax yarns exhibited a 142% higher elastic modulus and 48% higher strength compared to alkali-treated yarns. Alkali surface treatment did not notably affect the thermal decomposition properties of the fibers.
- The manufacturing process significantly influenced the mechanical behavior of the composites. The VARTM manufacturing technique resulted in up to 19% higher tensile strength and primary modulus compared to the hand layup process. Laser confocal microscopy confirmed superior compaction in VARTM. Consequently, hand layup composites showed varying degrees of delamination failure mode and VARTM composites exhibited a failure mode dominated by fiber rupture.
- FFRP composites with a CAN matrix, manufactured via VARTM, demonstrated an 8.2% increase in tensile strength and a 7.6% increase in primary modulus compared to conventional epoxy-based FFRP composites manufactured via VARTM. Moreover, the CAN matrix composite showed an 11% greater modulus retention than the conventional matrix composite. SEM images indicated better fiber-matrix adhesion in the CAN matrix, potentially attributed to disulfide hydrolysis followed by thiol-carbonyl addition, enhancing chemical adhesion.
- Hand layup composites prepared with alkali-treated fibers and CAN matrix displayed a 65% lower modulus and a 61% lower tensile strength compared to their counterparts with untreated fibers. This decrease was attributed to the degrading effect of alkali treatment on fiber properties and the resulting flax fabric wrinkling, leading to fiber misalignment during the manufacturing process.
- All FFRP composites, except those incorporating alkali-treated flax fabric, met the minimum required longitudinal tensile strength and modulus as specified in ASCE (2010).
- The preliminary study indicated that a solution of 2-mercaptoethanol with DMF effectively dissolved the resin, enabling the extraction and reuse of fibers.

Our ongoing works aims to characterize the effect of CAN matrix on fiber-matrix adhesion, self-healing properties of CAN matrix following fatigue cycles, as well as the durability properties of the composite.

The end goal of the project is to successfully demonstrate pultrusion of recyclable FFRP composites designed for civil infrastructure applications.

ACKNOWLEDGEMENT

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest associated with the work presented in this paper.

DATA AVAILABILITY

All necessary data is presented in this paper.

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