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Effect of surface treatments on interfacial properties of flax fiber-reinforced composites

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Flax fiber has become increasingly attractive as reinforcement in polymer matrix composites. Due to its lighter weight, flax fiber-reinforced composites can perform similar to glass fiber-reinforced composites on a specific property comparison. In order to maximize the mechanical performance of the flax-reinforced composites, different fiber surface treatments have been investigated by many studies. In this study, four different chemical modifications were selected to compare difference on the mechanical performance between flax/vinyl ester composites and E-glass/vinyl ester composites. Different unidirectional flax fiber/vinyl ester and E-glass/vinyl ester composites were produced via a modified vacuum-assisted resin transfer molding process. Higher specific properties of chemically treated flax fiber-reinforced composites over those of E-glass composites were obtained. Acrylic acid treatment increased both the interfacial shear strength and the interlaminar shear strength about 30% compared with untreated flax composites. It confirms that the specific mechanical properties of flax composites with a suitable surface modification were comparable with E-glass composites. In addition, a suitable composite processing procedure to manufacture the flax/vinyl ester composites was designed and fiber bundle pullout test for flax fiber composites were developed.

Keywords: flax fiber; composites; interfaces; surface treatment; pullout

1. Introduction

Natural fibers, such as flax, hemp, ramie, kenaf, sisal, henequen and jute, are environmentally-friendly alternatives to the glass fibers as reinforcement in engineered polymer matrix composites. These fibers present lesser concern with health and safety during handling. In addition, they also exhibit comparable mechanical properties as synthetic fibers, along with lower density and lower cost.[1] It is well known that the mechanical performance of a composite material depends on the nature and orientation of the fibers, and the nature of the matrix. Nevertheless, the quality of the adhesion between the two constituents is also critical, [2] especially at the interface between fiber and matrix. Therefore, the key to improving performance is dependent on controlling the chemical and mechanical properties of the fiber–matrix interface. Due to the presence of hydroxyl groups from cellulose and lignin,[3,4] flax fiber exhibits highly hydrophilic properties. This behavior makes fiber–matrix adhesion very difficult because most structural polymers are hydrophobic in nature. Surface treatment is a method to reduce the hydrophilicity of the fiber by reducing the number of hydroxyl groups in the fibers in order to improve the adhesion between flax fiber and polymer matrix.

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Alkaline treatment is one of the most popular treatments used on flax fibers. It is also used as a pretreatment in other types of chemical modifications for flax fibers.[5–8] One of the advantageous effects of alkaline treatment is that alkalis, such as NaOH [5,6] and KOH, can help the crystalline lattice of flax fiber transform from cellulose-I into the cellulose-II, which is more thermodynamically stable and readily penetrable by ions. Alkali treatments also can remove dirt, waxes, pectin, hemicelluloses, and other substances residing on the surface of flax fiber to smoothen the surface and thereby promoting compatibility between the fiber and polymer matrix.

Often, coupling methods constitute surface modification treatments. The coupling agents that are used contain chemical groups that can react with both the fiber and the polymer matrix. Covalent bonds and hydrogen bonds are formed, which improve the interfacial adhesion. Graft copolymerizations [9] are also common for natural fiber-reinforced composites, where the functional groups used can be methyl groups, isocyanates,[10] triazine,[11] benzoylation,[12,13] or organosilanes.[1,14–16] One of the most common reactions for lignocellulosic materials is acetylation. The principle of this method is that the hydroxyl groups of the flax fiber react to form acyl groups (RCO–).[5,16–20] X-ray diffraction (XRD) analysis [16] has showed that the acetylation treatments increase the crystallinity index of the fiber. Acrylic acid grafting is another popular surface treatment for natural fibers. The graft polymerization of acrylic acid, initiated by free radicals on the surface of flax fiber has been investigated,[8] where acrylic acid reacts with the hydroxyl groups of the flax fiber to form an ester. Acrylic acid and its esters readily combine with themselves or other monomers by reacting at their double bond, forming homopolymers or copolymers.[8,21,22]

The growth factors of flax fiber and bast fibers in general, further degrade the interfacial strength. Charlet et al. [23] found that the chemical composition and mechanical properties of the fibers were a strong function of their location in the stem. Therefore, within a single fiber, variations in diameter, surface roughness and defects, and variable chemical composition are common. Hence, the interfacial strength of the composite is a complex property arising from the complex nature of flax fibers.

Since it is difficult to control the properties of naturally grown flax fiber, improving the interfacial strength during composite manufacturing is the key to enhancing composite properties. In previous studies, a uniform 10% increase in the interfacial strength of flax/unsaturated polyester resin was attained just by cleaning/dewaxing the fiber surface by NaOH.[24] Therefore, the selection of the matrix and fiber surface treatment is extremely important to the final properties of flax fiber composites. Hot water can wash away the ashes and provide much cleaner fiber surface, which the cost is the lowest. Acetic anhydride treatment is a traditional method for cellulose, which is used widely in cellulose application. Acrylic acid treatment was chosen because it can build a bridge between cellulose fiber and vinyl ester.

In this research, four types of flax composites were prepared to determine the effect of the surface treatment; (1) untreated flax/VE composite, (2) hot water-washed flax/VE composite, (3) acetic anhydride-treated flax/VE composite, and (4) acrylic acid-treated flax/VE composite. In addition, E-glass/VE composites were prepared to compare the mechanical properties with flax. A modified vacuum-assisted resin transfer molding (VARTM) method was used to process unidirectional composite laminates with high fiber volume fraction.

2. Materials and processing

2.1. Materials

Linen flax fibers were obtained from Europe through General Bailey Homestead Farm, Greenfield, NY and had the following basic characteristics: Uncut, Natural Color, Full Length,

and Density of 1.4 g/cm^3. The resin system used for all studies was a vinyl ester system Hydropel® R037-YDF-40 from AOC resins. The hardener was a 2-butanone peroxide (Luperox® DDM-9) solution, obtained from Sigma-Aldrich Co. Acrylic acid anhydride (purum, $\geqslant$99.0%, GC) was also supplied by Sigma-Aldrich Co. Acetic anhydride (99.0%, GR) obtained from EMD Chemicals Inc. Unidirectional E-glass fabric (237 g/m^2, 0.96 m wide, 0.2 mm thick, 80 $\times$ 18 plain weave) was purchased from Northern Fiber Glass Sales.

2.2. Surface treatments

The flax fibers were loomed using cotton thread and the length of the fiber was maintained around 150 mm. The measured weight of each perform was 25–27 g before any surface treatment, was conducted to keep all fibers straight during treatments. The surface treatments were used as described here.

Hot water wash:

The loomed flax fibers were immersed into 100 °C distilled water for 10 min and dried in an oven for 24 h at 80 °C and then the cotton thread was removed.

Alkaline pretreatment:

The loomed flax fibers were immersed into 500 cm^3 of 10 g/L sodium hydroxide ethanol solution at 78 °C for 2 h, and then washed with absolute ethanol until no color left in ethanol and then dried in an oven for 24 h at 80 °C.

Acrylic acid treatment:

The alkali pretreated flax fibers were immersed into 100% acrylic acid at 50 °C for an hour, and then dried in an oven for 24 h at 80 °C.

Acetic anhydride treatment:

The alkali-pretreated flax fibers were immersed into acetic anhydride for 1 h at room temperature and dried in an oven for 24 h at 80 °C.

2.3. Preparation of the thermosetting composites

The untreated, hot water washed, acrylic acid treated, acetic acid-treated flax fibers and E-glass fiber loading of all specimens was targeted between 45 and 50% fiber volume fraction ($V_f = 0.45 - 0.50$). Samples were processed using a modified form of the VARTM. A caul plate was used underneath the vacuum bag to provide a uniform cross-sectional area. This also created a panel for testing with a smooth surface finish on both sides. In order to

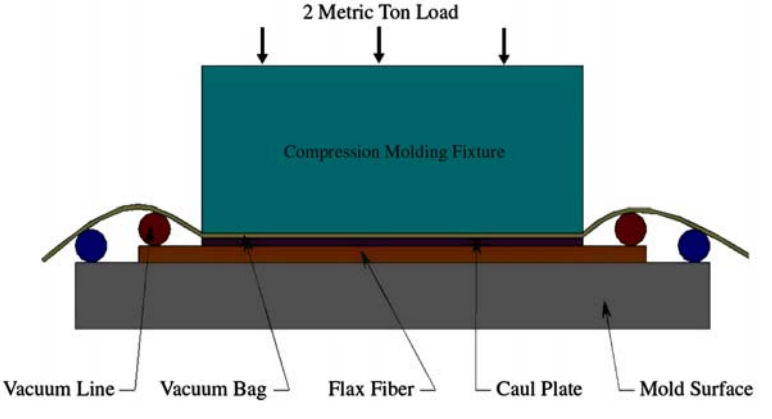

Figure 1. Compression-aided VARTM setup.

maintain an equivalent fiber volume fraction, the VARTM process was aided by compressing the vacuumed flax with two metric tons. The schematic of the setup is shown in Figure 1.

2.4. Materials characterization

FTIR spectra were obtained with untreated, sodium hydroxide ethanol solution-treated, acetic anhydride-treated, and acrylic acid-treated flax fiber samples. Thirty-two scans were taken between 4,000 and 650 cm^{-1} on a Nicolet 6700 FTIR spectrometer equipped with Spectrum software.

Flexural analysis was performed through three-point bend testing as specified in Procedure A of ASTM Standard D790, using a load frame manufactured by MTS System Corporation. The speed of the cross-head was 1 mm/min. Five specimens were tested for each sample. The mean value and standard deviation of specific flexural stress and specific flexural modulus was calculated for each sample set.

Tensile mechanical testing was performed to ASTM Standard D3039 on a five specimen sample set using an Instron model 5567 load frame. The speed of the cross-head was 1 mm/min. Each test was performed until tensile failure occurred. The maximum load was recorded and the specific tensile strength was calculated for each sample set.

Interlaminar properties were assessed through the short beam strength test (ASTM D2344) and a fiber bundle pullout test. Short beam shear tests were carried out in displacement control at a rate of 1 mm/min, according to ASTM Standard D2344. Five specimens for each sample were tested. Interlaminar shear strength (ILSS) was calculated to analyze the interlaminar properties for each sample set.

Fiber bundle pullout tests were used to measure the interfacial shear strength between flax fiber bundles and surrounding matrix. Testing was conducted using an Instron model 5567 load frame with a 2.0 kN-capacity load cell at a rate of 0.5 mm/min. Microscopy was used to determine the interfacial area of the pulled fiber bundle. With pullout perimeter, a modified Kelly–Tyson equation [25] is used to obtain the interfacial shear strength τ_i:

$$\tau_{\mathrm{i}} = \frac{F_{\max}}{CL_{\mathrm{e}} + A} \tag{1}$$

where $F_{\max}$ is the maximum load at pullout, C is the fiber bundle perimeter, L_{e} is the fiber embedded length, and A is the area of the visible surface of the fibers, which is encapsulated in resin and must be included in the surface area calculations.

3. Results and discussion

Three types of modifications can occur during the surface treatment of fibers: dissolution, coating, or a combination of both. The result of a hot washed treatment is dissolution, such as dewaxing and delignification. The acrylic acid treatment and the acetic anhydride treatment show a combination of dissolution and coating, which involved dewaxing, delignification, bleaching, and copolymerization. The alkaline pretreatment can clean and alter parts of the structure of cellulose lattices and the acrylic acid or acetic anhydride can react with the hydroxyl groups of cellulose,[5,17,20] which is similar to coating the surface of fibers to reduce hydrophilicity. Acrylic acid also can copolymerize with VE resin.

3.1. Density tests

The measured density of composite varied slightly with different surface treatments, as well as with the fiber volume fraction. The fiber volume fraction of samples was calculated from Equation (2).

$$V_f = (\rho_c/\rho_f)W_f \quad (2)$$

where V_f is the volume fraction of the fiber in composite, ρ_c is the density of the composite, ρ_f is the density of the fiber, and W_f is the weight percentage of fiber in composite. W_f is calculated by measuring the weight of the fiber and resin before the composite is processed and the weight of the composite after processing. During the VARTM process, the layer of flax fiber was lay out by hand, which was challenging. The amount of fiber and degree of spread dictated the density of composite and the fiber volume fraction. The density of VE resin used was 1.1 g/cm^3 and the density of untreated flax fiber was 1.42 g/cm^3. Table 1 shows the densities of various flax treated composites samples for different mechanical tests. The densities of all flax/VE composites ranged from 1.15 to 1.35 g/cm^3. For acrylic acid-treated flax/VE composites and acetic anhydride-treated flax/VE composites, the densities were higher than untreated flax/VE composites regardless of the fiber volume fraction. This increase in density can be attributed to acrylic acid and acetic anhydride reacting with cellulose to increase the density of flax fiber. However, the densities of all flax composites are lower than the E-glass composites with the similar fiber volume fraction.

3.2. *Surface modification*

The FTIR spectra of untreated and treated flax fiber are presented in Figure 2. The spectrum of the untreated flax fiber shows characteristic bands for cellulose: the hydrogen bonded OH stretching between 4000 and 2995 cm^{-1}, the CH stretching at 2938 cm^{-1}, the OH bending at 1643 cm^{-1}, the CH_2 bending at 1446 cm^{-1}, the CH bending at 1383 cm^{-1}, and the C–O stretching at 1038 cm^{-1}. The spectrum of NaOH/ethanol solution-treated flax shows the bands for cellulose as well. The CH stretching around 2940–2900 cm^{-1} showed resolved peaks as compared to the spectrum of the untreated flax, indicating the effectiveness of sodium hydroxide pretreatment in removal of surface contamination, which is the wax on the fiber surface. The spectrum of acetic anhydride-treated flax showed a band at 1710 cm^{-1}, which is typical of the carbonyl group. This peak supported the occurrence of a reaction between acetic anhydride and hydroxyl groups on cellulose.[26] The band observed at 1579 cm^{-1} can be assigned to asymmetric stretching of carbonyl groups. The spectrum of acrylic acid-treated

Table 1. Density and fiber volume fraction of different treated flax/VE composites and E-glass fiber/VE composites.

	Density (g/cm^3)	V_f (%)
Untreated flax/VE (ILSS)	1.25 ± 0.03	49.44
Untreated flax/VE (tensile)	1.29 ± 0.02	48.38
Hot water-treated flax/VE (ILSS)	1.15 ± 0.02	52.56
Hot water-treated flax/VE (tensile)	1.29 ± 0.03	43.24
Hot water-treated flax/VE (three-point bend)	1.34 ± 0.02	57.23
Acrylic acid-treated flax/VE (ILSS)	1.32 ± 0.01	54.58
Acrylic acid-treated flax/VE (tensile)	1.26 ± 0.03	43.36
Acrylic acid-treated flax/VE (three-point bend)	1.24 ± 0.09	56.63
Acetic anhydride-treated flax/VE (ILSS)	1.27 ± 0.03	48.21
Acetic anhydride-treated flax/VE (tensile)	1.30 ± 0.01	49.11
Acetic anhydride-treated flax/VE (three-point bend)	1.35 ± 0.01	51.34
E-glass fiber/VE (ILSS)	1.92 ± 0.02	56.73
E-glass fiber/VE (tensile)	1.83 ± 0.03	49.40
E-glass fiber/VE (three-point bend)	1.98 ± 0.02	58.12

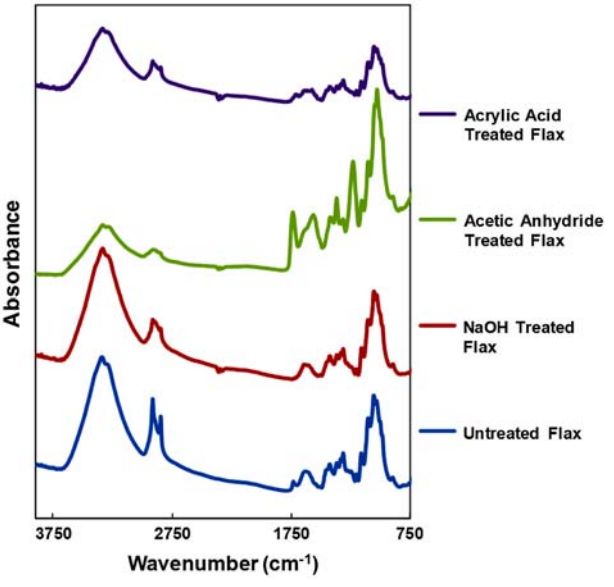

Figure 2. The infrared spectra of untreated and treated flax fibers.

flax also shows a weak band at 1708 cm^{-1} that is from the carbonyl groups formed because of acrylic acid reacting with hydroxyl groups on cellulose.[26] The band at 1610 cm^{-1} is typical of the carbon double bonds that are from the grafted acrylic acid.

3.3. *Flexural properties*

In Figure 3, the specific flexural properties of treated flax fiber-reinforced composites and E-glass fiber/VE composite, measured by three point bending tests are presented. In Table 2, the actual flexural properties are shown. E-glass/VE showed the highest in the specific flexural strength and hot water washed flax/VE performed the best in the specific flexural modulus. The specific flexural strength of acetic anhydride-treated flax/VE was 11% lower than E-glass/VE and the specific flexural modulus of acetic anhydride treated flax/VE was 15% higher than E-glass/VE. Compared with E-glass/VE composites, hot washed flax/VE showed 25% lower specific flexural strength and 25% higher specific flexural modulus.

The flexural properties of Acrylic acid treatment were the lowest among all investigated systems, especially flexural modulus. The modulus behavior is likely because cellulose can hydrolyze [27] in acrylic acid, leading to disintegration of the structure of flax fiber. A weight loss after acrylic acid treatment was observed along with a loss of color (fading) from yellow to white. The weight loss is due to the hydrolysis of cellulose during the acrylic acid treatment. On the other hand, the esterification in the acrylic treatment can increase the weight of the fiber. The weight loss of fiber after the acrylic treatment indicates that the degree of hydrolysis was predominant over degree of esterification.

However, during the acetic anhydride treatment, the hydrolysis of cellulose of flax is lower because of the nearly negligible amount of water generated by the esterification. In the acetic anhydride treatment, the change of weight was marginal and the color loss (qualitative) was apparently lower than the acrylic acid treatment. The degree of esterification was equal or larger than that of hydrolysis. The specific flexural modulus of acetic anhydride-treated flax/VE was 7% lower than hot water-treated flax/VE and its specific flexural strength was

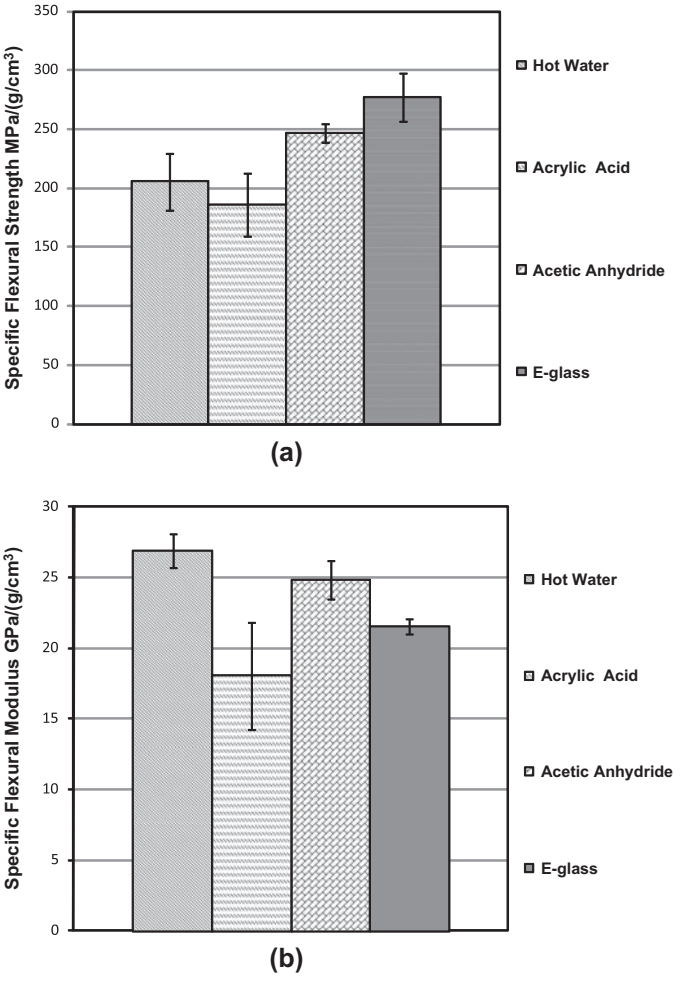

Figure 3. Specific flexural property comparison to E-glass composites; (a) specific flexural strength comparison, and (b) specific flexural modulus comparison.

Table 2. Flexural property comparison of treated flax/VE to E-glass/VE.

	Flexural strength (MPa)	Flexural modulus (GPa)	Density (g/cm^3)	V_f (%)
Hot water	275.77 ± 32.55	36.10 ± 1.63	1.34 ± 0.02	57.23
Acrylic acid	231.13 ± 33.27	22.45 ± 4.69	1.24 ± 0.09	56.63
Acetic anhydride	332.14 ± 10.52	33.44 ± 1.83	1.35 ± 0.01	51.34
E-glass fiber	548.90 ± 41.24	42.68 ± 1.00	1.98 ± 0.02	58.12

the highest in all treated flax/VE composites. Acetic anhydride treatment appeared as the best treatment leading to strength improvement. This fact is possibly related to a better fiber/matrix interphase. Acetate smoothed the different surface energy values of matrix and reinforcement fiber and helped achieve a better wetting of fiber.

Hot water washed flex/VE showed the highest value in specific flexural modulus, which performed better than other treatments and E-glass/VE. It showed the potential that unidirectional

flax can replace E-glass as the reinforcement for composites. Hot water treatment removed some ash, wax and other substances on the surface of flax, but it would not break down the fiber bundle. All other chemical modifications can affect the mechanical properties of flax, which is due to the breakage during these treatments: alkaline treatment can break down partial of fiber bundles; acrylic acid and acetic anhydride can lead the hydrolysis of cellulose in the flax fiber.

3.4. Tensile properties

Tensile testing was performed to determine the effects of both fiber loading and processing methodology had upon the untreated and treated flax fibers composite system vs. E-glass fiber/VE composite. The resulting specific tensile property results are shown in Figure 4 and the actual properties are provided in Table 3.

A 40% improvement (36% specific) in tensile strength due to acetic anhydride treatment was obtained as compared to untreated flax fiber. There did not appear to be any significant improvement from other treatments investigated in this study. However, the glass fiber composite showed the highest specific tensile strength. Tensile strengths of all the analyzed composites were lower than that for the E-glass fiber composite likely because the treatments did not reach an optimum adhesion between fiber and matrix. The specific tensile strength for

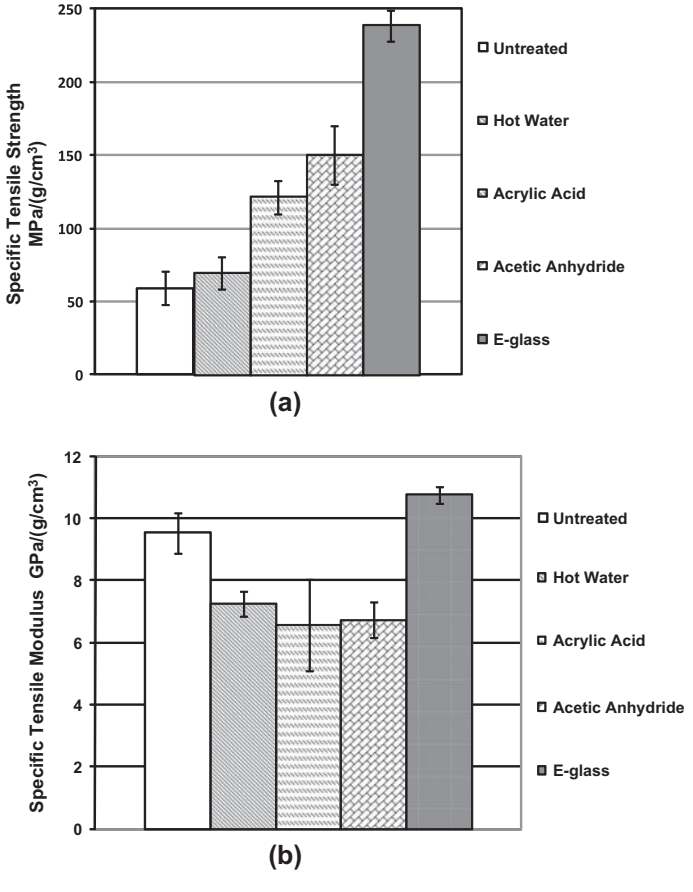

Figure 4. Specific tensile properties comparison of treated Flax/VE to E-glass/VE composites; (a) specific tensile strength comparison, and (b) specific tensile modulus comparison.

Table 3. Tensile properties comparison of treated flax/VE to E-glass/VE.

	Tensile strength (MPa)	Tensile modulus (GPa)	Density (g/cm^3)	V_f (%)
Untreated	76.32 ± 14.67	12.30 ± 0.85	1.29 ± 0.02	48.38
Hot water	89.87 ± 14.50	9.34 ± 0.53	1.29 ± 0.03	43.24
Acrylic acid	153.24 ± 14.60	8.27 ± 1.86	1.26 ± 0.03	43.36
Acetic Anhydride	195.64 ± 25.75	8.75 ± 0.74	1.30 ± 0.01	49.11
E-glass fiber	437.27 ± 19.52	19.70 ± 0.50	1.83 ± 0.03	49.40

the acrylic acid treatment was equivalent to that of the hot water treatment. This observation confirmed that the hydrolysis occurred in acrylic acid treatment and the flax fiber was affected during the treatment. The acetic anhydride-treated flax/VE composite exhibited the highest tensile strength of all tested systems. A higher degree of esterification of hydroxyl groups of cellulose can lead to a stronger interphase. For acrylic acid treatment, the balance of the hydrolysis and esterification is very important, which warrants further study.

The tensile moduli of untreated and treated flax/VE composites were lower than that of E-glass/VE composite. All surface treatments decreased the tensile moduli and specific tensile moduli of their composites, confirming that the hydrolysis of cellulose in the acrylic acid treatment and acetic anhydride treatment disintegrates the flax fiber and reduces the properties of flax fiber. In addition, the variation of the fiber alignment affects the mechanical performance of the flax composites. However, the specific tensile modulus of untreated flax/VE was a marginal 11% lower than E-glass/VE with a similar fiber volume fraction.

3.5. *Interfacial properties*

Figure 5 shows the specific ILSS of treated flax fiber-reinforced composites and E-glass fiber/vinyl ester composite, measured by the short beam strength test. Table 4 provides the actual ILSS values measured. The comparison of untreated and treated flax composites shows all three treatments clearly improving the ILSS property. This observation supports the effectiveness of the treatments in enhancing the adhesion strength between matrix and fibers. Surface treatments and modification of the flax fiber creates more active surface molecules that would readily form the H-bonding with the matrix.

Acrylic acid treatment performed the best within the systems and increased 138% over untreated flax and 19% over the E-glass fiber composite. Acrylic acid treatment provided acceptable interfacial bonding between flax fiber and vinyl ester. This bonding occurs because

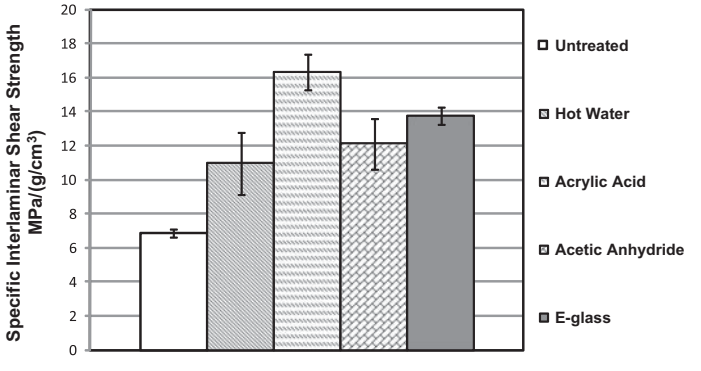

Figure 5. ILSS comparison of treated flax/VE to E-glass/VE composites.

Table 4. ILSS comparison of treated flax/VE to E-glass VE.

	ILSS (MPa)	Density (g/cm^3)	V_f (%)
Untreated	8.53 ± 0.22	1.25 ± 0.03	49.44
Hot water	12.64 ± 1.82	1.15 ± 0.02	52.56
Acrylic acid	21.54 ± 1.04	1.32 ± 0.01	54.58
Acetic anhydride	15.43 ± 1.48	1.27 ± 0.03	48.21
E-glass fiber	26.39 ± 0.52	1.92 ± 0.02	56.73

acrylic acid reacts with –OH of cellulose in flax fiber during the treatment and it also co-polymerizes with vinyl ester and forms covalent bonds during the composite processing. Acetic anhydride treatment showed 77% higher ILSS than the untreated flax composite, but showed lower ILSS than acrylic acid treatment. Acetic anhydride treatment only decreases the hydroxyl groups and the ester produced in the treatment cannot react with vinyl ester. The mechanical interlocking is critical for acetic anhydride treatment. As the carbon chain of acetic anhydride is short, the mechanical interlocking between fiber and matrix is limited. Therefore, the interfacial performance of acetic anhydride treatment is lower than the acrylic acid treatment. Hot water treatment also increased the ILSS by 60% compared with the untreated flax composite. It shows that hot water treatment can remove some surface contaminations and provide cleaner surfaces.

The fiber bundle pullout test was used to estimate the quality of interfacial bonding between fibers and matrix. In Figure 6 and Table 5, the interfacial shear strength of untreated and treated flax fibers, measured by pullout tests, are shown. The acrylic acid treatment performed most effectively and increased 30% over the untreated flax fiber, which is similar to the results of ILSS, 4% lower than E-glass fiber. These results demonstrated the improvements brought along by the treatments in wetting of the vinyl ester onto the modified fiber surface, thereby increasing the work of adhesion. However, the fiber bundles for pullout tests were carefully selected with straight alignment. In addition, the kinks on flax fiber play an important role for the fiber bundle pullout tests. Therefore, the trend of the pullout test is not the same as the results of ILSS. The synthetic E-glass fibers without any defects are more uniform than flax fibers. So the interfacial shear strength of E-glass is higher than most of flax fiber.

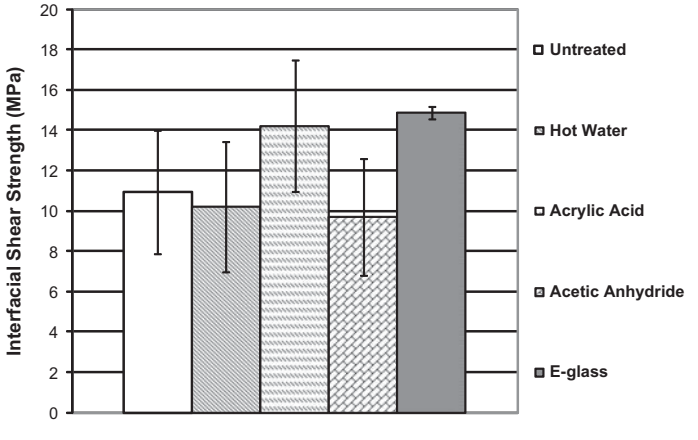

Figure 6. Interfacial shear strength comparison between surface treatments.

Table 5. Interfacial shear strength comparison between surface treatments.

	Interfacial shear strength (MPa)
Untreated	10.942 ± 3.061
Hot water	10.178 ± 3.224
Acrylic acid	14.204 ± 3.262
Acetic anhydride	9.691 ± 2.887
E-glass fiber	14.826 ± 0.288

3.6. Microscopy

Optical microscopy (Figure 7) showed that the agglomerated-untreated fibers and voids in the composite, especially the untreated flax and hot water-washed flax. There is lots of cuticles and pectin to bond fibers together. These contaminations may have contributed also to the unclear bands of the spectrum of the untreated flax. Hot water washing only can remove partial of substances on the surface of flax, so the agglomeration of flax still existed. Acrylic acid treated fibers before being processed into composite laminates appeared to be the least entangled, which can also be seen in the micrograph of the acetic anhydride treated fibers. The diameter of fiber bundle of acetic anhydride treatment and acrylic acid treatment showed smaller than that of hot water-washed flax fiber. It indicates the acetic anhydride treatment and the acrylic acid treatment remove more noncellulosic chemical and separate the bundles. Separating fibers into fibrils exposed larger contact area to the matrix and hence the composite properties are increased by increase in interfacial strength between fiber and matrix. From the micrographs, different surface treatments have noticeable differences. The

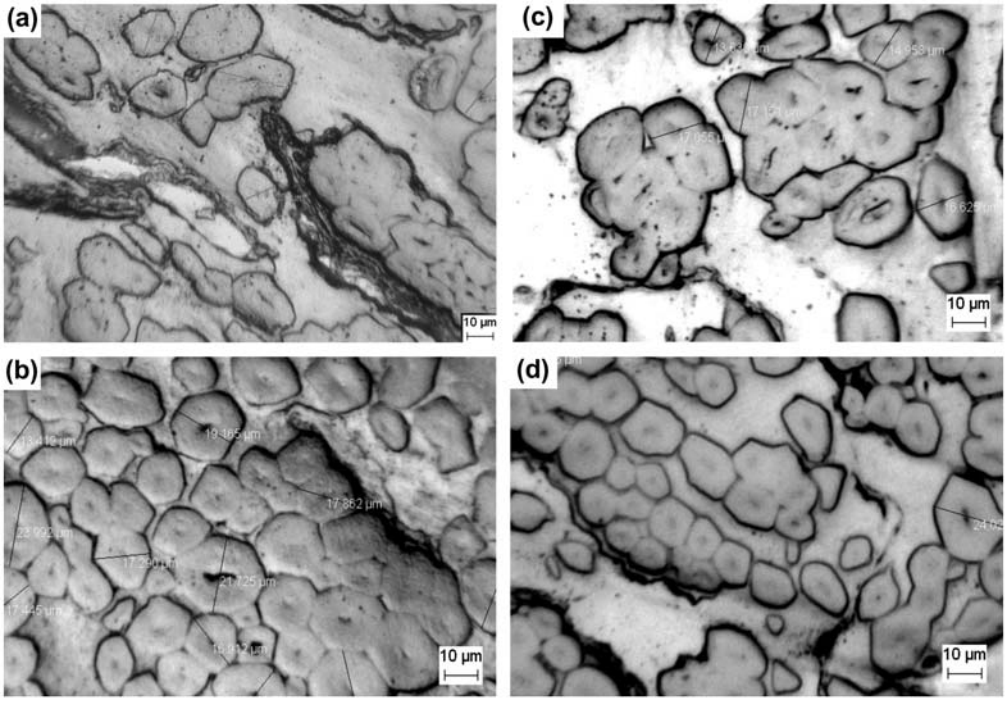

Figure 7. Micrographs of Untreated and Treated Flax Fiber Composites: (a) untreated flax/VE; (b) hot water-treated flax/VE; (c) acetic anhydride-treated flax/VE and (d) acrylic acid-treated flax/VE.

acetic acid treated fibers appear to be more elongated and deformed than the other fibers. While improving the interfacial strength, the treatment can reduce the load bearing capability of the fiber if the fiber was damaged or modified by the treatment.

4. Conclusions

Flax fiber has shown promise as reinforcement in polymers, which confirms the previous studies. The specific properties of flax/VE are competitive with E-glass/VE composites, especially in specific flexural modulus and specific interfacial properties. The specific flexural strength and interfacial properties of acrylic acid treat flax/vinyl ester composites showed the best balance of property improvement compared with other flax composites. However, the degree of hydrolysis during acrylic acid treatment should be further investigated to better optimize properties in the future. The full realization of the mechanical properties of the flax fiber has not been possible, in spite of excellent initial fiber properties. The inherent nature of flax fiber to have variable characteristic within few millimeters can lead to variation in composite property. This is further complicated with variation in fiber properties due to fiber growth, processing, treatment, and composite manufacture. This nature of flax fiber has hindered wide spread industry adoption due to limitation in controlling end-product quality.

With increased research, more in-depth understanding of flax fiber, fiber-processing fiber treatment, and composite manufacture has been attained. While there is opportunity for optimization of these process, composites that exceed glass fiber composite in term of specific properties have already been achieved. The nature of flax fiber might limit the possibility of producing composites with properties similar to that of single fiber. However, current technology is capable of producing flax fiber composites with reasonable mechanical properties to be used in applications such as automotive, furniture, textile, structural, etc.

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