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EFFECT OF SALT-WATER AGING ON THE MECHANICAL PROPERTIES OF FLAX-WOVEN FABRIC-REINFORCED EPOXY COMPOSITES

VPLIV STARANJA S SLANO VODO NA MEHANSKE LASTNOSTI PLATNENEGA MATERIALA OJAČANEGA Z EPOKSIDNIMI KOMPOZITI

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In this investigation four varieties of plain derived-irregular basket-woven-flax fabric-reinforced epoxy (F-E) composites pre-treated with alkali and trimethoxymethylsilane (ATS) were prepared with a hand lay-up process by varying their weight fraction of fiber loadings (0; 25; 35; 45) *w*/%. A water-absorption test (salt water) as per ASTM D 570-98 was performed over the fabricated composites and studied its consequences on their static mechanical properties (such as tensile, flexural, impact and interlaminar shear strength) in accordance with the ASTM standards. The results revealed that salt-water-soaked ATS-treated F-E composites exhibited poorer mechanical properties than unsoaked ones. Moreover, this study elaborated the kinetics of water absorption and showed that the moisture-absorption rate depends on the weight fraction of fibre content. Furthermore, scanning electron microscopy (SEM) disclosed fiber splittings and severe damage at the fiber-matrix interface as experienced by soaked F-E composites.

Keywords: flax/epoxy composites, DMA, moisture absorption, silane treatment, NFRP

V članku je predstavljena raziskava štirih različnih vrst sestave tkanih platen za koše, ojačanih z epoksijem (F-E), ki so jih predhodno obdelali z alkalno raztopino (NaOH) in trimetoksimetilsilanom (ATS). V procesu izdelave so bili uporabljeni različni delež vlaken (0; 25; 35; 45) masnih %. Avtorji so izvedli teste absorpcije po standardu ASTM D 570-98 na izdelanih kompozitih in preučevali njen vpliv na njihove statične mehanskih lastnosti (natezna in upogibna trdnost, udarna in medlamelarna strižna trdnost) v skladu z ASTM standardi. Rezultati preiskav so pokazali, da imajo s slano vodo namočeni in z ATS obdelani F-E kompoziti slabše mehanske lastnosti v primerjavi z nenamočenimi. Preučevana je bila tudi kinetika absorpcije vode. Ugotovljeno je bilo, da je hitrost le-te odvisna od vsebnosti vlaken v kompozitu. Opazovanja z vrstičnim elektronskim mikroskopom (SEM) so pokazala, da prihaja do cepljenja vlaken in resnih poškodb na meji med vlakni in matrico pri z vodo namočenih F-E kompozitih.

Ključne besede: kompoziti platno/epoksi, DMA, absorpcija vlage, obdelava s silanom, NFRP

1 INTRODUCTION

In recent years, employing flax fiber as a potential alternative to a synthetic fiber such as carbon fiber and glass fiber in the making of fiber-reinforced polymer composites (FRPCs) have gained attention among researchers.[1,2] Flax fibers possess a few unique properties e.g., low density, low cost and biodegradability (i.e., easy disposal at end of life) compared to glass and carbon fibers.[3] However, flax fibers tend to have high water absorption owing to their porous structure.[4,5] Thus, the interaction between hydrophobic matrix and hydrophilic flax fiber deteriorates leading to a poor fiber and matrix interface, dimensional instability, severe matrix damage, and eventually the mechanical properties of flax-fiber-reinforced polymer composites suffer.[6,7] There are some experimental studies pertaining to the effect of moisture absorption on the mechanical behaviour of natural fiber-reinforced polymer (NFRP) composites. E. Munoz et al.[8] demonstrated the effect of water absorption on the mechanical properties of flax-woven fiber-reinforced bio-epoxy composites. K Mak et al.[9] explored the comparison studies between flax-fiber-reinforced polymer composites and glass-fiber-reinforced polymer composites to understand the effect of short- and long-term exposure in a salt-water environment (at high temperature) on their tensile properties. M Gupta et al.[10] studied experimentally the effect of varying the unidirectional sisal fiber content (w/%) on moisture absorption, the mechanical and dynamic mechanical behavior of the sisal/epoxy composites. Rajeshkumar[11] in his study confirms that the moisture-absorption rate of Phoenix sp. fiber-reinforced epoxy composite increases with an increase in the fiber-volume fraction, fiber dimension (length), and immersion temperature (10 °C to 60 °C) as a result of which the tensile strength and flexural strength of the moisture absorbed sample drops to 15 % and 7 %, re-

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spectively. However, such drops are not very significant in NaOH (alkali) treated composites.

The properties of NFRP composites are based on the matrix, fiber and fiber-matrix interface. The interfacial bonding of the fiber and matrix in the composite plays a very critical role in the materials.[12,13] In NFRP composites, many problems occur at the fiber and matrix interface owing to incompatibility.[13,14] Hence, the surface modification of fiber by means of a chemical treatment is done to improve the compatibility and interfacial bonding strength of the NFRP composites. However, the type of chemical treatments, processing conditions and fiber morphology influence the surface of the natural fibers.[15] The alkaline treatment of fibers following a coating with silane coupling agents are considered as an effective method for improving their surface properties and more importantly, the interfacial bonding of composites is improved and so the mechanical properties of the NFRP composites, though they are subjected to different environmental conditions.[15,16] For instance, P K Kushwaha et al.[17] explored the effect of alkali and different silane (coupling agent) treatments on the water-absorption property of bamboo-mat-reinforced polyester composites. The experimental result showed that the alkali treatment reduced the water absorption in the bamboo composite by 35 % to 51 %. A further heavy reduction in the water uptake was observed for silane-treated bamboo/polyester composites, especially aminopropyl triethoxysilane-treated bamboo composites. M H Ja et al.[18] experimentally studied the effect of moisture absorption on the mechanical properties of the untreated and NaOH-treated Napier grass-fiber-reinforced polyester composites. The result showed that untreated composites absorbs more moisture content than the NaOH-treated composites. Moreover, the water-absorption behavior of the composites obeyed a Fickian diffusion mechanism. Also, the study showed that an increase in the water-absorption rate reduced the mechanical performance of the composites is attributed to an excess of the moisture absorption, which leads to the swelling of fiber, resulting in the formation of micro cracks in the matrix. This facilitates the waters to easily penetrate inside the composites, resulting in the debonding of the fiber and the matrix. M Gupta et al.[19] fabricated short-fiber (10 mm) sisal-reinforced polyester composites to evaluate the effect of PLA and alkali treatments on the water absorption, static and dynamic mechanical properties of the composites. Their investigation revealed that PLA-coated sisal/polyester composites showed water resistance, tensile strength, flexural strength and impact strength of the PLA-coated sisal/polyester composites were enhanced by 33 %, 49 %, 48 %, and 27 %, respectively, compared to the untreated composites. The DMA properties of the composites also improved over the untreated and alkali-treated composites. Hestiawan[20] studied the effect of alkali and alkali-silane treatments on the thermal, mechanical and moisture-absorption (salt water) behavior of woven-fan palm-fibers-reinforced polyester composites. The result reveals that the treated composites exhibited a higher tensile and flexural property than the untreated composites. Salt-water-immersed composites provided lower mechanical properties than the dry composites; however, the treated composites showed good resistance to moisture absorption

From the literature survey it is identified that there are several factors influencing the properties of the NFRP composites, namely, fiber length, concentration (w/%) of coupling agents, types of chemical treatment, volume of fiber and matrix. processing conditions, methods of fabrication, woven architecture of the fabrics, aerial density of the fabrics, direction of fibers, hybridization of fibers, etc. From the previous report presented by the authors,[15] it was found that epoxy composites reinforced with novel-irregular basket-woven flax fabric (plain derived) exhibited superior static and dynamic mechanical properties than other NFRP composites. Hence, here we have extended our previous investigation to explore the effect of salt-water absorption on the static mechanical properties of the same ATS-treated F-E composites. To the best of the authors' knowledge, such a study has not been reported in the literature.

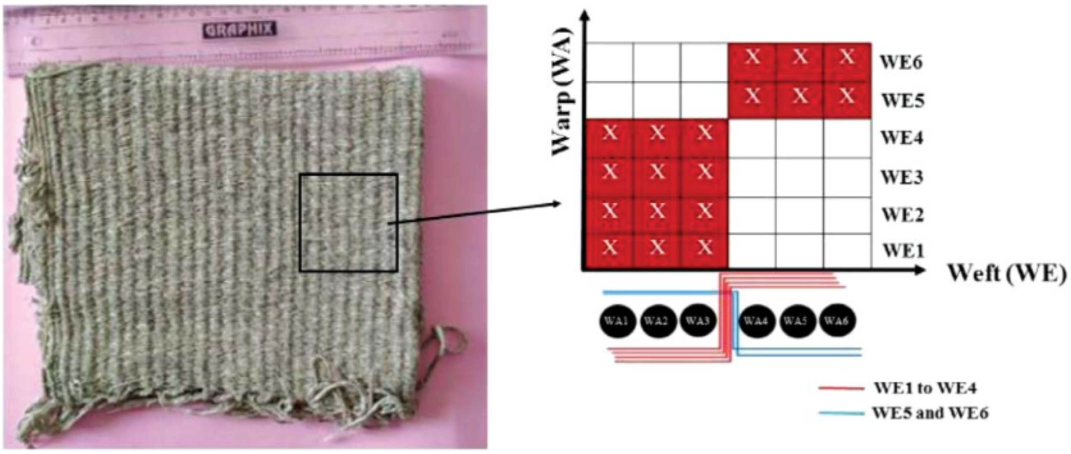

Figure 1: Plain derived Irregular basket woven flax fabric

2 EXPERIMENTAL PART

2.1 Materials

In this study, flax yarn of 6LEA was procured from a local vendor and weaved into a plain derivative form of irregular basket woven (4/2) (as shown in the **Figure 1**) using a sophisticated table-top loom (Make: ERGO G2). The aerial density of the woven plain derived fabric was 578 g/m^2 with ends per inch (EPI) and picks per inch (PPI) as 12 and 36 respectively. Sodium hydroxide and trimethoxymethylsilane, employed for chemical treatment of fabric, was supplied by Precision scientific co, Coimbatore, India. The polymer matrix used for the fabrication of the F-E laminates is epoxy resin (grade VBR 8912) with hardener VBR1209.

2.2 Chemical treatment of the flax fibers

2.2.1 Alkaline treatment

Flax fabrics were soaked in a 2 % concentration of sodium hydroxide (NaOH) solution at room temperature for 60 min. Then, it was thoroughly washed using distilled water to ensure the maximum cleaning of NaOH sticking on its surfaces. A few drops of acetic acid were added to the distilled water to further enhance the removal process of NaOH from the fibers. During this process, the pH of the water was maintained at 7 and finally washed fabrics were kept for drying in an oven at 65 °C for 24 h.

2.2.2 Trimethoxymethylsilane treatment

The surface of the flax fibers (alkalized) was further coated with a trimethoxymethylsilane coupling agent. Alkalized flax fabrics were immersed for 60 min. in a silane solution containing 0.1 % of trimethoxymethylsilane in an acidified distil water (volume basis). These treated fabrics were dried in an oven for 24 h at 65 °C.

2.3 Fabrication of the ATS treated F-E Composites

Figure 2 illustrates the complete steps involved in the fabrication of the composites with their outcomes. In this study, the fabrication of the F-E composites was accomplished with a hand lay-up process, followed by curing under compression in a moulding machine. At the outset, the lower mild steel mould (250 mm × 250 mm × 35 mm) was coated with silicone spray over laid with Teflon sheet as the mould-releasing agents. The required quantities of resin and hardener were premixed and impregnated with the known weight of the fabric. The resin-impregnated fabric was stacked one above the other up to four layers on the Teflon sheet and cured under compression (17.5 bars) in the mould machine for 24 h at room temperature (27 °C). The cured laminates were released from the mould and cut in accordance with the ASTM standard for evaluating the effect of water absorption on the static mechanical properties of the F-E composites. **Table 1** provides the composition of the ATS-treated F-E composites.

Table 1: Composition of the ATS treated F-E composites

Sample Code	Weight percentage (w/%)		Fabric layers used	Density of the composites (g/cm^3)		
	Flax fiber	Epoxy resin		Experimental density	Theoretical density	Void (%)
Neat Epoxy	0	100	4	1.16	1.22	4.91
25-TFE	25	75	4	1.19	1.24	4.03
35-TFE	35	65	4	1.21	1.27	4.73
45-TFE	45	55	4	1.30	1.34	2.98

2.4 Water-absorption test

The water-absorption test of F-E composites was conducted in accordance with ASTM D 570-98. The

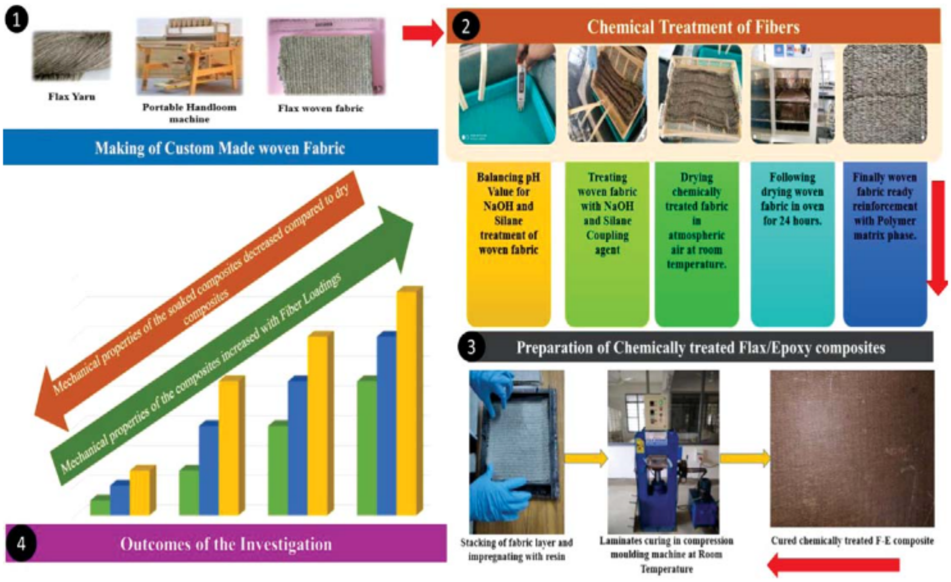

Figure 2: Steps involved in the preparation of flax-epoxy composites

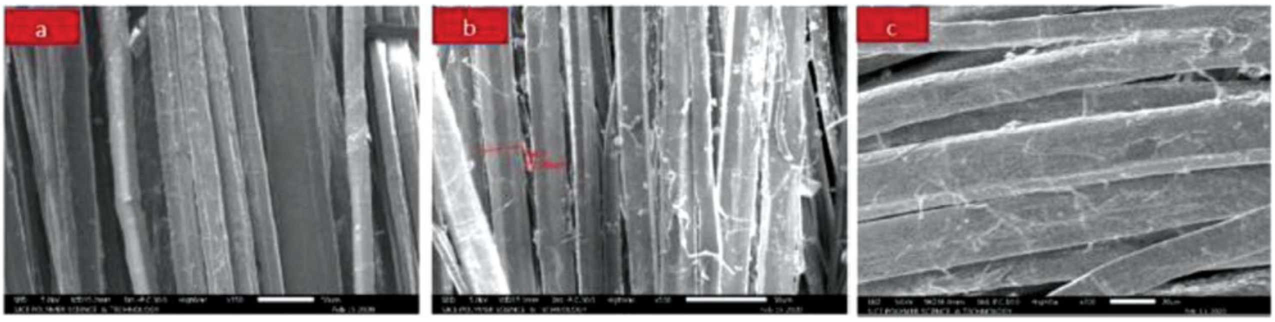

Figure 3: SEM images of flax fiber: a) raw/untreated, b) 2 % NaOH treated, c) NaOH-Silane treated

weight of the F-E composite specimens are noted before being immersed in salt water (room temperature). After 24 h of immersion the specimens were taken off and wiped with tissue paper to remove the water from their surface. These composite specimens were re-weighed using an analytical weighing balance with a resolution of 0.001 mg. In this way, at every regular interval of 24-h, the composite specimen's weight is measured until it reaches an equilibrium value. The percentage weight gain of the F-E specimen is computed using Equation (1).

$$M_{\mathrm{t}} = \frac{w_{\mathrm{t}} - w_0}{w_0} \times 100 \qquad (1)$$

where M_{t} – moisture percentage gain, w_{t} – mass of the F-E specimen at different time intervals during aging, and w_{o} – mass of the F-E specimen before aging.

2.5 Testing of Mechanical Properties

Four different mechanical properties of the F-E composites analysed in the present work are tensile, flexural, impact and inter-laminar shear strength (ILSS). The tensile test is conducted as per the ASTM D-638-14 standard, while the flexural strength (3-point bending test) is conducted in accordance with the ASTM D-790-10 standard. The Izod-impact test and the ILSS is conducted as per the ASTM D-256-10 and ASTM D2344 standards, respectively.

3 RESULTS AND DISCUSSION

3.1 Surface morphology of the Flax fiber

Figure 3a to **3c** present the SEM images of the untreated and chemically treated flax fibers. Raw fibers have inherently possessed surface roughness characteristics owing to the presence of wax, lignin, oil and other non-cellulosic content and these were removed from the NaOH treatment. From **Figure 3b** of the 2 % NaOH treated fiber it is evident that treated fiber shows a few ridges due to the elimination of non-cellulosic and wax contents, which are likely to enhance the better interlocking between fiber and resin.

3.2 Effect of fiber content on water-absorption behavior of F-E composites

Natural fibers have a tendency to absorb moisture when they are exposed to close contact with the water environment since the natural fibers are hydrophilic in nature due to the presence of hydroxyl groups. So it is very imperative to understand their behavior as reinforced with matrix phase of the composites. Water absorption in the NFRP composites depends on how well the diffusion of water molecules takes place between the micro gaps of the polymer chains and also around the fiber-matrix interface. Furthermore, it also relied on the propagation of the micro crack attributed to swelling of the fibers.[21] **Figure 4** shows the variation of the water absorption versus immersion time for the ATS-treated F-E composites after being immersed in salt water. It is evident that, water absorption in the composites increased with an increase in the immersion period until it reaches the saturation time and thereafter it remained constant. The saturation time varies based on the composition of the composites and the environmental conditions to which the specimens are exposed. It is evident from **Figure 4** that as the flax fiber content in the epoxy increases, the water absorption rate also increases. This may be because of increasing in the cellulose content favouring F-E composites to absorb more moisture. Moreover, an increase in fiber content paves the way for im-

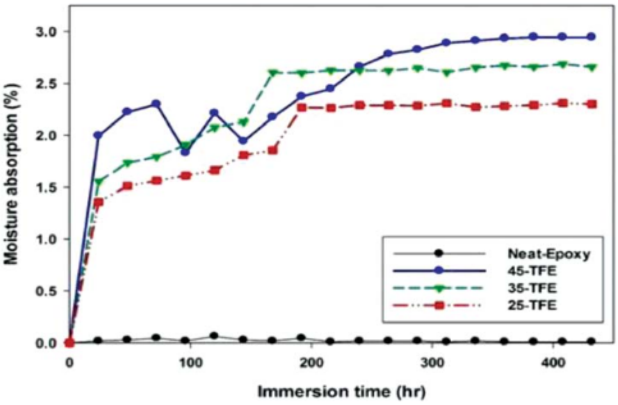

Figure 4: Water absorption (%) versus immersion time during salt-water ageing of ATS-treated F-E composites

proving the fiber-fiber interconnection owing to incomplete wetting of the fabric by epoxy resin. This mechanism could also have possibly enhanced the moisture absorption rate of the highest fiber loaded F-E composites. Another reason may be the presence of micro-crack in the composites.

3.3 Moisture Absorption Kinetics of the ATS treated F-E composites

Generally, water absorption in the NFRP composites takes place by means of the following mechanisms:

a) Movement of the water molecules through the micro gap of the resin chain,
b) Diffusion of water molecules through weakest interfacial region due to poor fiber-matrix bonding,
c) Diffusion of water molecules by means of voids and micro-crack of the matrix phase.

Despite knowing the mechanisms are not enough to understand the water-absorption behavior of the composites until their diffusion mechanisms are modelled. Experimental absorption data has been fitted to Equation (2) in order to clearly understand the diffusion mechanisms endured by the ATS-treated F-E composites.

$$\log\left(\frac{M_\mathrm{t}}{M_\mathrm{s}}\right) = \log(k) + n\log(t) \tag{2}$$

where M_t and M_s indicates the moisture absorption at time t and the saturated moisture absorption respectively. Whereas *k*, and *n* are constant.

The constant '*k*' denotes the interaction between the composite sample and water, whereas '*n*' indicates the kind of transport mechanism taking place inside the composite. These aforementioned constants are determined for F-E composites by the fitting the curve of log ($M_\mathrm{t}/M_\mathrm{s}$) vs log ($t$). According to Equation (2), if $n = 0.5$, then water absorption obeys the Fickian diffusion; if *n* lies between 0.5 and 1, then water absorption follows non-Fickian diffusion. If $n > 1$, then diffusion is said to be anomalous. The values of the *n* and *K* for ATS-treated F-E composites are shown in Table 2. Constant n values of the composites are close to 0.3, which means that, composites have exhibited pseudo-fickian diffusion behavior, which is as similar to Fickian behavior. The kinetics of the water-absorption constants and the transportation coefficients (*D*, *S* and *P*) obtained in the present investigation is in consistent with the result presented by other researchers.[22,23] Further it can also be noted that the '*n*' value decreases with increasing in the fiber content, resulting in more diffusion of the water absorption.[23]

Insight concerning the ability of the water molecules to enter the composite sample is studied by the important factor of diffusion model, called the diffusion coefficient (D), which is determined using Equation (3).

$$D = \pi\cdot\left[\frac{h}{4M_\mathrm{m}}\right]^2\left[\frac{M_2 - M_1}{\sqrt{t_2} - \sqrt{t_1}}\right]^2 \tag{3}$$

where, *h* indicates the specimen thickness (mm), M_m indicates the saturation value of the moisture absorption, and M_2 and M_1 represent the moisture-absorption percentage at moisture times t_2 and t_1 respectively.

The diffusion coefficient (*D*) value of the epoxy and its composites are presented in the **Table 2** and it is evident that the incremental rise in the fiber content, increases the diffusion coefficient (*D*). Amongst the fabricated lot, 45-TFE composites showed the highest *D* value because the cellulose content is increased due to the increase in the fiber loading, resulting in a higher diffusivity. Another important factor to be considered while studying the effect of water absorption in NFRP composites is the sorption coefficient (*S*) (or absorption coefficient) and it is computed using Equation (4).

$$S = \frac{M_\infty}{M_\mathrm{p}} \tag{4}$$

where *S* is the sorption coefficient, M_∞ and M_p indicate the mass of solvent (water) taken up at the equilibrium swelling and the mass of the sample.

The determined values of the sorption coefficient (*S*) for the F-E composites are depicted in **Table 2** and it is clear that the *S* value increases with an increase in the fiber. Moreover, the sorption coefficient follows the trend of the diffusion coefficient (*D*). Overall, the net effect of the sorption and diffusion is studied by the term "Permeability coefficient". It can be expressed as (Equation (5))

$$P = D \times S \tag{5}$$

From **Table 2** it is evident that *P* increases with increases in the fiber content. The highest *P* value can be noticed for 45-TFE composites, whereas neat epoxy showed the very least among the prepared composites.

Table 2: Water absorption properties of the epoxy and F-E composites during salt-water ageing condition

Types of Composites	Kinetics of Water absorption		Transportation Coefficients		
	n	*k*	*D* (mm²/s)	*S* (g/g)	*P* (mm²/s)
Neat Epoxy	0.205	0.136	3.316×10^{-07}	0.001	3.31×10^{-10}
25-TFE	0.218	0.552	4.663×10^{-06}	0.0230	1.07×10^{-07}
35-TFE	0.216	0.547	5.384×10^{-06}	0.0266	1.43×10^{-07}
45-TFE	0.224	0.565	6.121×10^{-06}	0.0294	1.84×10^{-07}

3.4 Effect of moisture absorption on the mechanical properties of the ATS-treated F-E composites

3.4.1 Effect of moisture absorption on the tensile property

Figure 5 shows the effect of the salt-water aging on the tensile strength of the epoxy and ATS-treated F-E composites. The tensile strength of the composites increased with an increase in the fiber content. All the fab-

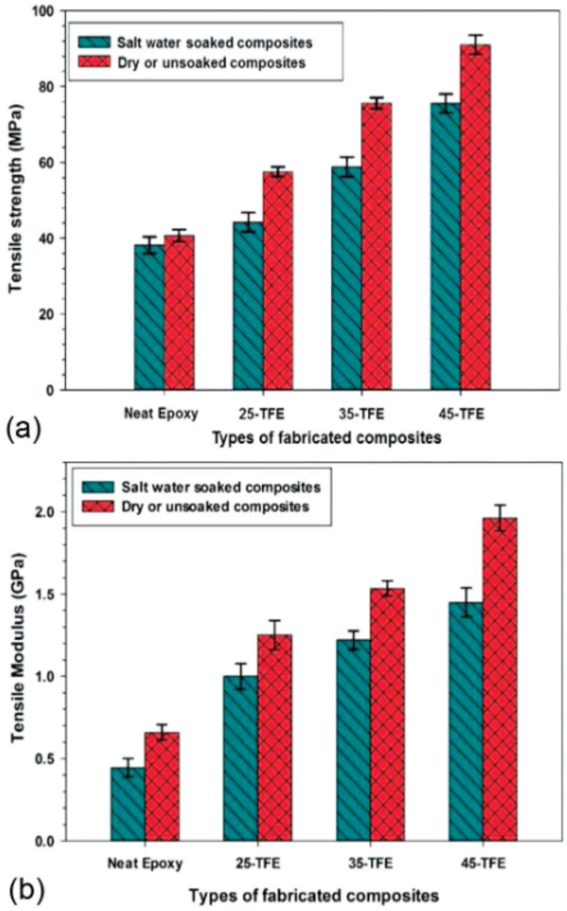

Figure 5: Variation of the tensile strength and tensile modulus of the soaked and unsoaked ATS-treated F-E composites

ricated samples are subjected to the salt-water immersion for a period of 432 h. **Figure 5** clearly indicates that, soaked composite samples have less tensile strength than the dry or unsoaked ones. This is because the epoxy matrix may have experienced huge swelling due to long exposure to the salt-water environment. In general, all inorganic polymer tends to absorb moisture, resulting in swelling and dissolving mechanisms thus, the mechanical properties of the composite decreases. However, on the other hand, natural fiber has higher affinity towards moisture absorption than the matrix phase. Because of this characteristic, water molecules effortlessly enter the interfacial zone of the fiber and the matrix. And in that case, if there is an existence of the poor interfacial bonding, then diffused water molecules sabotage the fiber and matrix interface, which eventually paves the way for a reduction of the mechanical properties of the composites. Similar findings were presented by the other researchers.[24,25] According to Sombatsompop & Chaochanchaikul,[26] moisture absorbed composite samples can experience a lubricant effect as imparted by the diffused water molecules (moisture), causing intense deterioration of the composite's interfacial bonding and therefore the tensile strength decreases. However, among the prepared samples, neat epoxy has not shown the least difference in tensile strength before and after immersion because moisture absorption capacity of the polymer is less compared to that of the reinforcement member.[27]

The tensile-modulus behavior of the ATS-treated F-E composites before and after salt-water aging has shown similar trend to that of the tensile strength. It is evident from **Figure 5** that the modulus of the F-E composites increased with increase in the flax fiber content and moreover, a lower tensile modulus is observed for the F-E soaked sample compared to the unsoaked ones. This may be due to the formation of hydrogen between flax fiber and water molecule.[27] In addition to that, diffused water molecules may have altered the physical bonding at the fiber-matrix interfacial region by promoting the lubricant effect, thereby isolated the flax fiber from the epoxy. In other words, a decrease in the modulus has occurred as a result of the interfacial degradation of the fiber-matrix interface. The maximum decrease in the tensile modulus as a result of salt-water aging for F-E composites and neat epoxy is 33.2 % and 31 %, respectively.

3.4.2 Effect of moisture absorption on the flexural property of the ATS-treated F-E composites

Figure 6 depicts that flexural strength of the F-E composites increased with an increase in the fiber con-

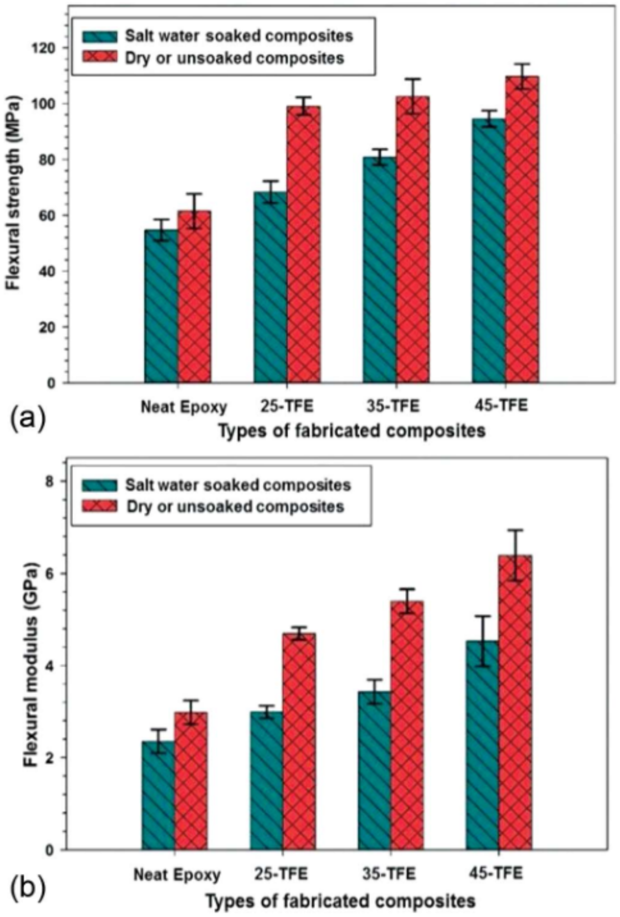

Figure 6: Variation of the flexural strength and flexural modulus of the soaked and unsoaked ATS-treated F-E composites

tent and moreover, soaked F-E samples exhibited a lower flexural strength than the unsoaked ones, which clearly conveys the bending strength has been significantly affected by the moisture uptake as similar to the tensile property. Among the prepared F-E composites, the highest margin decrement (37.2 %) of the flexural strength is exhibited by 25 *w*/% of F-E composites (25-TFE). This clearly suggests that, voids have played a significant role in the deterioration of the mechanical properties among the soaked or moisture-absorbed F-E composites.[25] The tensile and flexural properties of the F-E composites are fiber dependent and fibers are vulnerable to moisture absorption, causing severe interfacial damage of the fiber-matrix region and such zones are so weak that they are susceptible to easy failure when soaked composites were subjected to a bending load. Therefore, salt water conditioned ATS treated F-E composites exhibited lower flexural strength than unsoaked composites.[25] Furthermore, acceleration of the diffused water molecules inside the polymer chain increases the matrix cracking, leading to the degradation of the tensile and flexural strength. Similar observations were reported by the other researchers.[28]

Figure 6 conveys that the flexural modulus of the F-E composites has shown similar trend as that of the flexural strength. Higher flexural modulus is exhibited by 45-TFE composites under both environmental conditions. Similar to the flexural strength, decrease in the flexural modulus was experienced by the moisture-absorbed F-E composites, which is attributed to the degradation of the interfacial bonding of fiber-matrix as a result of the diffusion of the absorbed water molecules.

3.4.3 Effect of moisture absorption on the impact property of the ATS-treated F-E composites

Figure 7 shows the impact strength of the ATS-treated F-E composites increased with an increase in the fiber content (w/%) and this trend is applicable for both salt-water soaked and unsoaked samples. The highest impact strength is noticed for the 45-TFE composites and the lowest for neat epoxy. This clearly suggests that the brittleness of the epoxy material has been improved by the reinforcement of the chemically treated woven flax fabric. It means in other words: toughness of the composites has been enhanced. As similar to that of tensile and flexural property, the impact strength has also been influenced by the moisture-absorption ambiance. This may be attributed to the fact that, damaged interfacial bonding of the fiber and the matrix encouraged poor stress transmission between the matrix and reinforcement phase.[29] Moreover, polymer composites plasticize when they are subjected to water immersion.

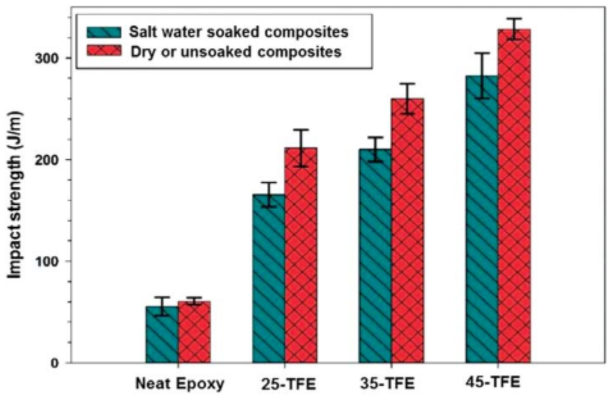

Figure 7: Variation of the impact strength of the soaked and unsoaked ATS-treated F-E composites

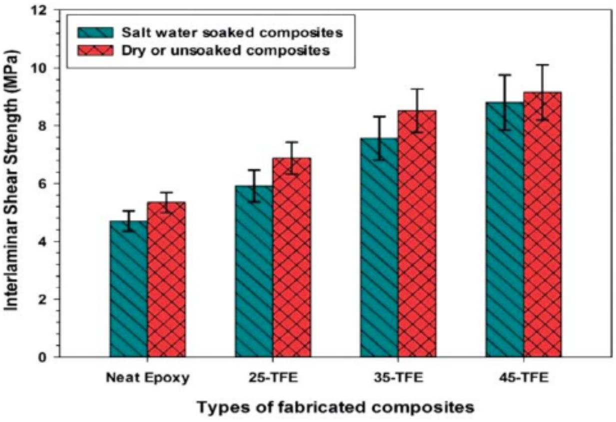

Figure 8: Variation of the ILSS of the soaked and unsoaked ATS-treated F-E composites

3.4.4 Effect on moisture absorption on ILSS property of the ATS-treated F-E composites

Figure 8 shows that the ILSS of the dry F-E composites increased with an increase in the fiber content and such a trend has been observed by water-soaked F-E samples too. A marginal improvement in ILSS is exhibited by the 35-TFE composites when compared between the soaked and unsoaked samples. The decreased ILSS observed for the soaked sample over the unsoaked F-E composites can be attributed to the deterioration of the interfacial region of the fiber and matrix and another reason is that the F-E composites could have endured plasticizing. Furthermore, immersed 45-TFE composites have not shown much difference in the ILSS compared to the dry or unsoaked composites. This may be because, as intake amount of the water absorption increases, the swelling of the fiber also increases, resulting in the reduction of fiber and matrix gap, which eventually assists the composite material to show some resistance for the applied load.

3.4.5 Fractography analysis

Figure 9 shows the SEM images of the moisture-absorbed 45-TFE composites fractured during the tensile test. It is clear from the micrograph that the matrix damage followed by the changes in the morphology of the fiber indicates that, moisture uptake has influenced to deterioration of the interfacial bonding. Moreover, water immersion has led the flax fiber surface rougher and lit-

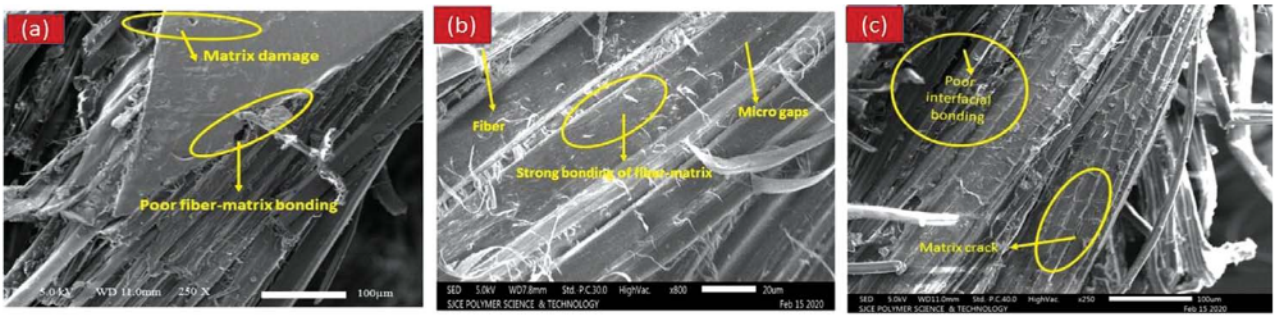

Figure 9: SEM images of the mechanically fractured salt water soaked F-E composites: a) 45-TFE tensile tested (250×), b) 45-TFE flexural tested (800×), c) 45-TFE impact tested (250×)

tle porous and even splitting into thin fibrils and it is clearly evident from the SEM pictures. Furthermore, from the micrographs it can be observed that there is a micron level gap between the fiber and the matrix, indicating dimensional instability has occurred as a result of the water absorption. Besides, it can also be noted that very fine thread of the fibrils is present on the surface of the aged fractured specimen. This is perhaps owing to the polymer dissolution.

4 CONCLUSIONS

The static mechanical behavior of the ATS-treated F-E composites under salt-water aging was systematically studied as per the ASTM standards and their conclusions are outlined as follows:

Water absorption study showed that the moisture absorption rate of the F-E composites increased with an increase in the fiber content. Furthermore, the kinetics of the water absorption demonstrated that transportation coefficients such diffusion coefficient (D), sorption coefficient (S) and permeability coefficient (P) were highly influenced by the salt-water aging. These values were found to be increased with an increase in the fiber content of the composites. The maximum values were found for 45-TFE composites owing to their higher cellulose content.

The mechanical properties of the F-E composites were increased with an increase in the fiber content, regardless of their aging conditions. The mechanical test results showed that neat epoxy material was least affected during water aging in contrast to other composites since they are hydrophobic by nature.

Both soaked and unsoaked 45-TFE composites showed a higher tensile, flexural, impact and ILSS property than other F-E composites. It was evident from the investigation that, moisture absorbed F-E composites suffers to exhibit better performance due to the deterioration of the fiber and matrix interface, despite the fibers being treated with a coupling agent. This was further clearly exposed by their fractured surfaces through SEM images.

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