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Influence of Water Aging on The Mode-I Fracture Toughness of Intraply Hybrid Carbon/Aramid/Elium Composites

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ABSTRACT

In this study, the fracture behavior of carbon/aramid intraply hybrid fiber-reinforced composites with a thermoplastic Elium matrix was investigated using the double-cantilever beam test. The composites were aged in distilled water for up to 6 months, and the fracture performance of unaged samples was compared with those aged for 2, 4, and 6 months. The maximum force and Mode-I fracture toughness of unaged samples were 152.84 N and 1131.43 J/m^2, respectively. After aging, these values increased by 26.99% and 32.14%, reaching 194.09 N and 1495.11 J/m^2, respectively. Notably, water aging positively affected the interlaminar delamination behavior of carbon/aramid/Elium composites. The findings of this study demonstrate that Elium matrix hybrid composites are a promising alternative for real-world applications in demanding environments such as marine and automotive, as their interlaminar fracture toughness increases even after water aging.

Suda Yaşlandırmanın Katman İçi Hibrit Karbon/Aramid/Elium Kompozitlerin Mod-I Kırılma Tokluğu Üzerindeki Etkisi

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ÖZ

Bu çalışmada, termoplastik Elium matrisli karbon/aramid katman içi hibrit fiber takviyeli kompozitlerin kırılma davranışı çift ankastre kiriş testi yapılarak incelenmiştir. Kompozitler, 6 aya kadar damıtılmış suda yaşlandırılmıştır ve yaşlandırılmamış numunelerin kırılma performansı, 2, 4 ve 6 ay boyunca yaşlandırılmış numunelerle karşılaştırılmıştır. Yaşlandırılmamış numunelerde maksimum kuvvet ve Mod-I kırılma tokluğu sırasıyla 152,84 N ve 1131,43 J/m^2 olarak bulunmuştur. Yaşlandırma sonrasında bu değerler sırasıyla %26,99 ve %32,14 artarak 194,09 N ve 1495,11 J/m^2'ye ulaşmıştır. Sonuç olarak, su yaşlandırması karbon/aramid/Elium kompozitlerinin tabakalar arası ayrılma davranışı üzerinde olumlu bir etki yapmıştır. Bu çalışmanın bulguları, Elium matris hibrit kompozitlerin, suda yaşlanma sonrasında bile tabakalar arası kırılma tokluğunun artması nedeniyle, denizcilik ve otomotiv gibi zorlu ortamlarda gerçek dünya uygulamaları için umut verici bir alternatif olduğunu göstermektedir.

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1. Introduction

Composites are engineered materials created by combining a matrix and reinforcements to achieve properties that individual or traditional materials lack (Karacor et al., 2020). Composites can be classified based on the type of matrix material as polymer, metal, or ceramic composites, and based on their structural components as fiber or particle reinforced, and laminated composites (Unal et al., 2022; Yalcin et al., 2024). Thermoplastic composites are more advantageous than thermoset composites because they are formable, recyclable, and repairable (Kaybal and Ulus, 2024).

Fiber-reinforced polymeric (FRP) composites are becoming widely used in a range of industries such as military, defense, aerospace, aeronautics, automotive, and energy for their lightweight and superior strength and durability properties (Coskun and Sahin, 2022; Bandaru et al., 2023). Thanks to their outstanding chemical resistance and exceptional thermal performance, FRP composites have found broad application across various sectors, including construction, architecture, food, and chemical industry (Sukur et al., 2020; Adem et al., 2025).

Carbon fibers are known for their strength, stiffness, and lightness, but are limited in energy absorption and impact resistance. Aramid fibers are recognized for their high energy absorption and impact resistance (Dharmavarapu and MBS, 2022). A combination of different fibers can be used to optimize mechanical properties, and hybrid structures containing two types of fibers can achieve superior properties (Cetin et al., 2022; Demir et al., 2023). Laminated composites are produced as interply (stacking different fabric layers on top of each other) or intraply (intra-layer hybrid fabric where the same layer is woven with different material warp and weft yarns) hybridization (Deniz and Karakuzu, 2025). Although there are studies that have characterized the properties of both interply and intraply Carbon/Aramid (CA) hybrid composites, this study is only considered for intraply CA hybrid FRP composites.

Kim et al. (2011) investigated the tensile properties of intraply CA fiber-reinforced epoxy composites and reported that fiber orientation significantly influenced tensile strength and modulus. In a later study, Kim et al. (2023) produced both interply and intraply composites via the resin infusion method and found that intraply composites exhibited superior tensile performance when carbon fibers were aligned in the loading direction. Alsaadi et al. conducted a series of studies examining the influence of hybridization with glass fibers and the addition of nano-silica and nano-clay particles on the tensile and flexural behavior of CA composites (Alsaadi et al., 2018; Alsaadi et al., 2020). Improvements up to 20-35% in mechanical performance were reported with appropriate nanoparticle content. Sebaey and Wagih (2019) compared the flexural response of intraply and sandwich composites, noting different damage mechanisms and higher specific strength in sandwich structures. Yin et al. (2021) demonstrated that fiber orientation affected flexural strength, with carbon fiber direction yielding higher values than aramid. Quanjin et al. (2020) highlighted the potential of CA composites in automotive crash box applications due to their lightweight and energy absorption capabilities. Qi et al. (2024) validated tensile, compressive, and shear properties through both experimental methods and finite element analysis, showing a strong correlation between predicted and measured results. These studies highlight the potential of intraply CA fiber composites as high-performance materials for advanced structural applications.

Failure of composite materials can occur in different ways depending on the type of loading applied. Various types of loading, such as tension, compression, bending, buckling, and impact, can cause different failure mechanisms in the material (Coskun et al., 2024; Sozen et al., 2024). Fracture damage is often seen in composite materials. This damage occurs due to structural deterioration caused by microcrack propagation and weaknesses at the fiber-matrix interface (Ulus et al., 2019). Different types of loads can cause delamination cracking in layered composites. This can happen through opening (Mode-I), sliding (Mode-II), or tearing (Mode-III) fracture modes, or a combination of them (Pietras et al., 2023). Opening mode is the fracture mode where interlaminar failure occurs most easily, and fracture toughness is the lowest, Double-Cantilever Beam (DCB) testing is a commonly used method to measure Mode-I interlaminar fracture toughness.

Bhudolia et al. (2016) experimentally investigated the critical mechanical properties for racket-like sports products. They manufactured carbon fiber-reinforced composites using both Elium and epoxy resins through vacuum-assisted resin infusion and conducted tensile, flexural, and DCB tests for comparison. Their findings highlighted the significantly superior potential of Elium resin in resisting crack propagation. In a subsequent study, Bhudolia et al. (2018) used Elium resin with carbon fiber and reported the excellent Mode-I interlaminar fracture performance of Elium-based composites. Barbosa et al. (2019) explored the damage mechanisms resulting from delamination in composite materials. They produced carbon fiber-reinforced Elium matrix composites via vacuum infusion and conducted Mode-II interlaminar fracture toughness tests. The results revealed that Elium composites were 40% more resistant to interlaminar failure compared to epoxy-based counterparts. In another study, Khan et al. (2022) introduced initial cracks in carbon fiber-reinforced Elium composites and subsequently post-cured the samples at various durations and temperatures above the glass transition temperature of Elium. Mode-I interlaminar fracture toughness was evaluated using DCB tests, and results indicated that higher post-curing temperatures and longer durations significantly enhanced fracture toughness values. Chen et al. (2024) investigated the interlaminar delamination characteristics of unidirectional carbon fiber-reinforced Elium matrix composites through DCB tests. Their findings demonstrated that strengthening the fiber–matrix interface bond significantly increased the Mode-I interlaminar fracture toughness of the composites. These comprehensive studies demonstrate that Elium resin offers superior mechanical performance compared to epoxy, particularly in terms of crack propagation resistance and interlaminar fracture toughness in FRP composites.

In terms of the fracture behavior of carbon and aramid FRP composites, Kim et al. (2011) investigated the performance of intraply CA fiber-reinforced epoxy matrix composites using DCB samples. Test results showed that carbon fiber-reinforced samples exhibited higher performance than the intraply hybrid ones, while aramid fiber-reinforced samples exhibited fiber splitting. Furthermore, the Mode-I fracture toughness of the CA hybrid was found to be approximately equal to the average of the individual carbon and aramid fiber-reinforced samples. In contrast, Rajasekar et al. (2019) reported that the Mode-I fracture toughness of CA fiber-reinforced epoxy composites was higher than that of both single-fiber counterparts. This improvement was attributed to the bridging effect and enhanced fiber-matrix interfacial bonding, suggesting that intraply hybridization contributes positively to delamination resistance. Pincheira et al. (2018) also experimentally examined the influence of aramid fibers in CA fiber-reinforced epoxy composites and compared the results to carbon fiber composites. Although a slight decrease in stiffness was observed due to the aramid fibers, a significant improvement in impact and fracture resistance was reported, owing to the ductile nature of aramid compared to carbon. This was highlighted as a valuable advantage for high-performance applications such as aerospace. Alsaadi and Erklig (2021) explored the fracture behavior of aramid and carbon fiber-reinforced epoxy composites, including the effect of silicon carbide particle reinforcement. Using DCB samples for Mode-I fracture tests, they observed stronger bonding of particles in aramid/epoxy composites compared to carbon/epoxy. Bulut et al. (2020) experimentally investigated the effect of nano-clay and nano-silica particle additions on CA fiber laminates. They found increased Mode-II fracture toughness with 1.5 wt.% nano-silica and 2 wt.% nano-clay, and also reported that higher nanoparticle content led to increased water absorption in both cases. These studies demonstrate that the integration of aramid and carbon fibers significantly enhances the fracture resistance and mechanical performance of composites. The findings underscore the potential of hybrid fiber-reinforced materials for improving delamination resistance and fracture toughness, particularly for high-performance applications such as aerospace, where both strength and durability are critical.

Water aging is a critical factor in evaluating the long-term performance and durability of composites, particularly in environments where exposure to moisture is inevitable. The effects of water aging on Elium matrix composites have been summarized in the following studies.

Barbosa et al. (2019) studied the effects of distilled water aging on layered composites, using carbon fiber-reinforced Elium and epoxy matrix composites. The results showed that Elium composites exhibited 30% higher tensile strength than epoxy composites for non-aged samples, with the difference reducing to 14% after 8 weeks of aging at +80 °C. Epoxy composites absorbed more water due to higher void content. Bel Haj Frej et al. (2021) investigated the impact of hydrothermal aging on carbon fiber-reinforced Elium matrix composites at +70 °C in deionized water, observing minimal changes in tensile properties but significant reductions in interlaminar shear values. Their subsequent study showed that higher aging temperatures led to more significant mechanical effects (Bel Haj Frej et al., 2021). Devine et al. (2023) researched the behavior of glass fiber-reinforced Elium and epoxy composites after immersion in seawater at +50 °C, finding minimal impact on mechanical properties. Das et al. (2023) studied the behavior of flax and glass fiber-reinforced Elium and epoxy composites after aging at +23, +40, and +60 °C, noting that flax fiber composites absorbed more water than glass fiber composites. Kumar et al. (2024) examined glass fiber-reinforced Elium composites after two months in seawater at

+55 °C, finding a 25.6% decrease in tensile strength and a 14.8% decrease in flexural strength. Hussnain et al. (2024) studied the properties of glass fiber-reinforced Elium composites after aging in seawater at +35 and +70 °C for up to 135 days, observing significant reductions in tensile strength and modulus at higher temperatures. A study by Mohamad et al. (2025) investigated the properties of basalt fiber-reinforced Elium and epoxy composites. These composites were aged in seawater at +45°C for 45 and 90 days. The study found that the Elium composites exhibited superior mechanical properties compared to the epoxy composites, both initially and after aging. Specifically, the tensile strength of the Elium composites was found to be 33% higher, and the flexural strength was 71% higher. Furthermore, the Elium composites showed a smaller reduction in mechanical properties due to aging. These studies highlight the significant impact of water aging on the mechanical properties of Elium matrix composites, demonstrating varying degrees of degradation depending on fiber type, aging conditions, and temperature. Notably, Elium composites consistently exhibit better performance in terms of water absorption and mechanical retention compared to traditional epoxy composites, positioning them as a promising material for applications in challenging environmental conditions (Devine et al., 2023). According to the best of the authors' knowledge, there are no studies investigating the Mode-I fracture behavior of thermoplastic Elium matrix reinforced with CA hybrid fibers. Thus, composite samples reinforced with intraply CA hybrid fibers in Elium matrix were manufactured, and their interlaminar delamination properties were investigated. Fracture tests were also performed on samples subjected to distilled water aging for 2, 4, and 6 months.

2. Material and Method

2.1. Production of Composites

In this study, Elium, a thermoplastic resin based on methyl methacrylate and developed by Arkema, with a density of 1.19 g/cm^3 and a maximum operating temperature of +85 ºC, which is preferred in the production of FRP composites by vacuum infusion method, was utilized (Han et al., 2020). CA intraply hybrid twill fabric, composed of 61% carbon and 39% aramid fiber and having an areal density of 210 g/m^2, was used as the reinforcement for Elium. This specific intraply structure was chosen because the homogeneous distribution of fibers within the hybrid layer leads to superior mechanical properties and enhanced fracture performance compared to interply composites (Meninno and Chalivendra, 2021; Altaee and Mostafa, 2023; Huang et al., 2025). All materials and consumables for manufacturing were supplied by Dost Kimya Co. Ltd.

The composite laminates were produced utilizing a hand lay-up assisted vacuum infusion method as illustrated in Figure 1. Initially, a mixture of Elium resin and hardener (2% dibenzoyl peroxide) was applied to the CA hybrid fiber layers with a roller to ensure uniform distribution (hand lay-up). Following this, the vacuum infusion process was carried out, where the resin was drawn into the dry fiber stack under vacuum, allowing thorough impregnation. In the production of plates for the DCB test, a pre-crack is required. For this purpose, during the production of the plates, after half of the fabrics were placed, the Polytetrafluoroethylene (PTFE) film shown in brown in Figure 2-a was placed. On top of the PTFE film, the mixture was applied again, and the fabrics were continued to be placed. During the vacuum infusion process, a vacuum was applied for approximately 30 minutes using Elium resin, which has a viscosity of 100 mPa·s (Brookfield LVF #2, 60 rpm). Once the resin flow was visually confirmed to have finished, the vacuum pump was turned off (Guzel, 2025). After the production process, the composites were left at room temperature for 24 hours for pre-curing, followed by a post-curing stage at +80 °C for 4 hours. Figure 2-b shows the vacuumed composite plate. The manufactured and cured composite laminates were cut according to the sample dimensions for DCB tests.

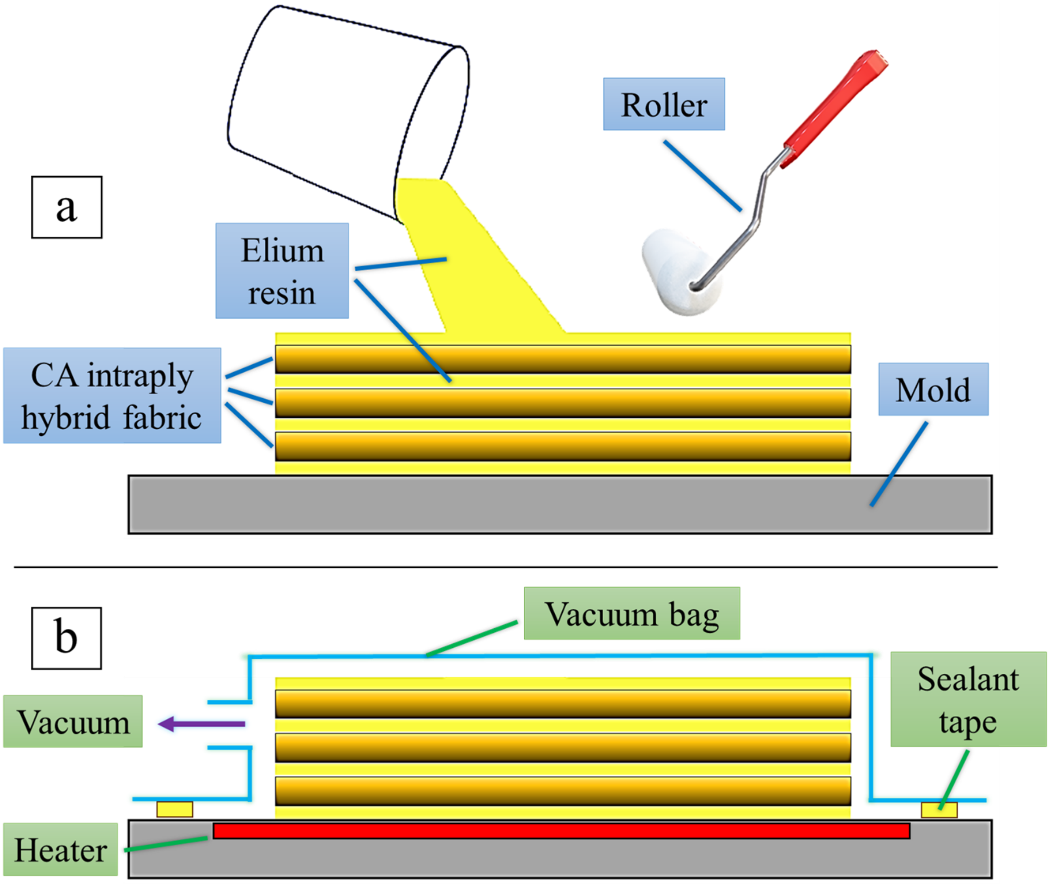

Figure 1. a) Hand lay-up, **b)** vacuum infusion method

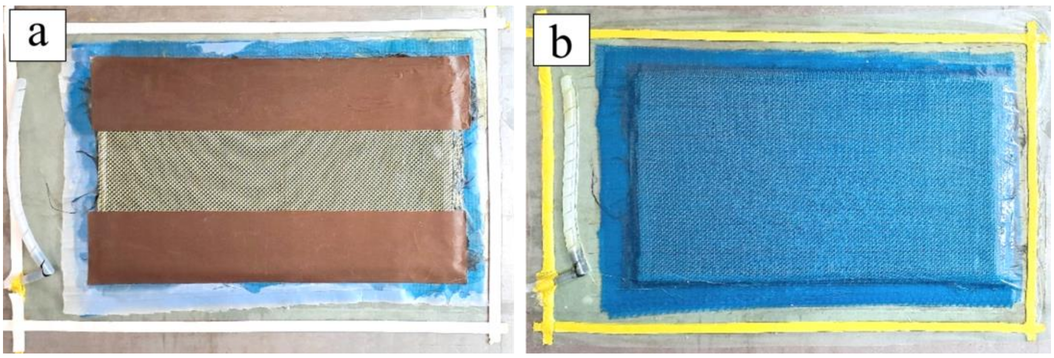

Figure 2. a) Production of samples for DCB, **b)** vacuumed composite plate

2.2. Water aging

The durability of composites is affected by environmental factors like moisture, temperature changes, UV exposure, and chemicals, which can impact long-term performance (Sukur and Onal, 2021; Yildirim et al., 2021). To assess the composites under realistic conditions, samples were immersed in distilled water at room temperature for 6 months to evaluate the effects of moisture on their mechanical properties. After the unaged samples were subjected to the DCB test, it was also performed on water-aged samples for 2, 4, and 6 months.

2.3. DCB test

DCB tests were performed on the Instron 8801 testing machine (Figure 3-a). All tests were carried out three repetitions at room temperature to obtain valid results. The tests were conducted according to ASTM D5528, and all DCB tests were performed at a cross-head speed of 2 mm/min. The length, width, and thickness of the samples were 140 x 25 x 5.8 mm. The length of the pre-crack created by the PTFE film was 70 mm. The loading applied to the samples in DCB tests is shown in Figure 3-b.

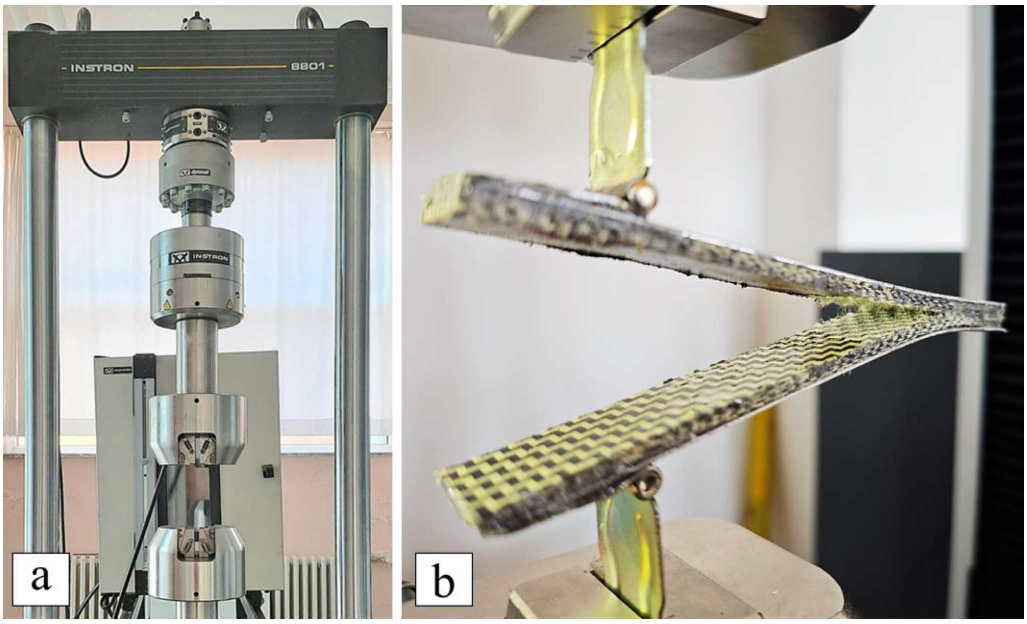

Figure 3. a) The Instron 8801 testing machine, **b)** performing DCB tests

2.4. Calculation of Mode-I Fracture Toughness with The Modified Beam Theory

Modified beam theory considers Mode-I fracture toughness as a result of the DCB test, as in Equation 1. Where; G_{Ic} is Mode-I fracture toughness in J/m^2, P is the force applied to the sample in N, δ is the displacement in mm, b is the sample width in mm and a is the crack length in mm.

$$G_{Ic} = (3\, P\, \delta)\, /\, (2\, b\, a) \qquad (1)$$

Since rotation is likely to occur in the delamination zone, the G_{Ic} values calculated by Equation 1 will be overestimated. The way to correct for this rotation is to assume that the crack length contains a slightly longer delamination. For this purpose, the normalized crack length, $|\Delta| + a$ is calculated. The graph showing the normalized crack length is presented in Figure 4.

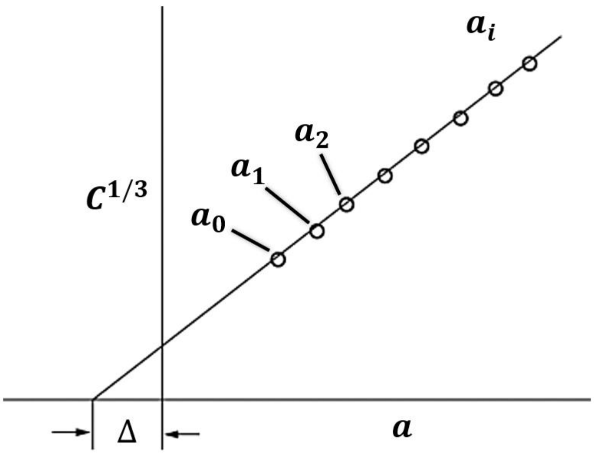

Figure 4. Finding the normalized crack length

C stands for compliance and is the ratio of the load point displacement δ to the applied force P ($C = \delta\ /\ P$). Accordingly, $|\Delta| + a$ is found experimentally from the relationship between the compliance C and the crack length a. As a result, the Mode-I fracture toughness value is obtained as in Equation 2.

$$G_{Ic} = (3\ P\ \delta\ )\ /\ \big(2\ b\ (|\Delta| + a)\big) \tag{2}$$

3. Results and Discussion

DCB tests were carried out on unaged and 2, 4, and 6 months water-aged samples and the force-displacement curves obtained are shown in Figure 5. These curves were generated by using the values of a specific sample for each aging time that showed the closest and similar result to the average. Accordingly, it is seen that the force values increase as the aging time increases.

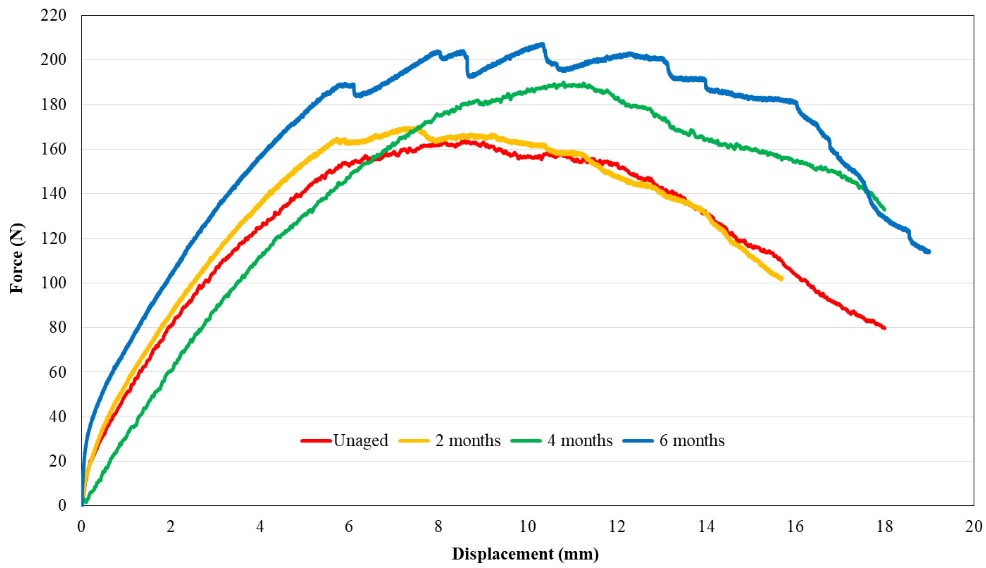

Figure 5. Force-displacement (N - mm) curves for composite samples subjected to varying aging periods (unaged, 2, 4, and 6 months)

Figure 6 shows the Mode-I fracture toughness-crack length curves according to aging time. The curves in this figure present the values of a specific sample that showed most similar result to the average for each aging time. Similar to the force-displacement curves, these curves also show that the aging duration has an effect that leads to an increase in fracture toughness. In unaged samples, fracture toughness increased as crack length progressed, whereas in the samples aged for 2 and 4 months, an increase is observed after the onset of crack propagation, followed by a behavior with less variability. In the samples aged for 6 months, fracture toughness increased at the beginning of crack propagation but showed a decrease as the crack continued to propagate, which can be attributed to the degradation of the matrix and the loss of fiber bridging efficiency after long-term aging as reported by Zhou et al. (2024).

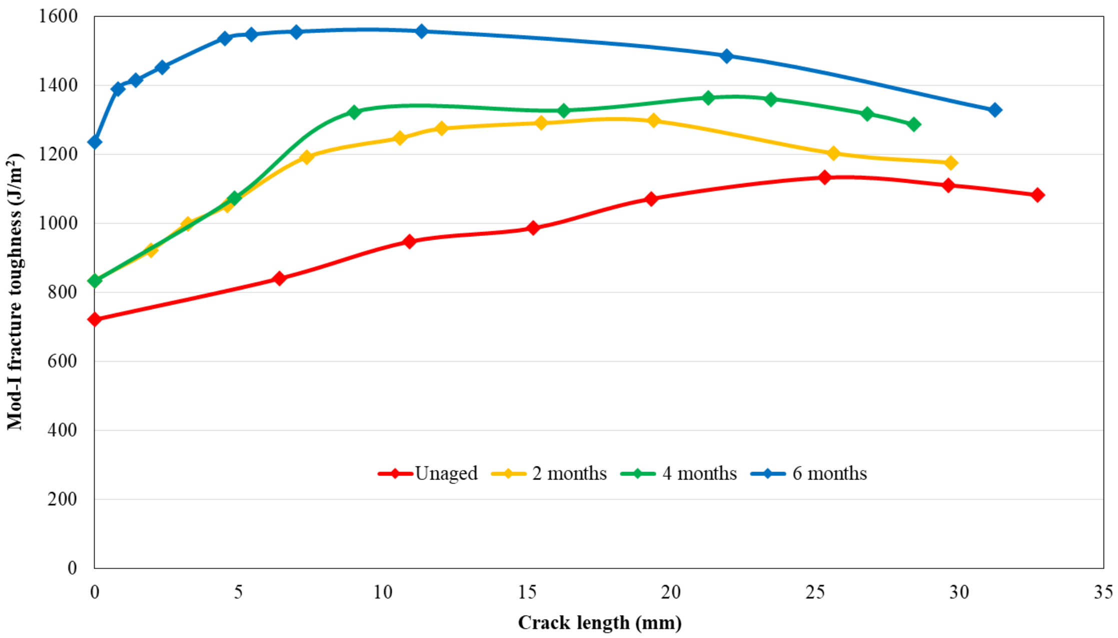

Figure 6. Mode-I fracture toughness-crack length (J/m^2 - mm) curves for composite samples subjected to varying aging periods (unaged, 2, 4, and 6 months)

The average maximum force and Mode-I fracture toughness values of the samples as a function of aging time are presented in Figure 7 and Figure 8, with standard deviations shown as error bars. The average DCB test results and their corresponding standard deviation values are also provided in Table 1. The increased values in the table are calculated with reference to unaged samples.

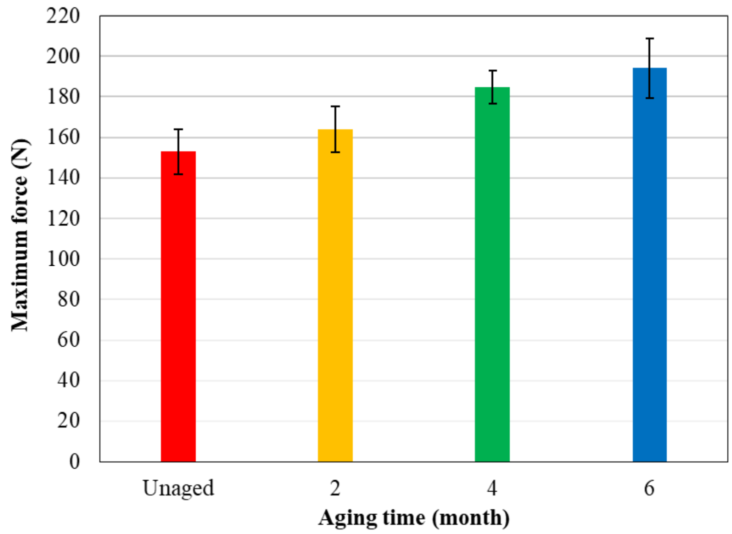

Figure 7. Average maximum force (N) of samples as a function of varying aging periods (unaged, 2, 4, and 6 months)

In the unaged samples, the average maximum force was determined to be 152.84 N, and the Mode-I fracture toughness was 1131.43 J/m^2. Following the aging process, an increase in maximum force was observed. After 2 months of aging, the maximum force increased by 7.22% to 163.87 N. A further increase of 13.65% was recorded after 4 months, reaching 184.73 N. After 6 months, an additional increase of 6.12% brought the maximum force to 194.09 N.

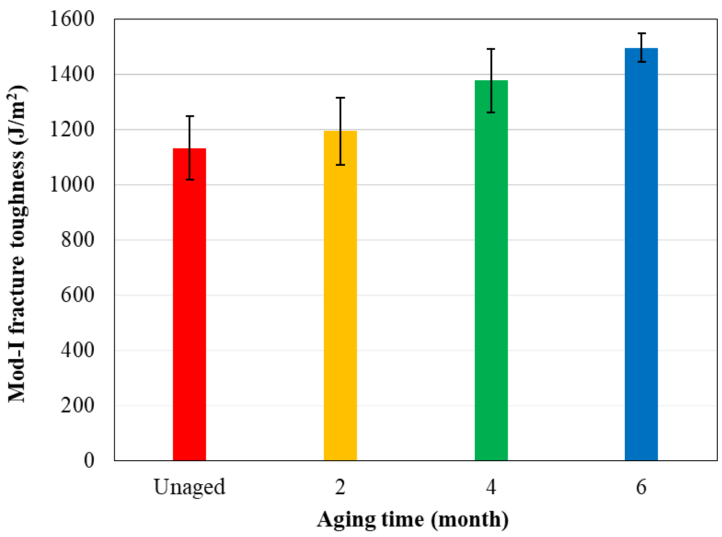

Figure 8. Average Mode-I fracture toughness (J/m^2) of samples as a function of varying aging periods (unaged, 2, 4, and 6 months)

Similarly, Mode-I fracture toughness also exhibited an increasing trend with aging duration. After 2 months, the fracture toughness increased by 5.41% to 1192.67 J/m^2. After 4 months, a further increase of 16.24% was observed, reaching 1376.37 J/m^2. At the end of the 6-month aging period, the fracture toughness increased by an additional 10.49%, reaching 1495.11 J/m^2.

In conclusion, after 6 months of aging, the maximum force and Mode-I fracture toughness showed increases of 26.99% and 32.14%, respectively, compared to the unaged samples.

The unaged DCB test results obtained in this study were evaluated in comparison with fracture toughness values reported in the existing literature for composite materials that were tested under similar conditions, specifically at room temperature and without exposure to any artificial aging processes. This comparative assessment aims to contextualize the current findings within the broader scope of previously published data, thereby providing a reference point for the performance of unaged composites. Such a comparison is essential for validating the reliability of the experimental results and for identifying any distinctive behavior of the composite system investigated in this study. When compared with existing literature, the Mode-I fracture toughness of 1131.43 J/m^2 obtained for the Elium matrix-based intraply CA hybrid composites at room temperature in this study falls within the expected range for similar composite systems. Rajasekar et al. (2019) reported Mode-I fracture toughness values ranging from 1015.76 to 1239.26 J/m^2 for CA fiber-reinforced epoxy composites, depending on the initial crack length. They noted that shorter initial crack lengths result in higher fracture toughness. Alsaadi and Erklig (2021) reported a Mode-I fracture toughness of 1093 J/m^2 for aramid fiber-reinforced epoxy composites. Kim et al. (2011) found a Mode-I fracture toughness of 942 J/m^2 for carbon fiber-reinforced epoxy composites, while Bhudolia et al. (2016) obtained a similar value of 970 J/m^2. In another study, Bhudolia et al. (2018) investigated Elium matrix-based carbon fiber-reinforced composites and reported a Mode-I fracture toughness of 1310 J/m^2, suggesting that the Elium matrix may contribute positively to fracture toughness. Overall, the results of this study are in good agreement with previous findings and indicate that the combination of hybrid fiber reinforcement and a thermoplastic matrix offers a promising approach to improving the fracture performance of composite materials.

Table 1. Average DCB test results according to aging time

Aging time	**Maximum force**	**Increase in maximum force**	**Mode-I fracture toughness**	**Increase in Mode-I fracture toughness**
Month	**N**	**%**	**J/m^2**	**%**
Unaged	152.84 ± 11.22	-	1131.43 ± 115.03	-
2	163.87 ± 11.26	7.22	1192.67 ± 120.46	5.41
4	184.73 ± 8.00	20.87	1376.37 ± 114.78	21.65
6	194.09 ± 14.62	26.99	1495.11 ± 52.45	32.14

In this study, the effect of water aging on fracture properties was evaluated. In their investigation of the impact of long-term aging on fracture performance, Bandaru et al. (2023) reported that the Mode-I fracture toughness of glass fiber-reinforced Elium composites increased by 90.15%, from 751 to 1428 J/m^2, after 60 days of aging. In contrast, Xu et al. (2024) observed a 16.67% decrease in Mode-I fracture toughness after immersing carbon fiber-reinforced epoxy composites in water at +75°C for 108 days. Similarly, Ulus et al. (2022) reported that the Mode-I fracture toughness of basalt fiber-reinforced epoxy composites decreased from 1190 to 720 J/m^2, a reduction of 39.7%, after six months of exposure to seawater. In conclusion, while water aging leads to a reduction in fracture properties in epoxy-based composites, it has been observed to enhance the fracture performance of Elium matrix-based composites. Furthermore, considering the interlaminar fracture behavior after water aging, it can be concluded that Elium matrix-based intraply CA hybrid fiber-reinforced composites offer reliable performance for long-term use.

Fourier Transform Infrared Spectroscopy (FTIR) analysis (Figure 9) was performed to examine the chemical changes occurring in the composite material after water aging, and the results revealed that the fundamental structure of the Elium thermoplastic matrix did not undergo any significant degradation. In both unaged and 6 months aged samples, the characteristic C=O stretching peak of the resin around 1720 cm^{-1} was largely preserved in terms of position and intensity. In contrast, a slight decrease was observed in the C-O stretching band around 1140 cm^{-1}, accompanied by a minor increase in the O-H band near 3300 cm^{-1}. These changes indicate that the absorbed water partially diffused into the matrix, resulting in limited hydroxylation and chain relaxation. In addition, the decrease or disappearance of the bands corresponding to the aramid fiber at 1540 cm^{-1} (Amide II) suggests interfacial bond weakening or fiber detachment from the surface (Das et al., 2023; Alsaadi et al., 2025). Furthermore, the partial plasticization observed in the FTIR spectra, along with the weakening of the fiber-matrix interfacial bonding, is believed to have contributed to the increase in fracture toughness observed in the DCB tests. This behavior can be attributed to water diffusion, enhancing the matrix's energy dissipation capability, which allows for greater energy absorption during crack propagation.

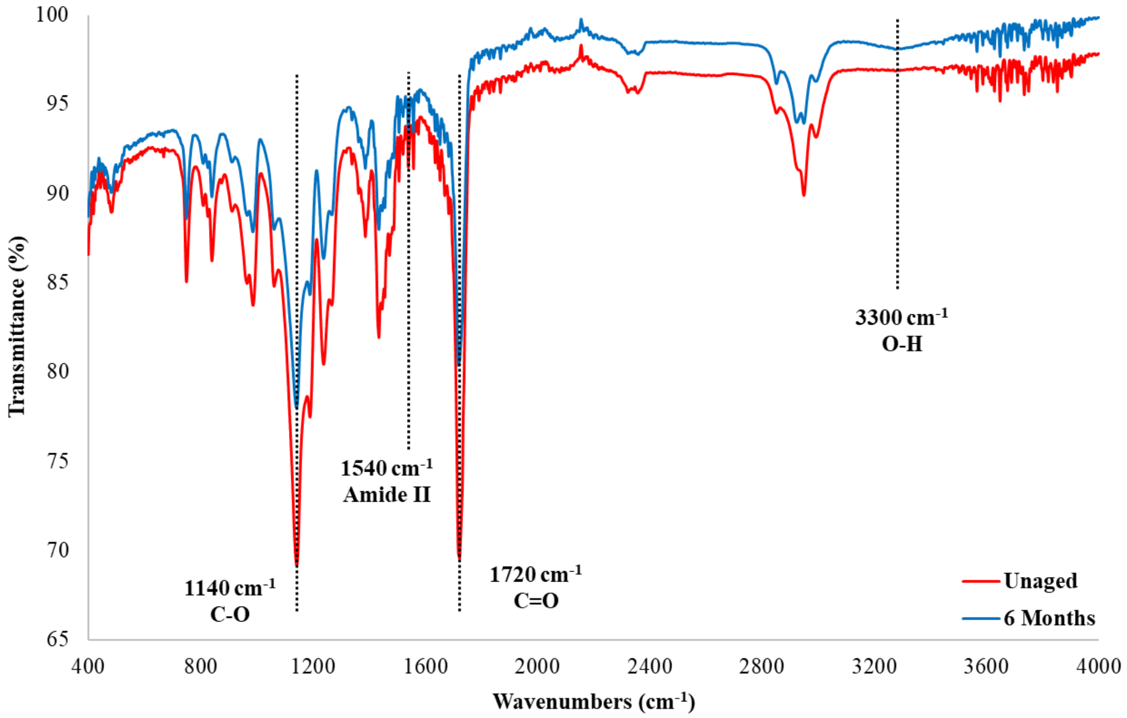

Figure 9. ATR-FTIR spectra of unaged and 6 months aged CA intraply hybrid composites

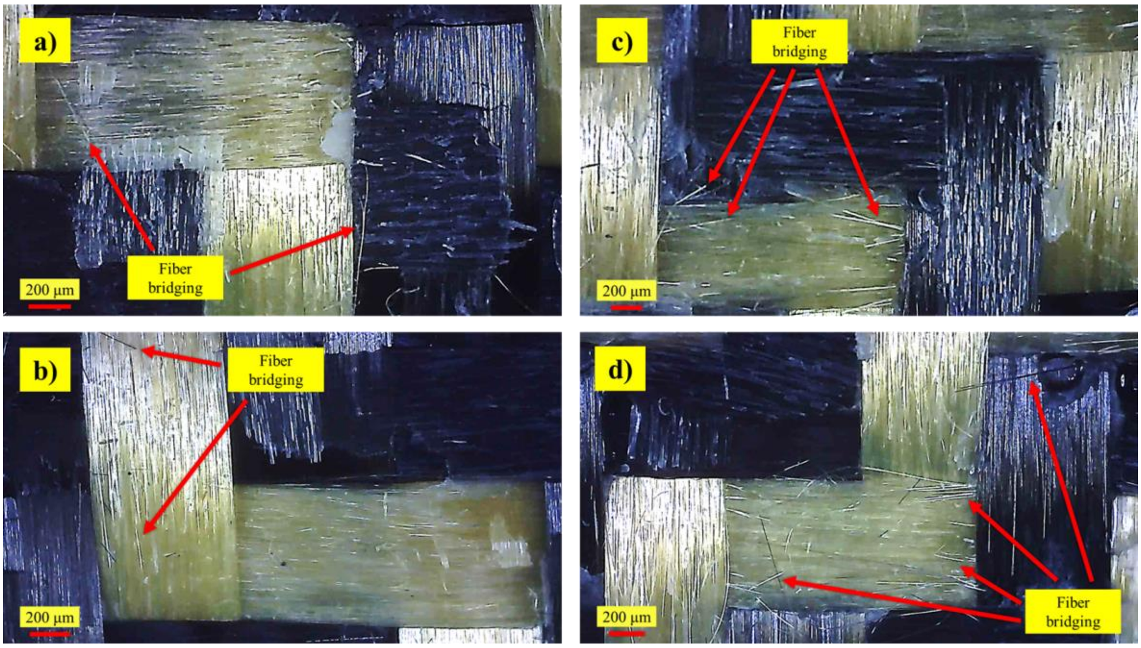

Figure 10. Macro failure images of DCB test of varying aging periods: a) unaged, b) 2 months aged, c) 4 months aged, d) 6 months aged

Figure 10 shows macro failure images of DCB test samples after aging. The images were taken from the surfaces completely separated by crack propagation starting from the pre-crack. Resins become plasticized and more ductile upon water absorption (Zhu et al., 2024). In this study, the plasticization of the Elium matrix due to water aging allowed the matrix to absorb more energy during crack propagation, leading to an increase in the fracture toughness of the samples (Alejandro Rodriguez-Gonzalez et al., 2018). Simultaneously, the weakening of the fiber-matrix interfacial bonding -which is often considered a negative property- also contributed to the enhanced performance in DCB tests (Rodriguez-Gonzalez and Rubio-González, 2021). This interfacial weakening enabled fibers to debond more easily from the matrix, resulting in a more pronounced fiber bridging mechanism (Williams et al., 2025). The increased fiber bridging led to higher energy absorption as the crack propagated, thereby increasing the Mode-I fracture toughness (Han et al., 2022; Duan et al., 2024). As the water aging duration increased, a more pronounced fiber bridging mechanism was observed. The weakening of the fiber/matrix interface led to easier fiber pull-out, which resulted in extensive fiber bridging. Increased fiber bridging hindered crack propagation and contributed to the enhancement of Mode-I fracture toughness (Bandaru et al., 2023; Liu et al., 2025).

Scanning Electron Microscope SEM images detailing the fracture surfaces of CA-reinforced Elium composites following the DCB test are presented in Figure 11, revealing the distinct influence of aging on the delamination mechanism. Unaged specimens exhibited a smooth fracture surface morphology, indicating a tendency for brittle matrix fracture (Obande et al., 2019). This morphology, combined with good interfacial bonding, constrained the energy dissipation during crack propagation. In contrast, the fracture surface of the specimens subjected to 6 months of aging was characterized by interfacial weakening and a rough fracture surface. This environmentally induced interfacial degradation facilitated easier debonding of the fibers from the matrix, leading to a significantly more pronounced fiber bridging and fiber pull-out mechanism, which contributes substantially to the composite's toughness (Bhudolia et al., 2018). This result demonstrates that despite environmental conditioning weakening the interfacial bond, it concurrently triggers a highly effective bridging mechanism, thereby enhancing the ultimate delamination toughness of the composite (Bhudolia et al., 2023).

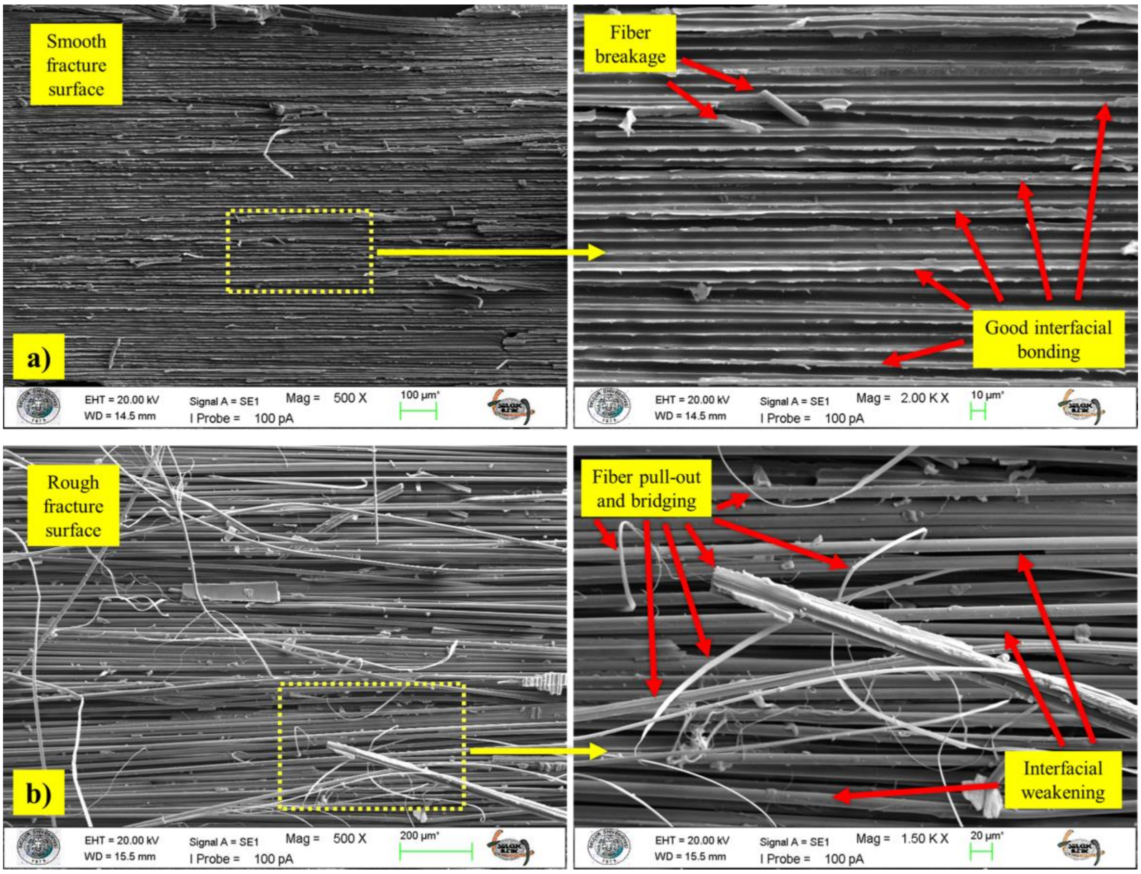

Figure 11. SEM images of DCB fracture surfaces after testing: a) unaged and b) 6 months aged

4. Conclusions

In this study, the DCB behavior of CA intraply hybrid fiber-reinforced composites with a thermoplastic Elium matrix was experimentally investigated after being aged in distilled water for 6 months. The fracture performance of unaged samples was compared with those aged in water for 2, 4, and 6 months. The key findings are as follows:

- In the DCB tests, the maximum force and Mode-I fracture toughness obtained for the unaged samples were 152.84 N and 1131.43 J/m^2, respectively. After aging, these values increased by 26.99% and 32.14%, reaching 194.09 N and 1495.11 J/m^2, respectively.
- The aging process positively influenced the interlaminar delamination behavior, which indicates that water aging can enhance certain aspects of fracture in hybrid fiber-reinforced composites.
- The results indicate that hybrid fiber composites with a thermoplastic matrix are a reliable and durable option for long-term use. This is because they not only improve fracture toughness but also maintain their performance under aging conditions.
- FTIR analysis revealed moisture-induced interfacial weakening and minor chain relaxation, suggesting that the absorbed water degraded the fiber/matrix bonding but preserved the Elium matrix's fundamental structure. This chemical change was corroborated by SEM fractography, which showed that the transition from a smooth (unaged) to a rough fracture surface (aged) was

a direct result of the highly effective fiber bridging and fiber pull-out mechanism triggered by the weakening interface, leading to enhanced Mode-I toughness.

The findings of this study demonstrate that Elium matrix hybrid composites are a promising alternative for potential real-world applications in demanding environments such as aerospace, marine, automotive, and humid settings. Specifically, the increased interlaminar fracture toughness even after water aging highlights the potential of these materials for applications requiring long-term durability and reliability. While some studies in the literature have utilized accelerated aging conditions, this work was limited to water aging at room temperature. Therefore, future research can build upon these findings by conducting tests under temperature-controlled accelerated aging conditions, which will enable a more comprehensive assessment of the material's aging behavior.

Additionally, to further advance these findings, investigating Mode-II and mixed-mode (Mode-I/Mode-II) fracture behaviors will provide a more comprehensive understanding of the material's failure mechanisms. Fatigue tests and longer-term aging experiments at different temperatures and salinity levels will also allow for a more thorough assessment of the durability performance of these composites for a broader range of applications.

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Statement of Conflict of Interest

The authors declare that there is no potential for conflict of interest to the research, authorship, or publication of this article.

Author's Contributions

The authors declare that they have contributed equally to the article.

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