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# Effect of Weathering on the Physical and Mechanical Performance of Natural Fiber and Carbon-Hybrid Composites for Athletic Prosthetic Foot Applications

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**ABSTRACT**

Natural fiber reinforced composites have attracted increasing consideration for athletic prosthetic applications because of their renewability, low density, and relatively low manufacturing cost. In the present work, hemp, sisal, and bamboo fibers were employed as reinforcements in epoxy laminates, while carbon fiber plies were incorporated to produce hybrid structures. The laminates were manufactured using a vacuum lay-up method to guarantee adequate resin saturation and laminate quality. Following a preliminary assessment of several configurations, 12-ply and 12-ply with 3 carbon-ply laminates were selected for detailed investigation. The selected laminates were characterized in terms of density, water absorption, and flexural, impact, and compressive properties before and after 100 h of accelerated weathering. Weathering resulted in slight reductions in density (less than 1%), increased moisture uptake, and moderate losses in mechanical performance. The hybrid laminates consistently exhibited higher residual properties; for example, the hemp/carbon hybrid retained a flexural strength of 271 MPa and a compressive strength of 103 MPa after weathering. In general, the hybrid configurations preserved approximately 85% of their initial flexural and impact properties, indicating improved resistance to environmental degradation. Among the investigated systems, hemp-based laminates exhibited the highest residual mechanical strengths. These results indicate that carbon-fiber hybridization is a good approach for improving the environmental stability of natural fiber composites as a potential candidate for lightweight athletic prosthetic foot structures.

## 1. INTRODUCTION

In recent years, the need for lightweight, environmentally sustainable, and high-performance materials has increased markedly, particularly in applications such as athletic prosthetic devices where both mechanical efficiency and durability are essential [1-4]. Natural fiber reinforcements have appeared as promising alternatives to conventional artificial materials because of their low density, renewability, and acceptable mechanical properties [5-7]. Among the most commonly used natural fibers, hemp, sisal, and bamboo have attracted considerable attention because of their availability and their distinct structural and chemical characteristics [8-10].

Despite these advantages, the durable performance of natural fiber composites remains a critical concern, especially when submitted to environmental circumstances such as moisture, temperature variations, and ultraviolet (UV) radiation [11-13]. These conditions, commonly simulated through weathering tests, can considerably influence the fiber–matrix interface and cause degradation in mechanical properties such as impact resistance, compressive strength, and flexural behavior [14-16]. Therefore, evaluating the performance of these materials before and after weathering exposure is essential for applications involving outdoor service and repeated loading, such as athletic prosthetic feet [17, 18].

In addition, the selection of suitable matrix and natural fiber combinations plays a major role in determining the overall structural behavior of composite materials [19, 20]. Hybridization with high-performance fibers can further enhance mechanical performance by combining the advantages of different reinforcements within a single laminate structure [21, 22]. Moreover, understanding the influence of environmental weathering on such hybrid composites is crucial for improving their reliability and service life [23]. The utilization of natural fiber composites in prosthetic products may also contribute to reducing manufacturing costs and environmental impact compared with conventional synthetic composites [24]. Consequently, extensive experimental evaluation is necessary to identify the most effective material configurations for durable and efficient athletic prosthetic devices [25]. Furthermore, environmental exposure may promote moisture ingress and microcrack formation within the matrix, thereby reducing the efficiency of stress transmission at the matrix- fiber interface. As a result, the ability of a composite to retain its properties after weathering is as important as its initial mechanical performance. In this regard, carbon-fiber hybridization has emerged as a promising approach to mitigate weathering-induced degradation by enhancing stiffness, limiting crack propagation, and reducing moisture sensitivity. Therefore, a comprehensive assessment of both physical properties, including density and water absorption, and mechanical properties after weathering is essential for the development of durable and reliable materials for athletic prosthetic foot applications.

Yu et al. [26] reviewed the aging performance of bamboo fiber-reinforced polymer composites under environmental conditions, including moisture, UV radiation, and thermal exposure. The study reported that environmental aging deteriorates the fiber–matrix interface, causing a decrease in tensile, flexural, and impact properties. The authors also highlighted that fiber surface processing and shielding coatings can effectively enhance the durability and service life of bamboo fiber composites.

Yorseng et al. [27] developed a hybrid lightweight composite reinforced with hemp fibers and a bio-epoxy matrix to evaluate their mechanical performance and durability. The study showed that the hybrid composites exhibited good flexural and tensile properties and retained satisfactory mechanical performance after accelerated weathering. The authors concluded that hemp fiber-based bio-epoxy composites are favorable, maintainable materials for lightweight structural use because of their promising environmental durability and mechanical properties.

Similarly, Zuccarello et al. [28] examined the influence of accelerated environmental aging on high-performance sisal fiber-reinforced green epoxy biocomposites under UV radiation, humidity, and temperature cycles. The results showed that environmental aging considerably reduced the mechanical behavior of the composites, with tensile and delamination strengths decreasing after prolonged exposure due to fiber–matrix debonding and matrix degradation. The authors concluded that sisal fiber composites are susceptible to outdoor environmental conditions, emphasizing the importance of improving their long-term durability for structural use.

Hou et al. [29] studied the mechanical characteristics of bamboo fiber-reinforced composites after environmental aging under cold–hot cycles and UV radiation dry–wet exposure. The results showed that bamboo fiber composites exhibited significant anisotropic behavior, while accelerated aging, particularly UV dry–wet exposure, caused noticeable reductions in tensile and compressive properties due to surface cracking and deterioration of the fiber–matrix interface. The authors concluded that environmental aging noticeably affects the long-standing durability of bamboo fiber composites used in structural applications.

To enhance the overall performance, hybridization has been widely explored. Pulleti et al. [30] investigated the mechanical performance of hemp/carbon and hemp/glass hybrid epoxy composites with different stacking sequences. The results showed that incorporating carbon fiber layers noticeably enhanced the tensile, compressive, flexural, and interlaminar shear properties compared with pure hemp composites. In addition, placing the carbon fiber layers on the external surfaces provided the greatest enhancement in flexural performance, demonstrating the effectiveness of hybridization for lightweight structural applications.

Depending on the foregoing studies, it is clear that although natural fiber composites offer attractive mechanical characteristics and sustainability benefits, their long-term durability under environmental exposure remains a challenge. Moreover, direct comparisons of weathering-induced changes in physical properties, such as density and water absorption, together with flexural, impact, and compressive performance for different natural fiber/carbon hybrid systems are still limited. Therefore, the present work aims to indicate the effect of accelerated weathering on the physical and mechanical behavior of hemp-, sisal-, and bamboo-based epoxy laminates with carbon fiber hybrid counterparts; the objective was to identify durable and lightweight composite configurations as potential candidate materials for athletic prosthetic foot applications.

## 2. MATERIALS AND METHODS

An epoxy resin system (Movacryl Rigid Lamination Resin, IB-ER, Turkey) and a powder hardener (Ottobock 617P37, Germany) were employed as the matrix system. The hardener was incorporated at 3 wt.% of the resin, and the mixture was stirred until a uniform consistency was obtained. Composite laminates were made by the vacuum lay-up process using woven hemp, bamboo, and sisal fabrics, with selected laminates further hybridized by incorporating three carbon-fiber plies. The reinforcements were carefully aligned during stacking to guarantee uniform fiber distribution and minimize processing defects, as summarized in Table 1. Continuous vacuum was maintained throughout curing to promote resin impregnation and laminate consolidation. After curing under ambient laboratory conditions, the laminates were demolded and machined into test specimens.

Further details regarding the fabrication procedure and specimen preparation are available in our previous publication [31].

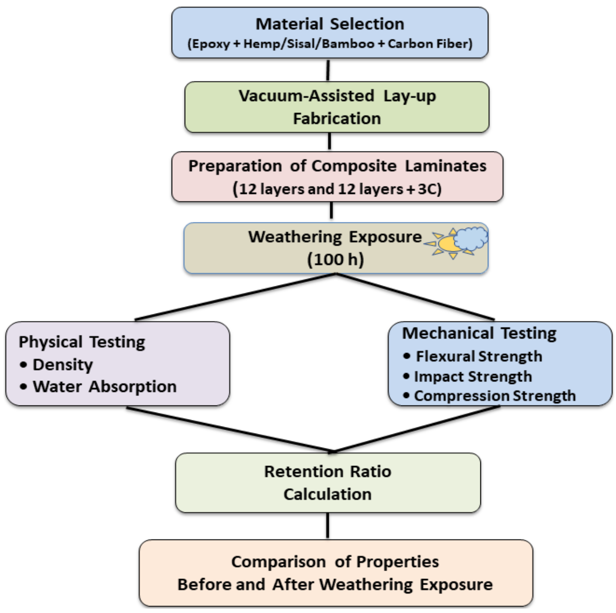


**Figure 1.** Flowchart of the experimental procedure

The selected specimens were subjected to 100 h of artificial accelerated weathering using a QUV/spray accelerated weathering tester (Q-Lab, Australia) equipped with UVA-340 fluorescent UV lamps, in accordance with American Society for Testing and Materials (ASTM) D4329-13, Cycle A [32]. The specimens were exposed to UV radiation at a wavelength of 340 nm and an irradiance of 0.89 W/m²·nm. The exposure cycle consisted of 8 h of UV irradiation at 60 ℃ followed by 4 h of condensation at 50 ℃. During the condensation stage, the specimens were exposed to moisture during the light-off period to simulate the combined effects of UV radiation, heat, and moisture encountered during outdoor environmental exposure. The total weathering duration was 100 h. The specimens were evaluated before and after weathering to assess changes in their physical and mechanical properties and to determine the influence of accelerated environmental exposure on the developed composites.

The flowchart of the experimental procedure is shown in Figure 1.

In this study, the laminate symbols B, H, S, and C denote bamboo, hemp, sisal, and carbon fibers, respectively, while the preceding numbers indicate the number of fiber layers. Accordingly, 12B, 12H, and 12S represent laminates containing 12 layers of bamboo, hemp, and sisal fibers, respectively, whereas 3C represents three layers of carbon fiber.

**Table 1.** Selected composite laminates explanation

| Laminations | Total No. of Layers | Layers' Symbol | Lamination Layup Procedures |
|---|---|---|---|
| Laminate (1) | Epoxy + Bamboo Fiber (12B) | 12B | - |
| Laminate (2) | Epoxy + Bamboo Fiber (12B) + Carbon Fiber (3C) | 12B + 3C | 1C + 6B + 1C + 6B + 1C |
| Laminate (3) | Epoxy + Hemp Fiber (12H) | 12H | - |
| Laminate (4) | Epoxy + Hemp Fiber (12H) + Carbon Fiber (3C) | 12H + 3C | 1C + 6H + 1C + 6H + 1C |
| Laminate (5) | Epoxy + Sisal Fiber (12S) | 12S | - |
| Laminate (6) | Epoxy + Sisal Fiber (12S) + Carbon Fiber (3C) | 12S + 3C | 1C + 6S + 1C + 6S + 1C |

Note: B = Bamboo fiber; H = Hemp fiber; S = Sisal fiber; C = Carbon fiber.

### 2.1 Physical test

Physical tests were conducted to evaluate the changes in the basic physical characteristics of the composite laminates following accelerated weathering exposure. Three specimens were tested for each laminate configuration for the physical tests, and the reported values represent the mean values obtained from the tested specimens.

#### 2.1.1 Density test

Density measurements were performed to monitor any changes in laminate compactness and structural integrity after weathering exposure. Variations in density may indicate moisture ingress, matrix degradation, or the development of internal defects such as microcracks and voids. Therefore, density serves as a simple indicator of the overall physical stability of the composites. The results also assist in correlating physical changes with the observed mechanical performance after weathering.

The density measurements were carried out in accordance with ASTM D792 [33] using three specimens for each laminate configuration. The specimens were circular with a diameter of 50.8 mm and a thickness of 4 mm. Density was determined using a high-precision density measuring device (Model GP120 S) with an accuracy of ± 0.0001 g/cm³ based on the Archimedes immersion method.

The mass of each specimen in air and its apparent mass during immersion in distilled water were measured, and the specific gravity and density were calculated using the equations described below.

$$Specific\ gravity = \frac{m1}{(m1 + w - m2)} \quad (1)$$

$$Density = (Specific\ Gravity) \times (997.5) \quad (2)$$

where, $m1$ = Mass of specimen in the air, $m2$ = mass of specimen and sinker (if used) in the water, $w$ = Mass of completely immersed sinker if employed and dipped wire. The value 997.5 kg/m³ represents the density of distilled water at room temperature, which was used to convert specific gravity into density.

#### 2.1.2 Water absorption

Water absorption testing was conducted to assess the susceptibility of the weathered laminates to moisture uptake. Weathering may create additional pathways for water penetration through matrix degradation and interfacial damage [34]. Evaluating water absorption thus provides insight into the durability of the fiber–matrix interface and the long-term environmental resistance of the composites.

The water absorption test was performed in accordance with ASTM D570 [35] using three specimens for each laminate configuration. The specimens were prepared using the same dimensions adopted for the density test specimens. The specimens were initially weighed in their dry condition to obtain the dry mass (WD). They were then completely immersed in distilled water at a controlled temperature of 23 ± 2 ℃ for 24 h. After immersion, the specimens were removed from the water, and their surfaces were gently wiped with a clean cloth to remove excess surface moisture. The specimens were then weighed to determine their mass after immersion (WS). The water absorption percentage was calculated using the following equation:

$$Water\ Absorption = \frac{Ws - WD}{WD} \times 100\% \quad (3)$$

where, $WD$: Dry sample mass before immersion; $W_S$: sample mass after immersion in distilled water for 24 h at room temperature.

### 2.2 Mechanical tests

A series of mechanical tests were conducted to evaluate the performance of the developed hybrid laminated composites intended for athletic prosthetic foot applications. All specimens were fabricated and tested under standardized laboratory conditions. Three specimens were tested for each laminate configuration for each mechanical test, and the reported values represent the mean values obtained from the tested specimens.

#### 2.2.1 Flexural test

Three-point bending tests were performed according to ASTM D790 [36] to assess the retention of bending stiffness and load-carrying capability after environmental exposure. Since prosthetic feet operate primarily under cyclic bending, flexural strength is a key indicator of structural durability. The tests were conducted using the same loading conditions before and after weathering to enable a direct evaluation of weathering-induced degradation.

2.2.2 Impact testing

Izod impact tests (International Organization for Standardization ISO 180) [37] were carried out to determine the effect of weathering on the ability of the laminates to absorb sudden loads and resist crack propagation. The absorbed impact energy was measured under identical conditions for the unweathered and weathered specimens, providing insight into the influence of weathering on damage tolerance.

2.2.3 Compression testing

Compressive properties were determined in accordance with ASTM D695 [38] to evaluate the resistance of the composites to sustained service loads following weathering exposure. Maintaining compressive strength after weathering is essential for the safe operation of athletic prosthetic feet. The use of identical test conditions before and after weathering allowed the extent of mechanical property retention to be quantified.

### 2.3 Retention ratio

To evaluate the influence of accelerated weathering on the developed composites, the retention ratio was calculated for each measured physical and mechanical property. The retention ratio represents the percentage of the original property retained after weathering and is widely employed to evaluate the durability and environmental stability of composite materials. Higher retention values indicate better resistance to environmental degradation and greater ability to preserve the original performance under service conditions. The retention ratio was calculated using Eq. (4) [39], which expresses the ratio of the property value after weathering to its corresponding value before weathering. This approach enables a direct comparison of the durability of different laminate configurations and facilitates evaluation of the effect of carbon-fiber hybridization on property retention.

$$Retention\ ratio = \frac{Property\ after\ weathering}{Property\ before\ weathering} \times 100\% \quad (4)$$

For water absorption, the same ratio is not interpreted as a retention ratio because an increase in water absorption represents greater moisture uptake rather than retention of the original property. Therefore, the water absorption results were expressed as the Water Absorption Increase Ratio (WAIR) using Eq. (5):

$$WWAI = \frac{Water\ Absorption\ after\ weathering}{Water\ Absorption\ before\ weathering} \times 100\% \quad (5)$$

A value of 100% indicates no change in water absorption after weathering, whereas values greater than 100% indicate an increase in water absorption. Accordingly, higher WAIR values indicate a greater increase in moisture uptake following weathering.

## 3. RESULTS AND DISCUSSION

### 3.1 Density results

Figures 2-4 show that, after weathering, the density of the non-hybrid laminates decreased slightly from 1.412 to 1.404 g/cm³ for 12H, from 1.171 to 1.160 g/cm³ for 12B, and from 1.398 to 1.387 g/cm³ for 12S. A similar but less pronounced reduction was observed for the hybrid laminates, with 12H + 3C decreasing from 1.624 to 1.617 g/cm³, 12B + 3C from 1.274 to 1.267 g/cm³, and 12S + 3C from 1.554 to 1.547 g/cm³. These minor decreases indicate that the 100 h weathering exposure was associated with limited changes in the matrix and internal structure of the composites, while the carbon-fiber layers contributed to maintaining the structural integrity of the hybrid laminates.

In Table 2, the density retention ratios of all laminates remained above 99%, indicating that the 100 h weathering exposure caused only minor changes in the bulk structure of the composites. The hybrid laminates exhibited slightly higher retention ratios than their non-hybrid counterparts, suggesting that the carbon fiber layers contributed to preserving the structural integrity of the laminates and limiting weathering-induced changes.

**Table 2.** Density retention ratio

| Sample | Before (g/cm³) | After (g/cm³) | Retention Ratio (%) |
|---|---|---|---|
| 12H | 1.412 ± 0.007 | 1.404 ± 0.0062 | 99.43 |
| 12H + 3C | 1.624 ± 0.0078 | 1.617 ± 0.0056 | 99.57 |
| 12B | 1.171 ± 0.0087 | 1.160 ± 0.0079 | 99.06 |
| 12B + 3C | 1.274 ± 0.0062 | 1.267 ± 0.0069 | 99.45 |
| 12S | 1.398 ± 0.0087 | 1.387 ± 0.0079 | 99.21 |
| 12S + 3C | 1.554 ± 0.0056 | 1.547 ± 0.0069 | 99.55 |

Note: B = Bamboo fiber; H = Hemp fiber; S = Sisal fiber; C = Carbon fiber.

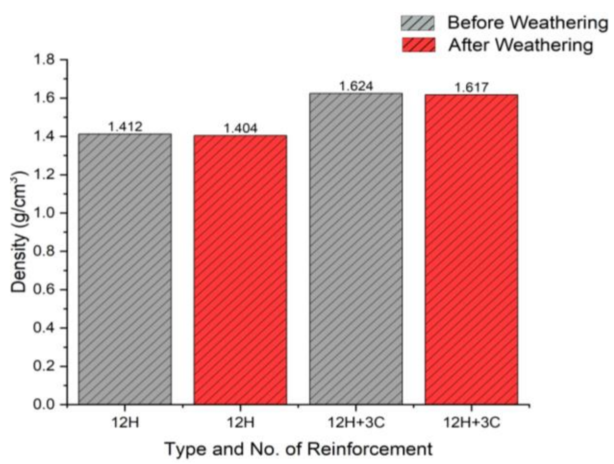


**Figure 2.** Comparison of the density of hemp fiber-reinforced composite laminates before and after weathering

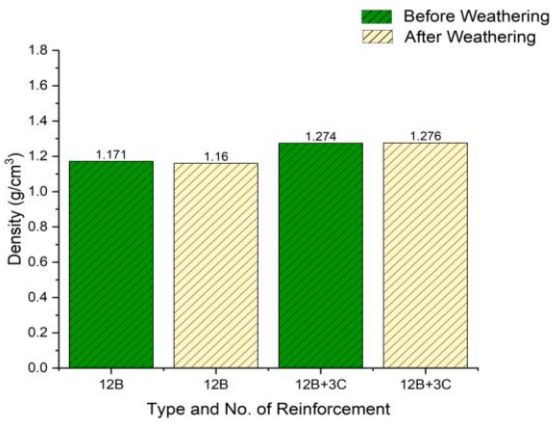


**Figure 3.** Comparison of the density of bamboo fiber-reinforced composite laminates before and after weathering

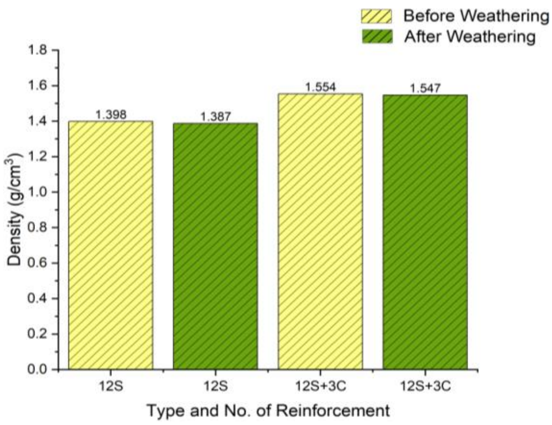


**Figure 4.** Comparison of the density of sisal fiber-reinforced composite laminates before and after weathering

### 3.2 Water absorption results

Figures 5-7 show that weathering increased the water uptake of all laminates, with the non-hybrid composites exhibiting a more pronounced rise than the hybrid ones. The water absorption of the non-hybrid laminates increased to 3.40% (12H), 5.50% (12B), and 3.70% (12S), whereas the corresponding hybrid laminates absorbed only 1.50%, 2.50%, and 1.90%, respectively. The water absorption increase ratio (WAIR) in Table 3 further confirmed this trend, ranging from approximately 122–128% for the non-hybrid laminates compared with only 113–116% for the hybrid counterparts. These values indicate that water absorption increased after weathering, with higher WAIR values corresponding to a greater increase in moisture uptake.

**Table 3.** Water absorption increase ratio (%)

| Sample | Before (%) | After (%) | WAIR (%) |
|---|---|---|---|
| 12H | 2.78 ± 0.0721 | 3.40 ± 0.0656 | 122.30 |
| 12H + 3C | 1.31 ± 0.0361 | 1.50 ± 0.0300 | 114.50 |
| 12B | 4.32 ± 0.0755 | 5.50 ± 0.0700 | 127.31 |
| 12B + 3C | 2.21 ± 0.0400 | 2.50 ± 0.0300 | 113.12 |
| 12S | 2.88 ± 0.0656 | 3.70 ± 0.0755 | 128.47 |
| 12S + 3C | 1.64 ± 0.0361 | 1.90 ± 0.0300 | 115.85 |

Note: B = Bamboo fiber; H = Hemp fiber; S = Sisal fiber; C = Carbon fiber.

This behavior could be attributed to the increase in moisture ingress resulting from changes in the matrix and fiber–matrix interfacial regions during weathering, while the carbon-fiber layers may have acted as a barrier to water penetration, thereby contributing to improved environmental resistance.

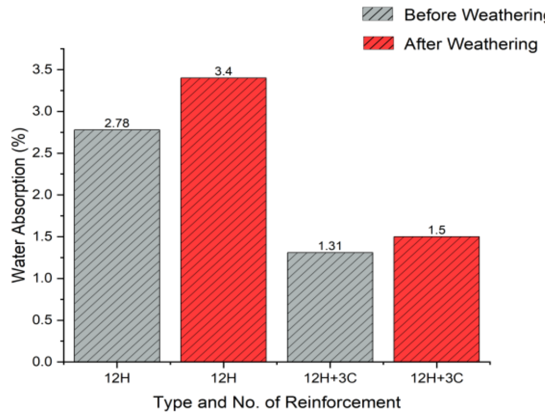


**Figure 5.** Comparison of water absorption in hemp fiber-reinforced composite laminates before and after accelerated weathering

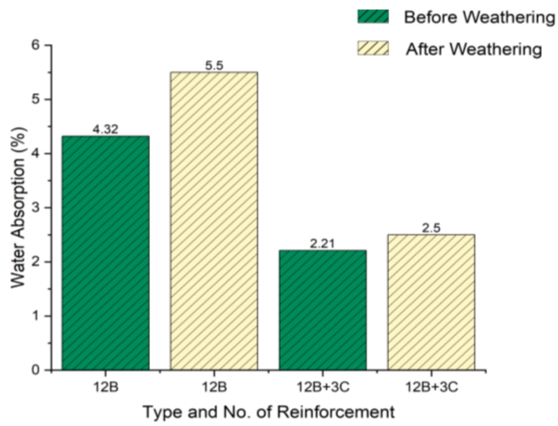


**Figure 6.** Comparison of water absorption in bamboo fiber-reinforced composite laminates before and after accelerated weathering

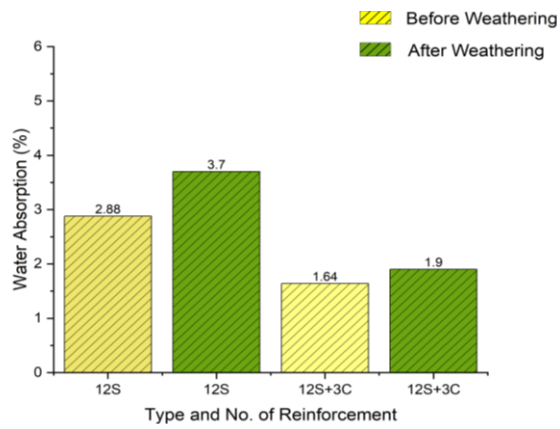


**Figure 7.** Comparison of water absorption in sisal fiber-reinforced composite laminates before and after accelerated weathering

### 3.3 Flexural test results

Figures 8-10 show that the flexural strength of the composites was slightly influenced after weathering due to environmental exposure that affected both the polymer matrix and the fiber–matrix bonding. Specifically, the flexural strength of the non-hybrid laminates decreased from 214 to 178.3 MPa for 12H, from 138.7 to 112.5 MPa for 12B, and from 92.5 to 81.5 MPa for 12S. Moisture absorption and UV radiation may have caused some degree of interfacial degradation and the formation of small internal defects, thereby reducing the ability of the laminates to resist bending stresses efficiently. Although the sisal composites retained a relatively high percentage of their initial strength, hemp composites maintained the highest residual flexural strength after weathering owing to their more compact structure and improved load-transfer capability. The hybrid laminates exhibited superior flexural stability, with the flexural strength decreasing from 315 to 271 MPa for 12H + 3C, from 255.7 to 221.2 MPa for 12B + 3C, and from 205 to 181.3 MPa for 12S + 3C. The carbon layers enhanced laminate rigidity and may have reduced the influence of environmental degradation. Therefore, despite the observed reduction, the hybrid configurations continued to exhibit promising mechanical behavior, indicating their potential as candidate materials for further evaluation in lightweight athletic prosthetic foot applications.

In Table 4, the flexural strength retention ratios further confirmed the beneficial effect of carbon-fiber hybridization. The hybrid laminates retained 86.0–88.4% of their initial flexural strength, compared with 81.1–88.1% for the non-hybrid laminates. The highest retention ratio was observed for the 12S + 3C laminate (88.44%), whereas the 12B laminate exhibited the lowest value (81.11%). These results indicate that the carbon layers effectively limited weathering-induced damage and helped preserve the load-transfer capability and structural integrity of the laminates during bending.

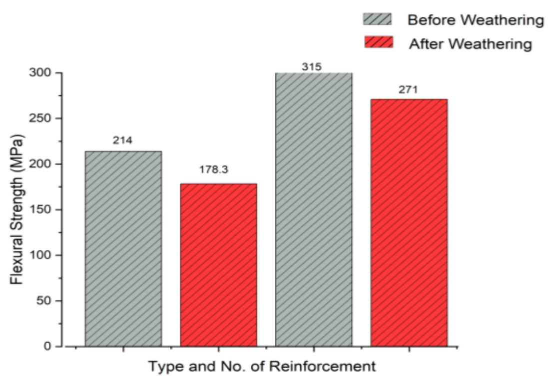


**Figure 8.** Comparison of flexural strength for hemp fiber-reinforced composite laminates before and after accelerated weathering

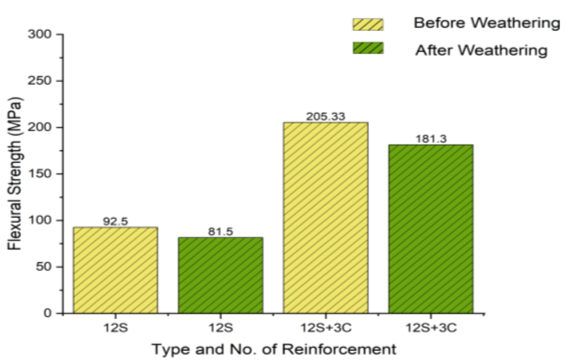


**Figure 9.** Comparison of flexural strength for sisal fiber-reinforced composite laminates before and after accelerated weathering

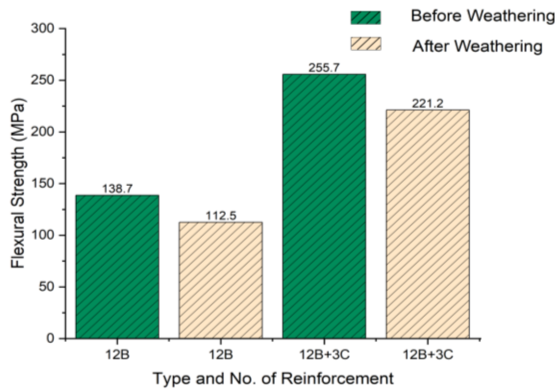


**Figure 10.** Comparison of flexural strength for bamboo fiber-reinforced composite laminates before and after accelerated weathering

**Table 4.** Flexural strength retention ratio

| Sample | Before (MPa) | After (MPa) | Retention Ratio (%) |
|---|---|---|---|
| 12H | 214.0 ± 2.36 | 178.3 ± 2.15 | 83.32 |
| 12H + 3C | 315.0 ± 3.56 | 271.0 ± 3.36 | 86.03 |
| 12B | 138.7 ± 2.66 | 112.5 ± 2.81 | 81.11 |
| 12B + 3C | 255.7 ± 3.18 | 221.2 ± 3.14 | 86.51 |
| 12S | 92.5 ± 2.35 | 81.5 ± 2.15 | 88.11 |
| 12S + 3C | 205.0 ± 3.46 | 181.3 ± 3.24 | 88.44 |

Note: B = Bamboo fiber; H = Hemp fiber; S = Sisal fiber; C = Carbon fiber.

### 3.4 Impact test results

Figures 11-13 show that the impact strength of the developed composites decreased slightly after weathering exposure, which may be associated with environmental effects on the matrix and interfacial regions [39]. Specifically, the impact strength of the non-hybrid laminates decreased from 32.62 to 29.70 kJ/m² for 12H, from 20.31 to 15.40 kJ/m² for 12B, and from 19.94 to 17.35 kJ/m² for 12S. Moisture penetration and UV exposure may have affected the flexibility of the epoxy matrix and the fiber–matrix interface, potentially leading to a lower energy-absorption capability during sudden loading. Hemp composites retained the highest residual impact strength, which may be related to their more uniform structure and stress distribution. In the hybrid laminates, the occurrence of carbon fiber layers markedly reduced the influence of weathering, with the impact strength decreasing from 57.19 to 49.30 kJ/m² for 12H + 3C, from 48.34 to 41.60 kJ/m² for 12B + 3C, and from 41.32 to 36.50 kJ/m² for 12S + 3C. The carbon layers may have contributed to limiting crack propagation and maintaining energy absorption efficiency. Consequently, despite the observed reductions, the hybrid composites maintained relatively high impact strength, indicating their potential as candidate materials for further evaluation under dynamic loading conditions relevant to athletic prosthetic foot applications.

In Table 5, the impact strength retention ratios further emphasize the beneficial role of carbon-fiber hybridization. The hybrid laminates retained approximately 86–88% of their original impact strength after weathering, whereas the non-hybrid composites exhibited a wider range of retention (75.8–91.1%). The lowest retention ratio was observed for the 12B laminate, indicating its greater susceptibility to weathering-induced damage. In contrast, the hybrid configurations maintained higher and more consistent retention ratios, suggesting that the carbon fiber layers contributed to preserving the energy-absorption capability of the laminates under dynamic loading.

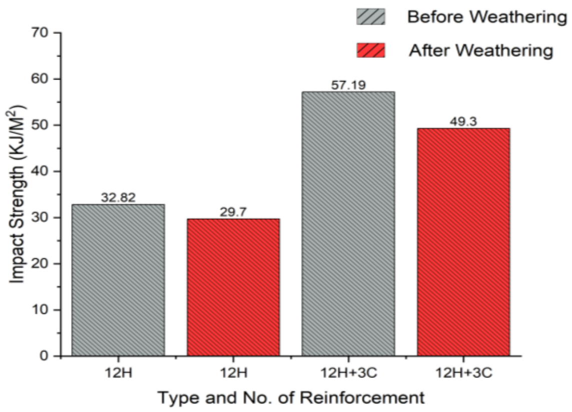


**Figure 11.** Comparison of impact strength for hemp fiber-reinforced composite laminates before and after accelerated weathering

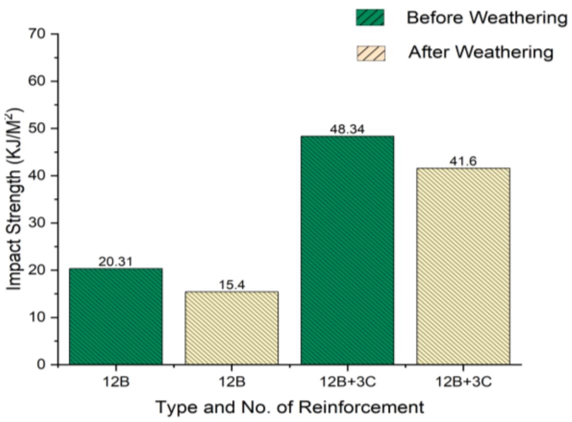


**Figure 12.** Comparison of impact strength for bamboo fiber-reinforced composite laminates before and after accelerated weathering

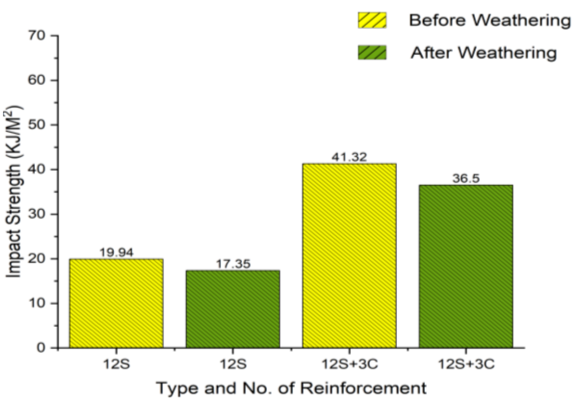


**Figure 13.** Comparison of impact strength for sisal fiber-reinforced composite laminates before and after accelerated weathering

### 3.5 Compression test results

Figures 14-16 show that the compressive strength of the composites showed a moderate reduction after weathering exposure that may be associated with changes in the epoxy matrix and fiber–matrix interface. Specifically, the compressive strength of the non-hybrid laminates decreased from 112 to 95 MPa for 12H, from 99 to 78 MPa for 12B, and from 60.33 to 48 MPa for 12S. Moisture absorption during environmental exposure could be associated with changes in the natural fibers and may have reduced the efficiency of stress transfer under compressive loading. In addition, UV radiation may have contributed to changes in the matrix and the formation of surface defects. Sisal composites exhibited the lowest absolute compressive strengths after weathering, whereas hemp composites retained the highest values owing to their more compact structure and improved fiber distribution. The hybrid laminates reinforced with carbon fibers maintained considerably higher residual compressive strengths, decreasing from 121 to 103 MPa for 12H + 3C, from 113 to 82 MPa for 12B + 3C, and from 62 to 53 MPa for 12S + 3C. These results indicate that carbon-fiber hybridization enhanced laminate rigidity and mitigated weathering-induced degradation. Consequently, the developed hybrid composites still possess sufficient mechanical integrity for potential use in athletic prosthetic applications.

**Table 5.** Impact strength retention ratio

| Sample | Before (kJ/m²) | After (kJ/m²) | Retention Ratio (%) |
|---|---|---|---|
| 12H | 32.62 ± 0.3 | 29.70 ± 0.27 | 91.05 |
| 12H + 3C | 57.19 ± 0.45 | 49.30 ± 0.41 | 86.20 |
| 12B | 20.31 ± 0.43 | 15.40 ± 0.38 | 75.82 |
| 12B + 3C | 48.34 ± 0.38 | 41.60 ± 0.36 | 86.06 |
| 12S | 19.94 ± 0.42 | 17.35 ± 0.43 | 87.01 |
| 12S + 3C | 41.32 ± 0.43 | 36.50 ± 0.39 | 88.34 |

Note: B = Bamboo fiber; H = Hemp fiber; S = Sisal fiber; C = Carbon fiber.

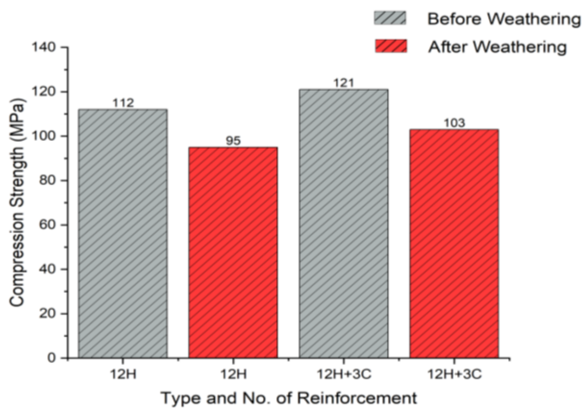


**Figure 14.** Compression strength of the laminated composite materials reinforced with hemp fibers before and after weathering

In Table 6, the compressive strength retention ratios further demonstrate the beneficial effect of carbon-fiber hybridization. The hemp- and sisal-based hybrid laminates retained 85.1% and 85.5% of their original compressive strengths, respectively, compared with 84.8% for 12H and 79.6% for 12S. The lowest retention ratio was observed for the 12B + 3C laminate (72.6%), indicating a greater susceptibility of the bamboo-based system to weathering-induced degradation under compressive loading. Overall, the relatively high retention ratios, particularly for the hemp- and sisal-based hybrids, confirm that carbon-fiber reinforcement effectively enhanced the structural stability and durability of the laminates during environmental exposure.

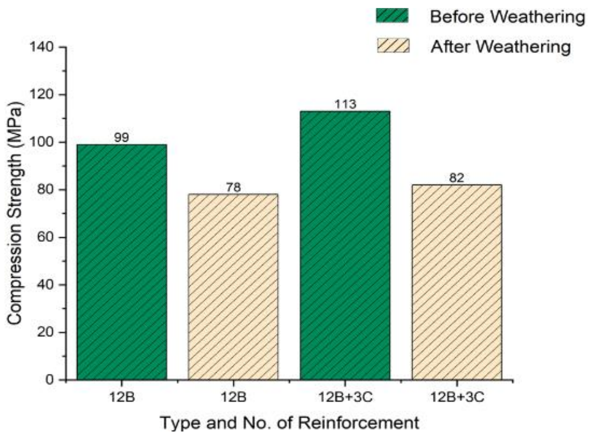


**Figure 15.** Compression strength of the laminated composite materials reinforced with bamboo fibers before and after weathering

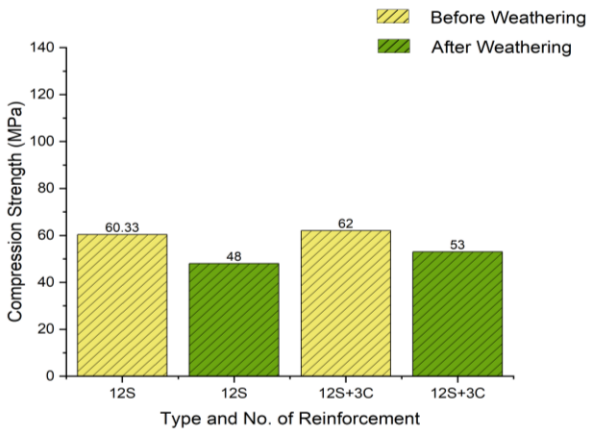


**Figure 16.** Compression strength of the laminated composite materials reinforced with sisal fibers before and after weathering

**Table 6.** Compression strength retention ratio

| Sample | Before (MPa) | After (MPa) | Retention Ratio (%) |
|---|---|---|---|
| 12H | 112.00 ± 1.37 | 95.00 ± 1.62 | 84.82 |
| 12H + 3C | 121.00 ± 1.80 | 103.00 ± 1.65 | 85.12 |
| 12B | 99.00 ± 1.66 | 78.00 ± 1.66 | 78.79 |
| 12B + 3C | 113.00 ± 1.71 | 82.00 ± 1.61 | 72.57 |
| 12S | 60.33 ± 1.41 | 48.00 ± 1.55 | 79.56 |
| 12S + 3C | 62.00 ± 1.40 | 53.00 ± 1.38 | 85.48 |

Note: B = Bamboo fiber; H = Hemp fiber; S = Sisal fiber; C = Carbon fiber.

## 4. CONCLUSION

The current study investigated the influence of accelerated weathering on the mechanical and physical behavior of natural-fiber and carbon-hybrid epoxy laminates intended for athletic prosthetic foot purposes. Although weathering caused measurable changes in the material properties, the laminates generally retained their structural integrity.

Natural-fiber and carbon-hybrid epoxy laminates were manufactured by vacuum-assisted lay-up with satisfactory quality for physical and mechanical characterization.

Among the non-hybrid laminates, hemp-based composites showed the highest residual flexural, impact, and compressive strengths after weathering.

The inclusion of carbon-fiber layers generally improved the initial mechanical properties and, in most cases, reduced the loss in performance after weathering. However, the effect of carbon-fiber hybridization depended on the natural-fiber type and the specific property evaluated, and improvement was not observed for all properties.

Weathering for 100 h resulted in a slight decrease in density, an increase in water absorption, and moderate reductions in impact, flexural, and compressive strengths, indicating the occurrence of moisture-induced and interfacial degradation.

Most hybrid laminates retained approximately 85% or more of their initial flexural and impact properties, reflecting improved resistance to environmental exposure.

The obtained results indicate that natural-fiber/carbon hybrid laminates have potential as candidate materials for further evaluation in the development of lightweight athletic prosthetic foot structures.

The present study was limited to the characterization of composite laminate specimens and did not include fatigue testing, gait-loading conditions, or evaluation of a complete prosthetic foot component. Therefore, the investigated laminates should be considered potential candidate materials requiring further mechanical, fatigue, gait-loading, and full-component validation before use in athletic prosthetic foot applications.

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