



Article

Investigation of Diffusion of Different Composite Materials on the Damage Caused by Axial Impact Adhesive Joints

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Abstract: In this study, the effects of exposure to seawater on the material properties of glass fiber-reinforced polymer (GFRP) and carbon fiber-reinforced polymer (CFRP) samples were investigated. The samples were stored in seawater with a salinity of 3.3–3.7‰ and a temperature of 23.5 °C taken from the Aegean Sea in September for different periods (1, 2, 3, 6 and 15 months). The samples prepared in accordance with the ASTM D5868-01 standard were subjected to axial impact testing. In the first stage of this study, moisture retention percentages were determined, and, then, axial impact tests were performed. In the tests, a total of 36 samples bonded with single-lap adhesive were subjected to 30 Joule impact energy, and their mechanical strength was evaluated. In line with the experimental results, moisture absorption and axial impact energy values were compared in order to determine the most durable composite material connection, and the most durable connection was selected by evaluating the mechanical properties. Damage analysis on the samples was performed at the DEU Science and Technology Application and Research Center with ZEISS GEMINI SEM 560. (Oberkochen, Germany). The fracture surfaces of the CFRP and GFRP samples after gold coating were examined in detail with a scanning electron microscope, and their interface properties and internal structures were observed. The fracture toughness of GFRP specimens increased from 4.6% in a dry environment to 27.96% after 15 months in seawater. CFRP specimens increased from 4.2% in a dry environment to 11.96% after 15 months in seawater, but the increase was less pronounced compared to GFRP. According to the experimental results, CFRP samples exhibited superior mechanical performance compared to GFRP samples.



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Keywords: adhesive; axial impact test; composite materials; joint; mechanical properties; seawater absorption; single lap

1. Introduction

GFRP and CFRP are widely used in the aviation, automotive, construction, marine and wind energy sectors with their advantages such as lightness, high strength and corrosion resistance. The most common method for connection is the adhesive technique, because it distributes the load homogeneously, prevents mechanical damage and reduces the risk of corrosion. The most important parameters affecting the connection type to be selected are the type of load, environmental factors and cost. The adhesive technique provides the most suitable connection by preserving lightness and strength in composites. Many articles have been published on the bonding of composite materials with adhesives recently.

These articles provide information on the bonding of composite materials with adhesives, discussing issues such as bonding methods, environmental effects, surface treatments,

fatigue performance and mechanical properties [1–6]. Humidity, temperature and aging have significant effects on the bonding of composite materials with adhesives [7–9]. There are studies on the examination of different types of joining in adhesive bonding [10–16]. All these studies are taken into consideration in the formation of bonded composite joints. In the study of Budhe et al. (2017), a comprehensive literature review was carried out on the factors that directly or indirectly affect the performance of composite bonded joints. Surface preparation, joint structure, material properties, and failure modes are important; new analytical models and finite element methods (FEMs) are also examined [17]. In the study of Silva et al. (2006) the most suitable adhesive type for the load-carrying capacity in single-ply joints and the effect of adhesive thickness on the joint strength were investigated. Three different adhesive types (brittle, medium and ductile) and three thicknesses (0.2, 0.5 and 1 mm) were tested. According to the results, as the adhesive thickness decreased, the overlap shear strength increased, and, as the bond toughness increased, the strength also increased. The effect of adhesive thickness was explained by the adhesive-adherent surface interfacial tensions [18]. Yang et al. (2024) reported in their study that, when the adhesive layer thickness was increased, there was a 21% decrease in sample strength in dry conditions at room temperature and a 52% decrease in different conditions [19]. Kırkayak (2019) studied the effects of adhesive geometry, i.e., thickness and shape, on the stress distribution in bonded joints. The results reveal that adhesive thickness significantly affects the stress distribution and hence the overall performance of the joint [20]. The thickness of the adhesive layer in bonded composite joints has a significant effect on its performance under impact loading. Studies have shown that, with an increase in the adhesive layer thickness, the strength of the joints tends to decrease [21]. Impact loads affect adhesive bonds in two main ways. Axial impact loads can create shear stresses between the adhesive and the boards, while vertical and lateral impacts can damage the adhesive or the board surfaces [22]. The adhesive layer plays a critical role in absorbing and dissipating energy during impact. The energy absorption capacity depends on the adhesive's thickness, toughness, and viscoelastic properties. Thick adhesive layers can absorb more energy but can increase stress concentrations, weakening the bond strength. Thin layers may not provide sufficient energy dissipation and may lead to brittle failures [23].

Axial impact tests are an important method for evaluating how adhesively bonded composite joints perform under dynamic loads. These tests measure how much energy the joint can absorb during impact, helping us understand its resistance to sudden axial forces. The research of Kemiklioglu et al. (2017) after vibration tests, the axial impact response of adhesively bonded composite joints, was investigated. The study highlighted the effects of vibration fatigue on the subsequent impact performance of the joints [24].

In their study, Demir et al. (2023) investigated the mechanical properties of sandwich composites with notched channels opened on their lateral surfaces after axial impact. The study evaluated the effects of notches and impact energy levels on the mechanical behavior of the material [25]. Ling et al. (2024) investigated the effects of varying polyethylene fiber content and different strain rates on the axial impact resistance of high-strength geo-polymer composites. The findings suggested how composite formulations could be optimized for improved impact performance and proposed a new model that includes fiber-bridging ratios [26].

Song et al. (2000) investigated the axial impact crushing behavior and energy absorption efficiency of composite wrapped metal tubes. Four typical collapse modes were identified. It was shown that the collapse mode is an important factor affecting the energy absorption mechanism and efficiency. The energy absorption efficiency was evaluated in terms of strain rate, composite wall thickness, fiber layer orientation and mechanical

properties of metal [27]. Impact test data were collected and analyzed to evaluate the composite material's damage resistance and ability to absorb impact energy [28].

In single-lap joints, the long-term effects of different composite materials and environmental factors can negatively affect bond strength. Thermal expansion coefficients of different materials and environmental factors (humidity, temperature, UV rays and chemical exposure) can change material properties and weaken bond strength. This uncertainty can reduce structural durability and lead to damage if the correct material selection, surface preparation and testing are not performed. This situation emphasizes the importance of examining the effects of different composite materials and one of the environmental factors, humidity, in single-lap joints.

In this study, findings are presented to understand the stage of damage that may occur in GFRP and CFRP composite samples subjected to axial impact tests in sea water for periods of 1, 2, 3, 6 and 15 months and to examine and evaluate how much energy they absorb at the time of impact.

2. Materials and Methods

The composite samples consist of seven-layer (0/90 orientation), 390 g/m² density twill-woven GFRP and eight-layer (0/90 orientation), 245 g/m² density twill-woven CFRP sheets produced by Fiber-mak Engineering. F-RES 21 epoxy and F-Hard 22 hardener were used in the production (Tables 1 and 2). Drum-type prepreg machine was preferred for prepreg production. Prepregs were coated with a resin system consisting of a mixture of epoxy and hardener by hand lay-up method and kept for one day. After the resin gelled, the composite material was produced by hot-pressing method at 120 °C and under 8–10 bar pressure. The dimensions of the obtained GFRP and CFRP composite plates were determined as 500 mm × 500 mm, and their thickness was determined as 2 mm. The samples were cut with CNC milling machine in accordance with ASTM D5868-01 [29] standard (Figure 1).

Table 1. F-RES 21 resin properties.

Viscosity (25 °C)	450–750 mPa.s
Intensity (25 °C)	1.05 g/cm ³

Table 2. F-Hard 22 hardener properties.

Viscosity (25 °C)	35,000–45,000 mPa.s
Intensity (25 °C)	1.1 g/cm ³

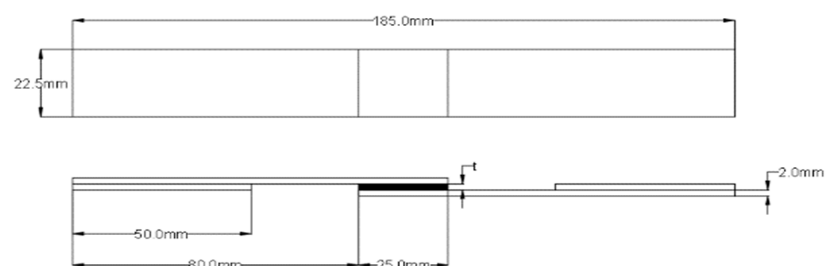


Figure 1. Geometry model of GFRP and CFRP test specimens according to ASTM D5868-01.

Loctite Hysol-9466 (Alpanhidrolik, Eskisehir, Turkey), is a two-component epoxy adhesive that cures at room temperature and uses a 2:1 ratio of resin and hardener for bonding. Loctite Hysol-9466 is an epoxy adhesive that offers strong bond strength, room temperature cure and high environmental durability. It adheres strongly to materials and

is resistant to impact, vibration, temperature, humidity and chemicals. Its low viscosity makes it easy to apply to difficult areas. The literature indicates that the adhesive layer should be 0.1–0.3 mm thick for better bond strength, while thicknesses above 0.6 mm reduce bond strength [30]. In this context, 0.2 mm thickness was selected, and application was carried out under a constant pressure of 0.1 MPa. The uniformity of the adhesive layer was checked by measuring with a digital caliper. The joints were tested after curing for 7 days to obtain full-strength performance.

In Table 3, the meaning of the sample coded G-7-K-1 is the sample number 1, which is 7-layered and was tested in dry environment (not kept in sea water) K, made of glass fiber-reinforced polymer (GFRP) with G. The meaning of the sample coded G-7-15A-3 in Table 3 is; It is sample number 3, has 7 layers, was kept in sea water for 15 months, was produced from glass fiber-reinforced polymer (GFRP) and was coded with G. The meaning of the sample coded C-8-K-1 is the sample number 1, which is 8-layered and tested in dry environment (not kept in sea water) K, made of carbon fiber-reinforced polymer (CFRP). The meaning of the sample coded C-8-15A-2 is in Table 3. It is sample number 2, has 8 layers, was kept in sea water for 15 months, was made of glass fiber-reinforced polymer (CFRP) and was coded with C. Figure 2 shows the coded examples of GFRP (a) and CFRP (b) samples.

Table 3. CFRP and GFRP sample coding.

Fiber Type	Number of Layers	Environment	Sample Coding
G (GFRP)	7	K (Dry)	G-7-K-1
			G-7-K-2
			G-7-K-3
G (GFRP)	7	1A (1 Month Sea Water)	G-7-1A-1
			G-7-1A-2
			G-7-1A-3
G (GFRP)	7	2A (2 Months Sea Water)	G-7-2A-1
			G-7-2A-2
			G-7-2A-3
G (GFRP)	7	3A (3 Months Sea Water)	G-7-3A-1
			G-7-3A-2
			G-7-3A-3
G (GFRP)	7	6A (6 Months Sea Water)	G-7-6A-1
			G-7-6A-2
			G-7-6A-3
G (GFRP)	7	15A (15 Months Sea Water)	G-7-15A-1
			G-7-15A-2
			G-7-15A-3
C (CFRP)	8	K (Dry)	C-8-K-1
			C-8-K-2
			C-8-K-3
C (CFRP)	8	1A (1 Month Sea Water)	C-8-1A-1
			C-8-1A-2
			C-8-1A-3

Table 3. Cont.

Fiber Type	Number of Layers	Environment	Sample Coding
C (CFRP)	8	2A (2 Months Sea Water)	C-8-2A-1
			C-8-2A-2
			C-8-2A-3
C (CFRP)	8	3A (3 Months Sea Water)	C-8-3A-1
			C-8-3A-2
			C-8-3A-3
C (CFRP)	8	6A (6 Months Sea Water)	C-8-6A-1
			C-8-6A-2
			C-8-6A-3
C (CFRP)	8	15A (15 Months Sea Water)	C-8-15A-1
			C-8-15A-2
			C-8-15A-3

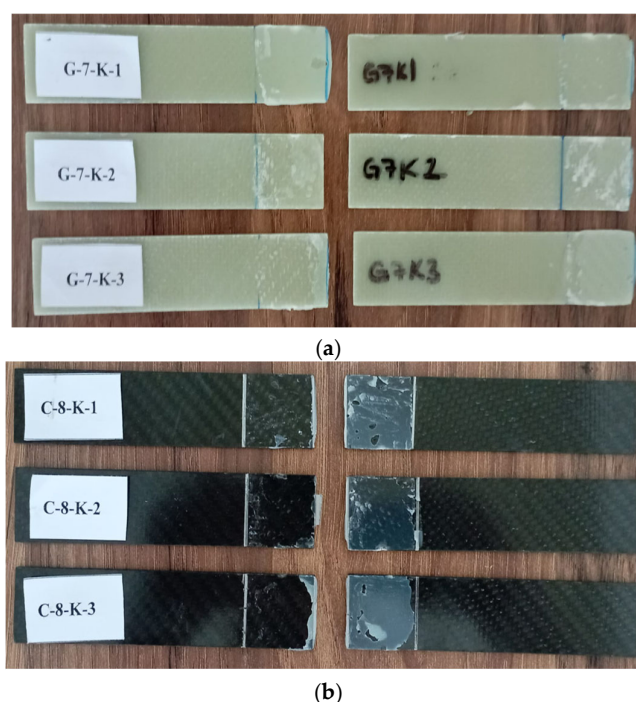


Figure 2. Coded examples of GFRP (a) and CFRP (b) samples.

Before the bonding process, the ends of each piece were marked with a ruler at 25 mm, and the adhesive was applied. The optimum adhesive thickness was determined as 0.2 mm, and a constant pressure of 0.1 MPa was applied to the samples. The thickness was kept at the same level in all samples by checking with a digital caliper. For the purpose of comparing the samples, 3 GFRP and 3 CFRP samples were stored in a dry environment that was not exposed to sea water. Then, the other samples were stored in sea water for 1, 2, 3, 6 and 15 months, respectively. For each month, 3 GFRP samples were obtained, making a total of 15 samples, and 3 CFRP samples were obtained, making a total of 15 samples. Then, these samples stored in sea water were compared with the samples in the dry environment (Figure 3). In this study, the effects of the adhesive on the seawater exposure time and the adhesive joint were investigated.

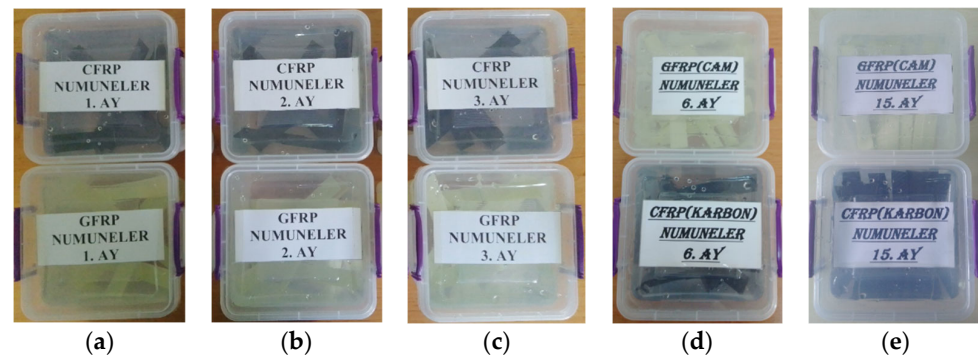


Figure 3. Soaking of GFRP and CFRP samples in sea water for (a) 1st month, (b) 2nd month, (c) 3rd month, (d) 6th month and (e) 15th month.

2.1. Sea Water Moisture

Single-lap bonded GFRP and CFRP specimens were tested using three samples from each group. Moisture retention rates were determined by measuring the weights of the specimens after immersion in seawater for 1, 2, 3, 6 and 15 months. These weights were calculated by comparing with the initial weights, and the results were visualized with graphics. Measurements were performed using a Daihan Biomedical analytical balance (DAIHAN Sci. Lab & Med. Inst. Mf, Korea) with a sensitivity of 0.1 mg (Figure 4).

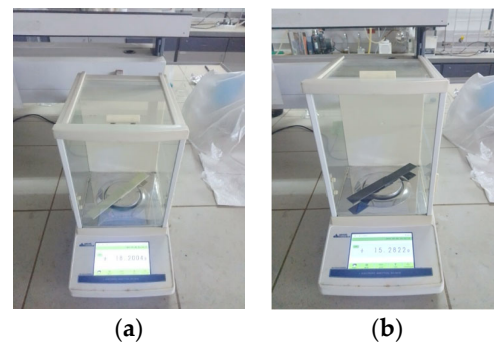


Figure 4. Daihan biomedical precision scale device: (a) GFRP and (b) CFRP.

2.2. Axial Impact Tests

Axial impact testing is a critical method for evaluating the energy absorption and damage resistance of composite materials under high-speed loading conditions. After the connection processes were completed, and the adhesive was completely cured, axial impact tests were performed to investigate the performance of GFRP and CFRP single-lap adhesive joints. These tests were conducted in the Composite Research and Testing Laboratory of the Mechanical Engineering Department at Dokuz Eylül University. During the test, a 48 cm long and 45° angled pendulum rod was released from a specified point, and an axial impact of 30 Joule was applied to the samples. The samples were placed in the apparatus shown in Figure 5a to transmit the impact energy from the axis to the bonding region. The test was based on determining the fracture energy of the sample by measuring the potential energy difference between the starting and ending positions of the pendulum [31]. It was evaluated as an indicator of the fracture resistance of the material (Figure 5b). For months 1, 2, 3, 6 and 15, a total of 30 samples were prepared, 15 from each GFRP and CFRP sample. In addition, 3 GFRP and 3 CFRP samples were also prepared in dry conditions (not stored in sea water). A total of 36 samples were obtained. Then, the samples stored in sea water were compared separately with the samples prepared in dry conditions.

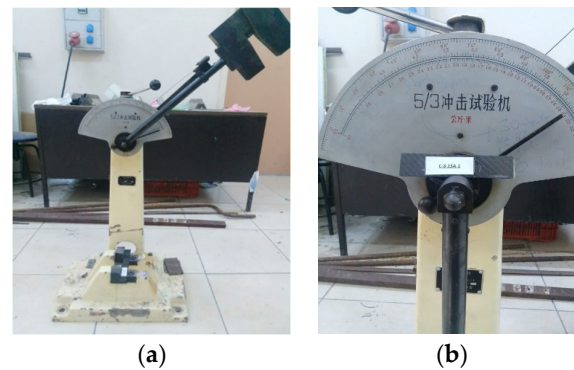


Figure 5. Application of axial impacts to the specimen: (a) mounting; (b) impact measurement.

The fracture energy of a material can be determined using the difference in potential energy of the hammer before and after impact. This energy represents the material's fracture resistance and is usually expressed in Joules (J) [32]. It is how much energy that the material absorbs before breaking.

It is given by the following:

The fracture energy,

$$W(a - b) = mgR(\cos \beta - \cos \alpha) \quad (1)$$

α : Hammer release angle ($^{\circ}$).

β : Angle of rise after impact ($^{\circ}$).

R : Pendulum arm (m).

m : Mass of the hammer (kg).

g : Gravitational acceleration (m/s^2).

Wa : Potential energy of the hammer before release (m).

Wb : After the sample is broken, the potential energy of the hammer rising to a height (m).

In the axial impact test, a 48 cm pendulum was dropped at a 45° angle, and a 30 J impact was applied.

3. Results

3.1. Sea Water Moisture Retention Rates

CFRP and GFRP samples were cleaned with moisture-absorbing paper before weight measurements, and their moisture retention rates were calculated with the relevant equation (Tables 4 and 5).

$$M(\%) = (m_y - m_k) / (m_k) \times (100) \quad (2)$$

Table 4. Moisture retention rate (%) of GFRP samples stored in dry environment and seawater for 1, 2, 3, 6 and 15 months.

Code	Weight (g)	Code	Weight (g)	Moisture Retention Rate (%)
G-7-K	17.2374	G-7-1A	17.3524	0.66
G-7-K	17.2374	G-7-2A	17.8593	3.43
G-7-K	17.2374	G-7-3A	17.9707	4.16
G-7-K	17.2374	G-7-6A	18.0389	4.65
G-7-K	17.2374	G-7-15A	18.0699	4.83

Table 5. Moisture retention rate (%) of CFRP samples stored in dry environment and seawater for 1, 2, 3, 6 and 15 months.

Code	Weight (g)	Code	Weight (g)	Moisture Retention Rate (%)
C-8-K	14.7965	C-8-1A	14.8808	0.57
C-8-K	14.7965	C-8-2A	14.9247	0.86
C-8-K	14.7965	C-8-3A	14.9252	0.87
C-8-K	14.7965	C-8-6A	14.9326	0.92
C-8-K	14.7965	C-8-15A	14.9385	0.96

Here,

m_k is the weight of the dry sample [g];

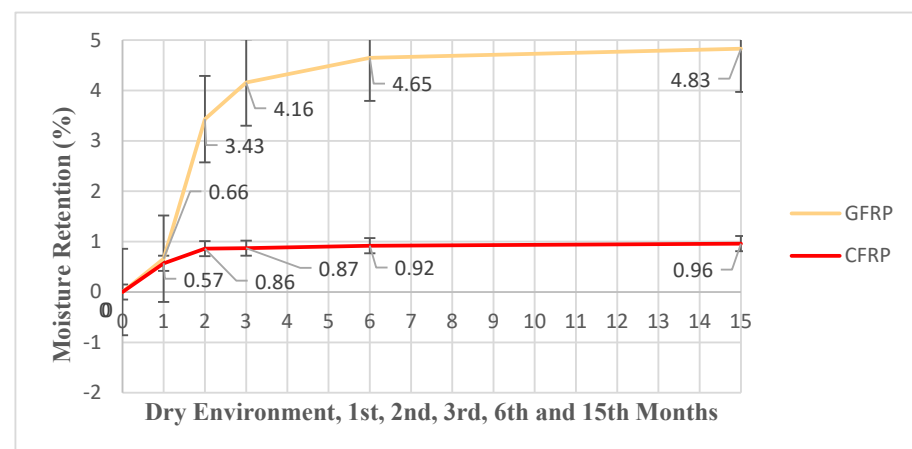
m_y is the weight of the wet sample [g];

M is the moisture retention percentage.

Figure 6 shows that the moisture retention rate increases as the residence time in seawater increases. Water generally enters the material through Fick diffusion. After a span of time, water molecules penetrate into deeper layers and increase the moisture retention percentage. However, this increase may slow down when a certain saturation level is reached [33]. Fickian theory helps to better understand the moisture diffusion mechanism of composite materials. Fick's first law describes the changes in the diffusion coefficient or concentration gradient. The second law deals with the cases where the diffusion coefficient changes with time or with the ambient conditions. According to Fick's second law of diffusion, the assumed moisture uptake (D) of composite materials is shown in Equation (3), and the theoretical mass change (M) due to immersion in water is shown in Equation (4). M_1 and M_2 denote the moisture content of the material at times t_1 and t_2 , while h denotes the thickness, L denotes the length, w denotes the width, and M_∞ denotes the maximum mass change.

$$D = \pi \left(\frac{h}{4M_\infty} \right)^2 \left(\frac{M_2 - M_1}{\sqrt{t_2} - \sqrt{t_1}} \right)^2 \left(1 + \frac{h}{L} + \frac{h}{w} \right)^{-2} \quad (3)$$

$$M = \left[1 - \frac{8}{\pi^2} \exp \left(-\pi^2 \frac{D_t}{h^2} \right) \right] M_\infty \quad (4)$$

**Figure 6.** Comparison of moisture retention rate of GFRP and CFRP in dry environment, 1st, 2nd, 3rd, 6th and 15th months.

Moisture uptake slows down with the accumulation of salt components on the composite surface and, according to Fick's law, it initially shows a linear increase and gradually decreases as saturation is reached.

Figure 6 shows that the increase continues in GFRP samples by reaching 0.66% in the first month, 3.43% in the second month, 4.16% in the third month, 4.65% in the sixth month and 4.83% in the fifteenth month. CFRP samples also show an increase, reaching 0.57% in the first month, 0.86% in the second month and 0.87% in the third month, 0.92% in the sixth month and 0.96% in the fifteenth month.

GFRP samples that were kept at 23.5 °C seawater temperature for 1, 2, 3, 6 and 15 months and single-lap adhesive joints that were formed were compared with dry environment (not exposed to seawater) samples (G-K-1, G-K-2 and G-K-3). Then, they were compared with CFRP samples (C-8-K-1, C-8-K-2 and C-8-K-3) in a dry environment (not exposed to seawater).

In Figure 6, the moisture content curves for both composites increased rapidly after 1 month of immersion in seawater. However, the moisture retention rates curves for GFRP and CFRP joint specimens show the same increasing profile at month 2, while the moisture gain is higher for GFRP single-lap joint specimens. At the end of month 3, GFRP single-lap joint specimens continued to show an increasing trend over time, while CFRP single-lap joint specimens showed a slightly increasing behavior. It shows that the moisture retention rate in GFRP continued to increase slowly until the sixth and fifteenth months. It is seen that the moisture retention rate in CFRP remained almost constant until the sixth and fifteenth months. This shows that GFRP single-lap adhesively bonded joint specimens tend to retain more moisture compared to CFRP.

Moisture retention rates (%) for single-lap adhesively bonded joints were 0.66%, 3.43%, 4.16%, 5.01% and 6.84% for GFRP samples for connections held in dry conditions and in seawater for 1, 2, 3, 6 and 15 months, respectively. In CFRP samples, the rates were 0.57%, 0.86%, 0.87%, 0.92% and 1.16%, respectively.

GFRP single-lap adhesive joint samples retained more moisture compared to CFRP. GFRP's higher porosity and tendency to microcrack formation facilitated water penetration. Since CFRP has higher chemical resistance, seawater absorption is limited. In GFRP single-lap adhesive joint samples, seawater absorption penetrated into the matrix material compared to CFRP, causing swelling, weakening of the polymer and deterioration at the fiber–matrix interface. This situation affected the mechanical strength of GFRP single-lap adhesive joint samples.

The reason why the GFRP single-lap adhesive joint retains more moisture over time is the tendency of the glass fibers to absorb water, the water absorption of the matrix material, and the microscopic voids at the fiber–matrix interface. In CFRP, it can be shown that carbon is more resistant to moisture due to its hydrophobic structure and denser crystal structure. Therefore, while the moisture retention rate of GFRP has increased over time, the change in CFRP has been minimal.

3.2. Axial Impact Tests

3.2.1. GFRP Specimens

Figure 7 shows that the GFRP subjected to an axial impact test was exposed to sea water for dry environment (a), 1 month (b), 2 months (c), 3 months (d), 6 months (e) and 15 months (f).

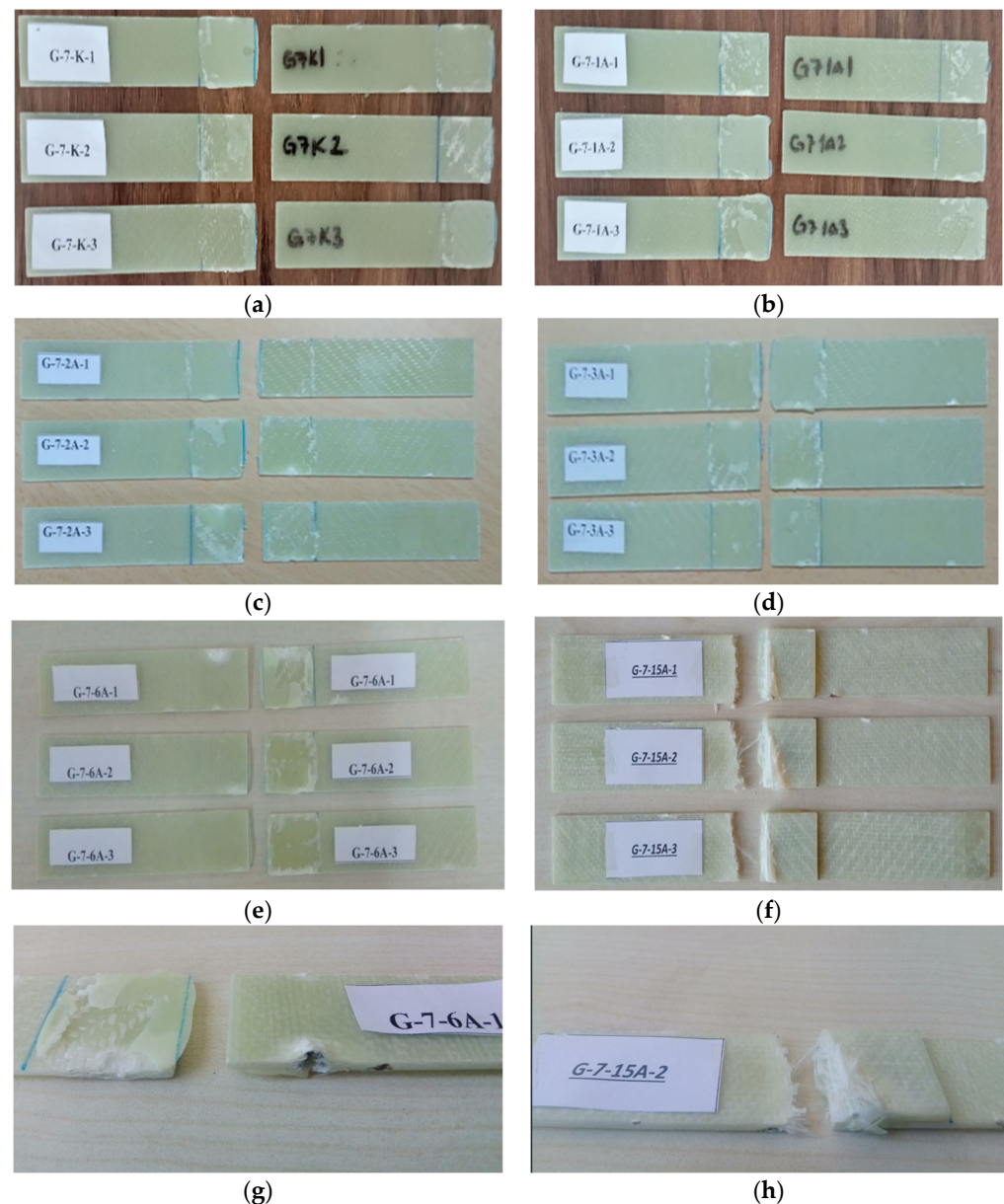


Figure 7. GFRP dry environment (a), 1st month (b), 2nd month (c), 3rd month (d), 6th month (e), 15th month (f), adhesive bondline fracture (6th month) (g) and interlaminar fracture, cohesive fracture (15th month) (h).

Figure 7 shows the images of the samples exposed to 30 J of impact energy in the dry environment, 1st, 2nd, 3rd, 6th and 15th months. As a result of the absorbed energy, stress concentrations occurred at the joint after the impact in all the samples in GFRP. The rupture started from the edges and progressed towards the inner parts [34]. The damage seen in GFRP dry environment samples is in the form of complete separation between the adhesive and the bonded surface (Figure 7a). In the GFRP samples kept in sea water for the 1st month, 2nd month, 3rd month and 6th month, the adhesive remained on both the upper and lower surfaces, and the rupture started off from the bond line. In other words, cohesive failure was observed [35]. In Figure 7f, fracture was observed in the samples starting from the 15th month.

Figure 7g shows interlaminar fracture (delamination), fiber rupture and matrix cracking in the GFRP sample. The separation between the layers indicates that the fiber–matrix bonds are weakened, while the fiber rupture occurred due to high impact or sudden load-

ing. In addition, the fragmentation of the matrix indicates that the material could not show sufficient strength under axial impact load.

Delamination, matrix cracking and crushing damages are seen in the GFRP samples in Figure 7h. On the left side, separation occurred between the layers, and fiber texture emerged. In addition, cracks and ruptures are observed in the matrix material. On the right side, a localized crushing damage is seen. Such damages negatively affect the mechanical strength of the GFRP and weaken its structural integrity. In addition, cohesive fracture damage was observed. This damage showed that the bond between the adhesive and the material was strong, but the internal structure of the material itself was not durable enough.

Table 6 presents the absorbed energy measurements of GFRP samples obtained with 30 J of impact in dry environment, 1st, 2nd, 3rd, 6th and 15th months. The average of G-K-7 dry environment samples subjected to an axial impact test is 1.39 J (G-7-1A). The average of samples kept in sea water for 1 month is 2.73 J (G-7-2A). The average of samples kept in sea water for 2 months is 4.42 J (G-7-3A). The average of samples kept in sea water for 3 months is 3.73 J (G-7-6A). The average of samples kept in sea water for 6 months is 4.91 J (G-7-15A). The average of samples kept in sea water for 15 months is 8.39 J (Figure 8).

Table 6. Measurements of GFRP specimens.

Samples	Measurements
G-7-K	1.39 J
G-7-1A	2.73 J
G-7-2A	4.42 J
G-7-3A	3.73 J
G-7-6A	4.91 J
G-7-15A	8.39 J

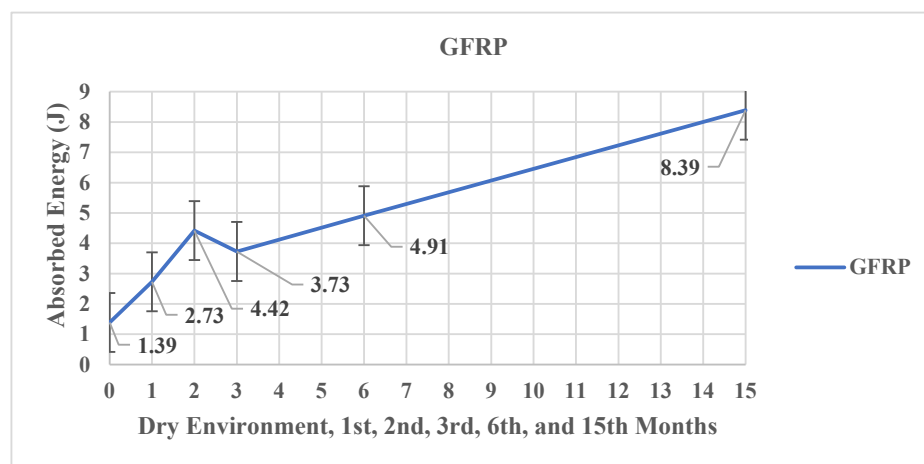


Figure 8. Absorbed energy amount graph of GFRP samples stored in dry environment and seawater for 1, 2, 3, 6 and 15 months.

3.2.2. CFRP Specimens

Figure 9 shows that the CFRP subjected to an axial impact test was exposed to sea water for dry environment (a), 1 month (b), 2 months (c), 3 months (d), 6 months (e) and 15 months (f)



Figure 9. CFRP dry environment (a), 1st month (b), 2nd month (c), 3rd month (d), 6th month (e) and 15th month (f), adhesive bondline fracture (6th month) (g) and cohesive fracture (15th month) (h).

Figure 9 shows the images of the samples exposed to 30 J of impact energy for the dry environment, 1st, 2nd, 3rd, 6th and 15th months. As a result of the absorbed energy, stress concentrations occurred at the joint after the impact in all CFRP samples. The damage observed in the CFRP dry samples is the complete separation of the adhesive from the substrate (Figure 9a). In the CFRP samples that were kept in seawater for the 1st month, 2nd month, 3rd month and 6th month, a break occurred at the bonding line. The composite layer and the bonding area were separated from each other. In Figure 9f, in addition to the breakage at the bonding line in the samples starting from the 15th month, some samples were broken. In Figure 9g, the failure of the adhesive bond line is generally related to the intensity and direction of the applied impact. In addition, seawater absorption and microcracks formed in the adhesive after the impact also caused the failure.

Figure 9h shows cohesive fracture damage. This is the fracture of the bonding material itself, while the adhesive bond line remains intact.

In GFRP and CFRP samples, as seawater absorption increased from the first month to the 15th month, the physical and mechanical properties of the resin matrix deteriorated due to plasticity. Water molecules increased chain mobility by acting as plasticizers [36]. Thus, the resin becomes both softer and more flexible [37]. However, the decrease in hardness and strength increases the ductility of the resin while also causing a loss of load-carrying capacity.

It was observed that the adhesive remained intact, but all of the samples broke, since the GFRP-bonded material, which was kept in sea water for 15 months, showed low strength under impact. In Figure 9f, it was observed that some samples broke, and some broke in CFRP. This is because the polymer matrix absorbs water, causing it to swell and become plastic [38]. This swelling weakens the matrix–fiber interface, creating internal stresses and microcracks that reduce the load-carrying capacity of the composite.

This weakens the adhesive bonds at the matrix–fiber interface, which negatively affects the overall structural integrity of the composite.

Table 7 shows the absorbed energy measurements of CFRP samples tested with 30 J of impact in dry environment in different months. While the average of dry environment samples is 1.28 J, the averages of samples stored in sea water are measured as 1.59 J (1 month), 1.93 J (2 months), 1.85 J (3 months), 2.45 J (6 months) and 3.59 J (15 months), depending on the durations (Figure 10).

Table 7. Measurements of CFRP specimens.

Samples	Measurements
C-8-K	1.28 J
C-8-1A	1.59 J
C-8-2A	1.93 J
C-8-3A	1.85 J
C-8-6A	2.45 J
C-8-15A	3.59 J

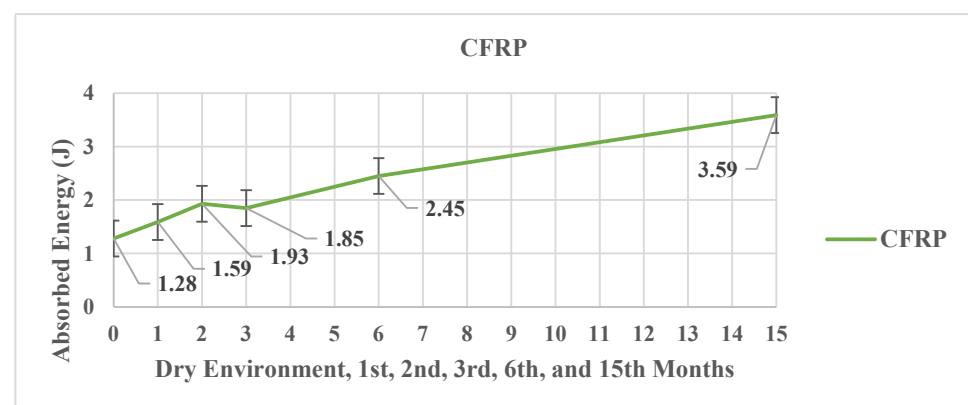


Figure 10. Graph of energy absorbed by CFRP samples in dry environment and sea water at different times (1, 2, 3, 6 and 15 months).

Absorbed energy measurements are shown in Figures 8 and 10. Here, as the immersion time in seawater increased, the amount of absorbed energy in GFRP increased more than in CFRP in the 6th and 15th months. This is because, as the GFRP composite material absorbed water, the water acted as a plasticizer and softened the material. This can lead to an increase in impact energy as it can become more flexible and less brittle over time. Also,

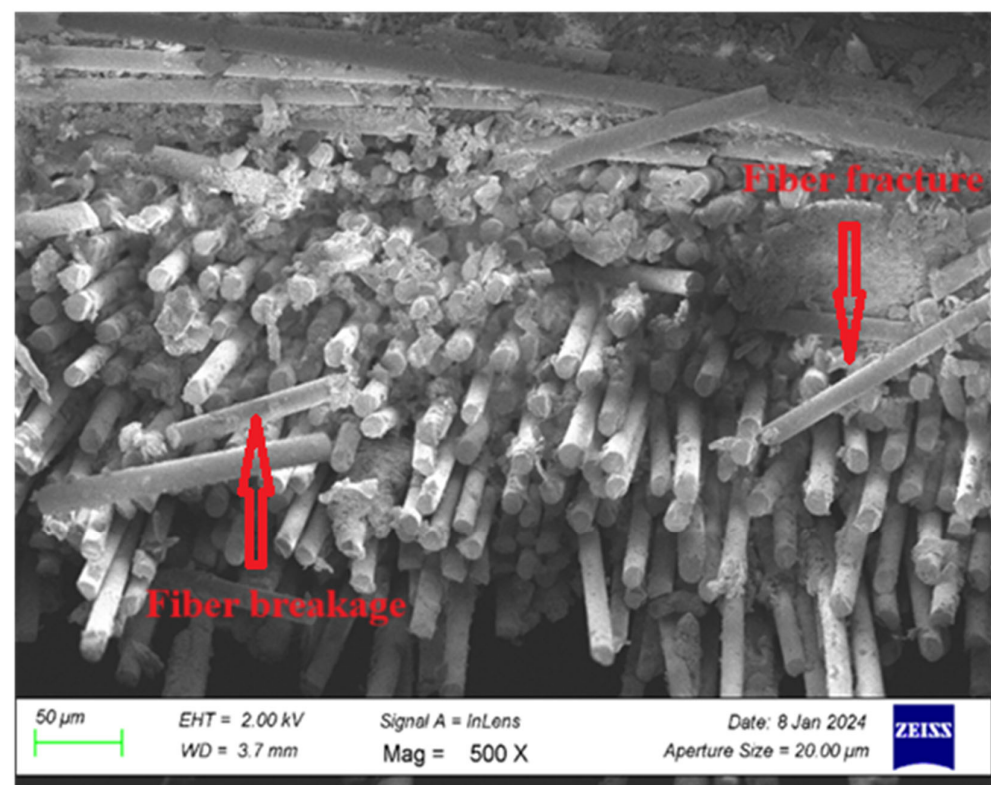
seawater contains salts and other chemicals that can interact with the matrix or fibers and cause chemical reactions such as hydrolysis [39].

These reactions can change the structure and properties of the material, potentially increasing its ability to absorb energy during impact.

3.3. SEM Analyses of GFRP and CFRP Specimens

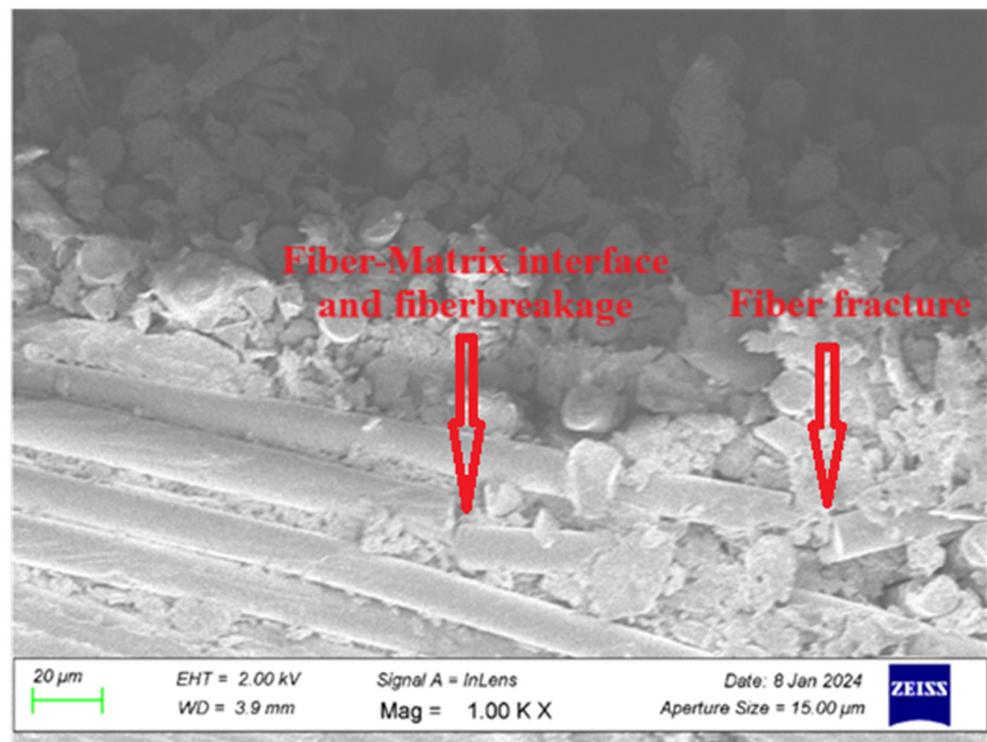
SEM images of GFRP and CFRP composite samples are given in Figures 11 and 12.

When the SEM image of the G-7-K sample is examined, irregular matrix pieces, rough vertical and cross-sectional surfaces of the fibers, are shown between the matrix and fibers (Figure 11a). Here, more fiber breaks and fiber ruptures are observed. In the G-7-1A sample, it was observed that the fibers broke off between 1.39 J and 2.73 J due to the deterioration of the matrix surface and that there were more gaps in the fiber–matrix interface bond compared to the sample kept in dry environment (Figure 11b). In the G-7-2A sample, fiber breaks, matrix leakage and the gap between the fiber–matrix interface bond increased even more at 4.42 J (Figure 11c). Figure 11d showed that the opening of the fiber–matrix bonds in the G-7-3A sample progressed a little more due to the penetration of the seawater solution into the matrix. In the G-7-3A sample, which was kept in seawater for 3 months, delamination occurred at 3.73 J, which caused the matrix to start cracking. In addition, the gaps between the fiber and the matrix increased, fiber breakage continued, and matrix leakage concentrated around the fibers in the transverse and vertical directions. The beginning of this delamination damaged the structure of the composite material. Matrix leakage, matrix ruptures and fiber breaks were observed in the G-7-6A sample (Figure 11e). It occurred between 1.85 J and 2.45 J. Intense fiber ruptures and fiber breaks were observed in the G-7-15A sample (Figure 11f). It occurred between 2.45 J and 3.59 J. When the SEM image of the C-8-K sample is examined, the fiber–matrix has a good interface bond (Figure 11f). The highest fiber breakage was observed in the C-8-K sample.

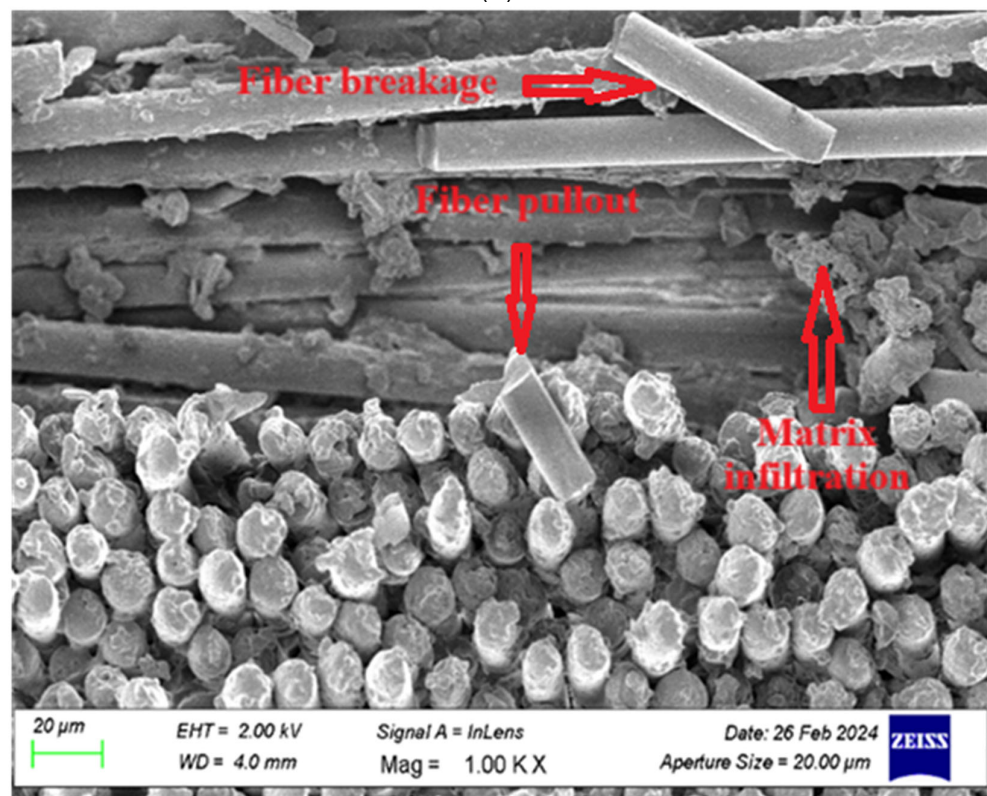


(a)

Figure 11. Cont.

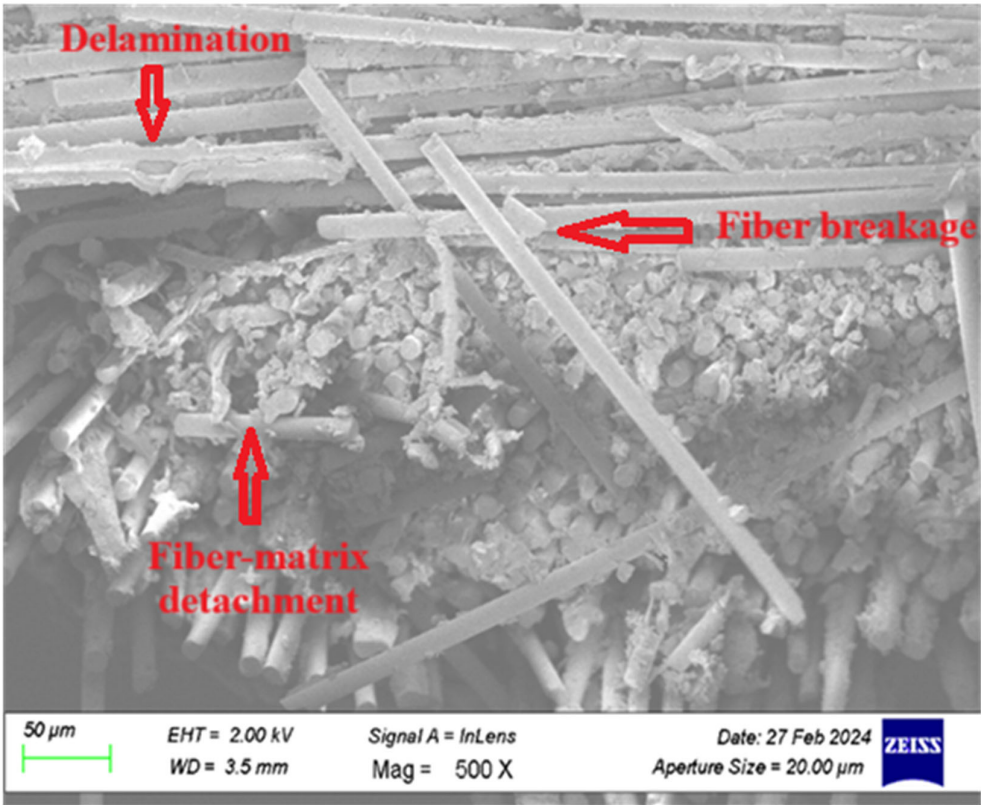


(b)

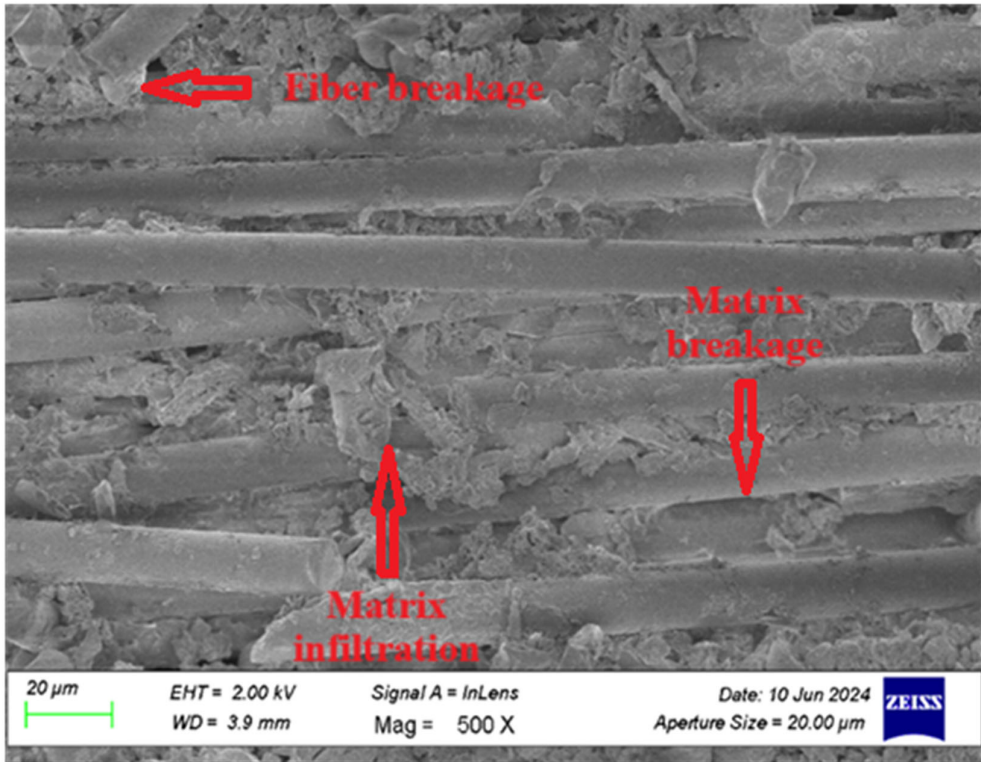


(c)

Figure 11. Cont.

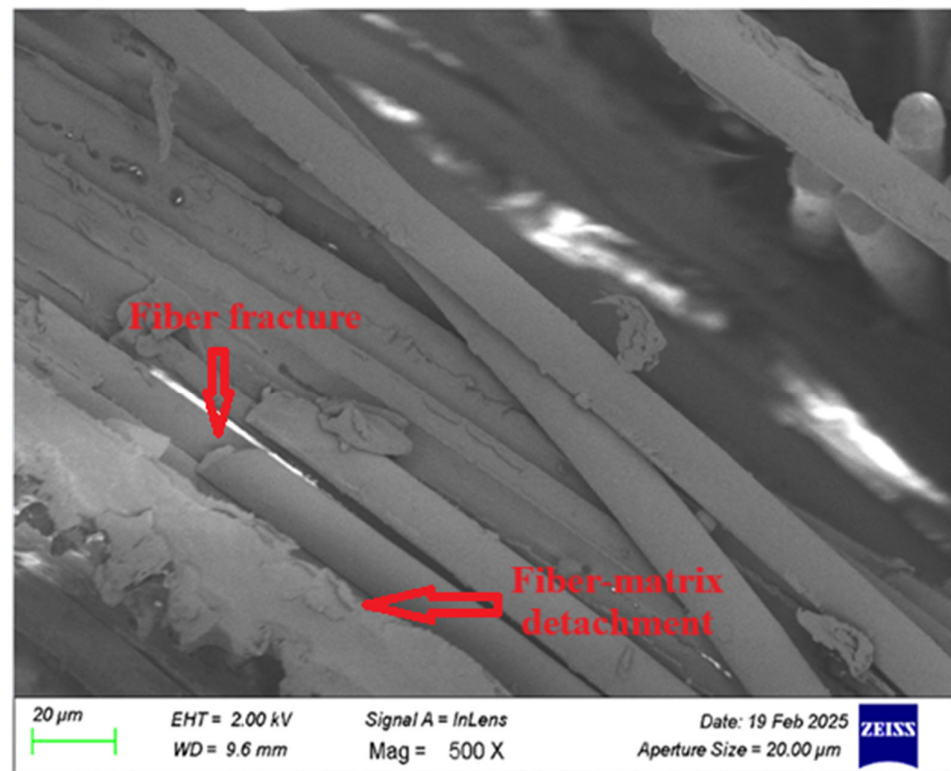


(d)



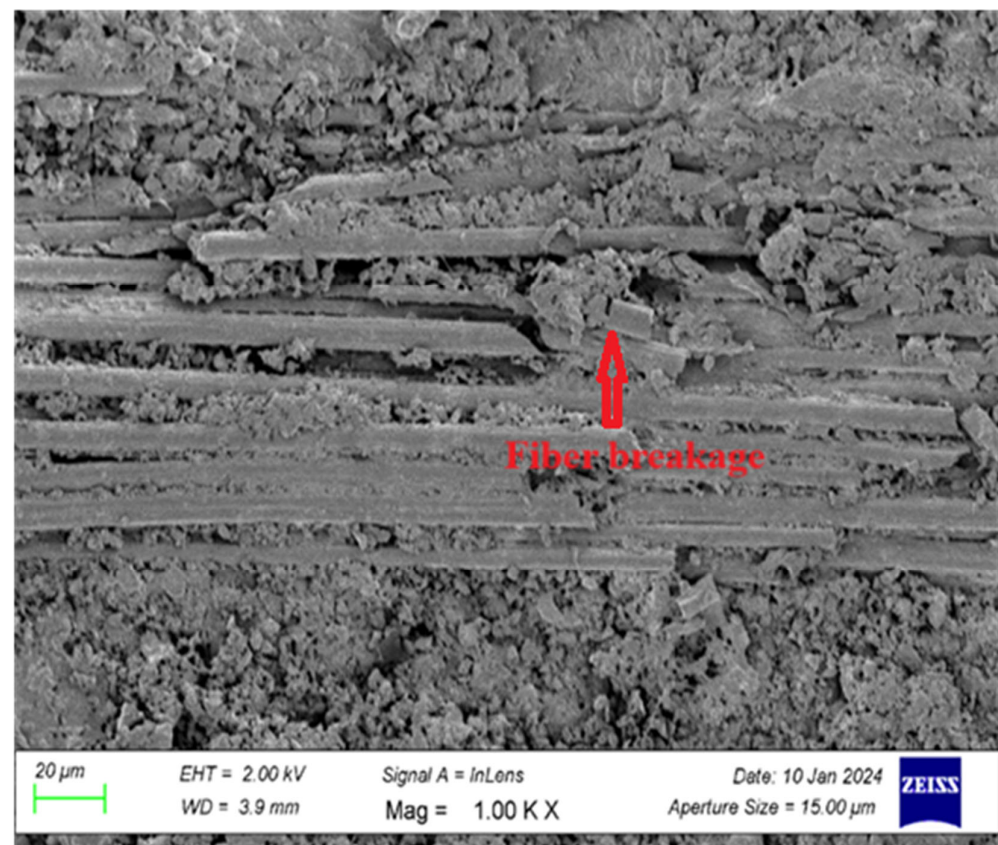
(e)

Figure 11. Cont.



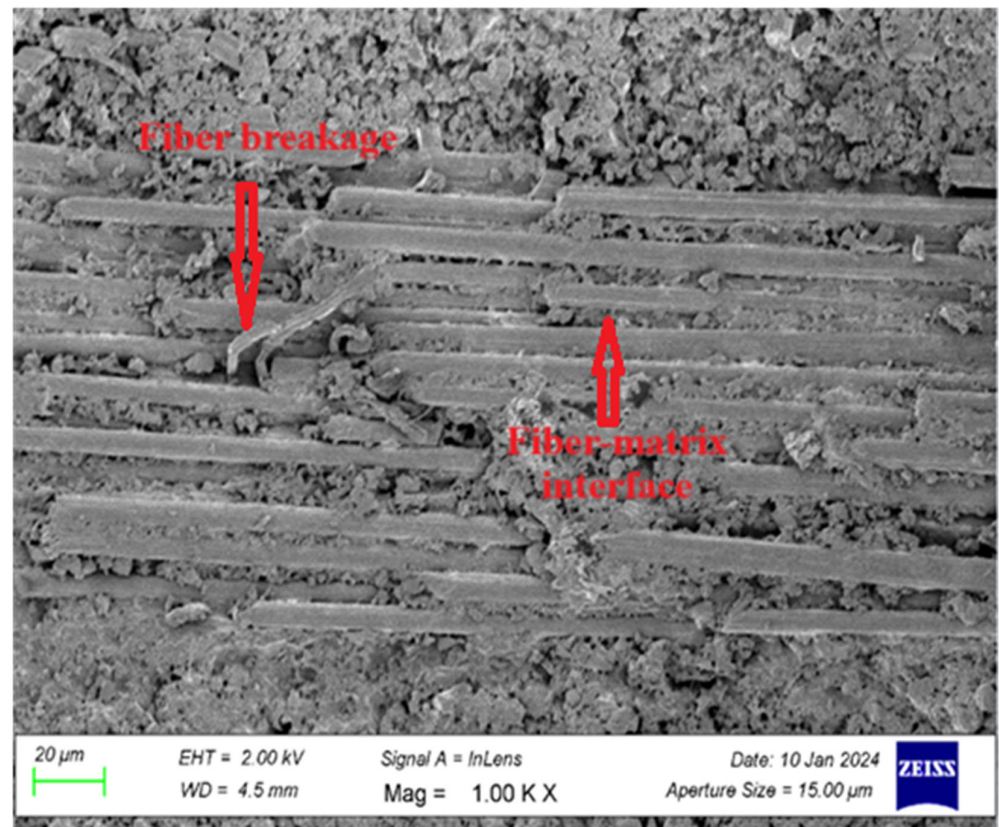
(f)

Figure 11. SEM image of GFRP composite material. (a) GFRP dry environment; (b) GFRP first month; (c) GFRP second month; (d) GFRP third month; (e) GFRP sixth month; (f) GFRP 15th month.

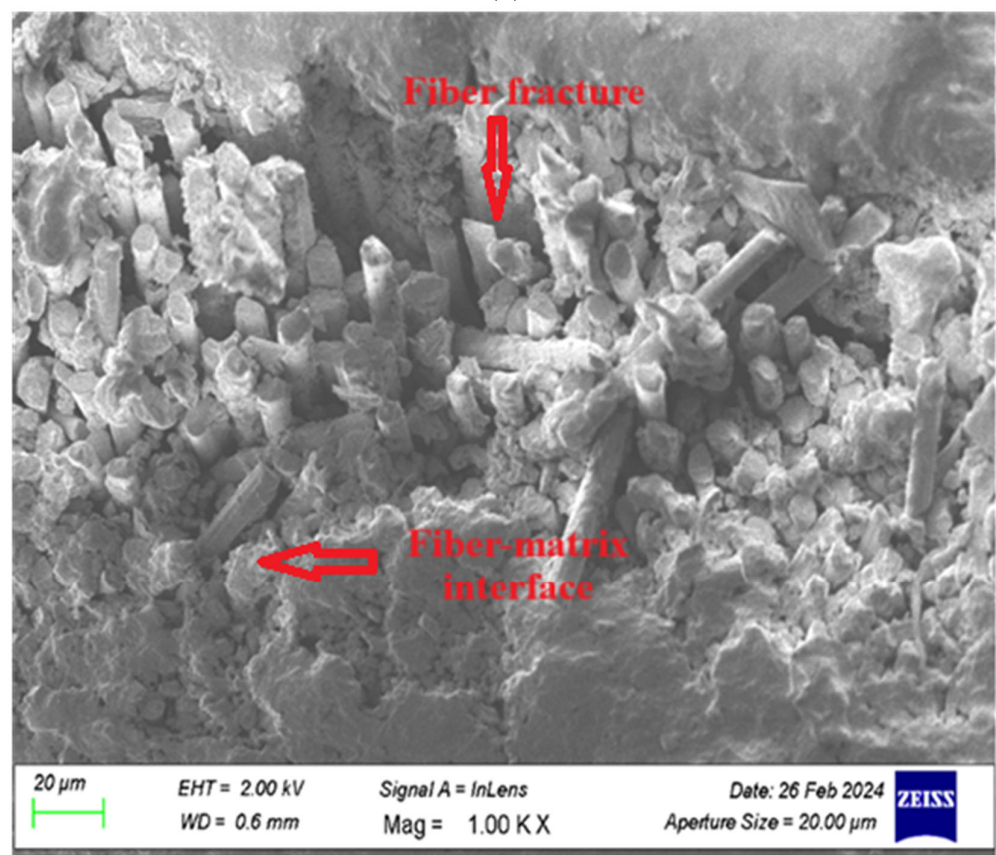


(a)

Figure 12. Cont.

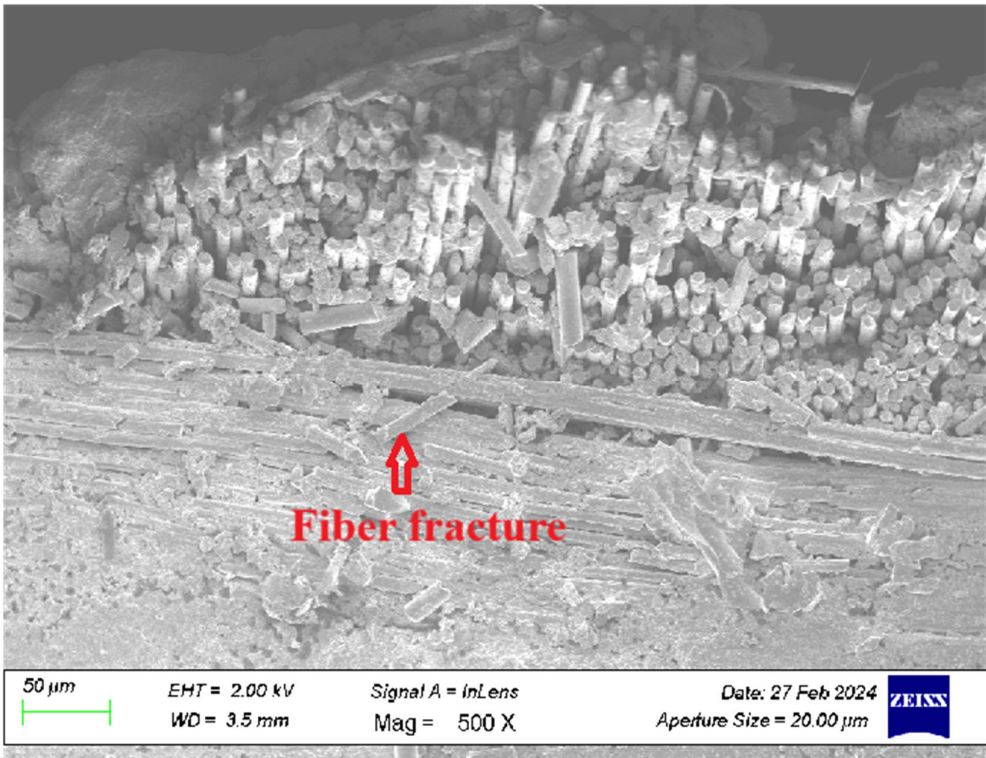


(b)

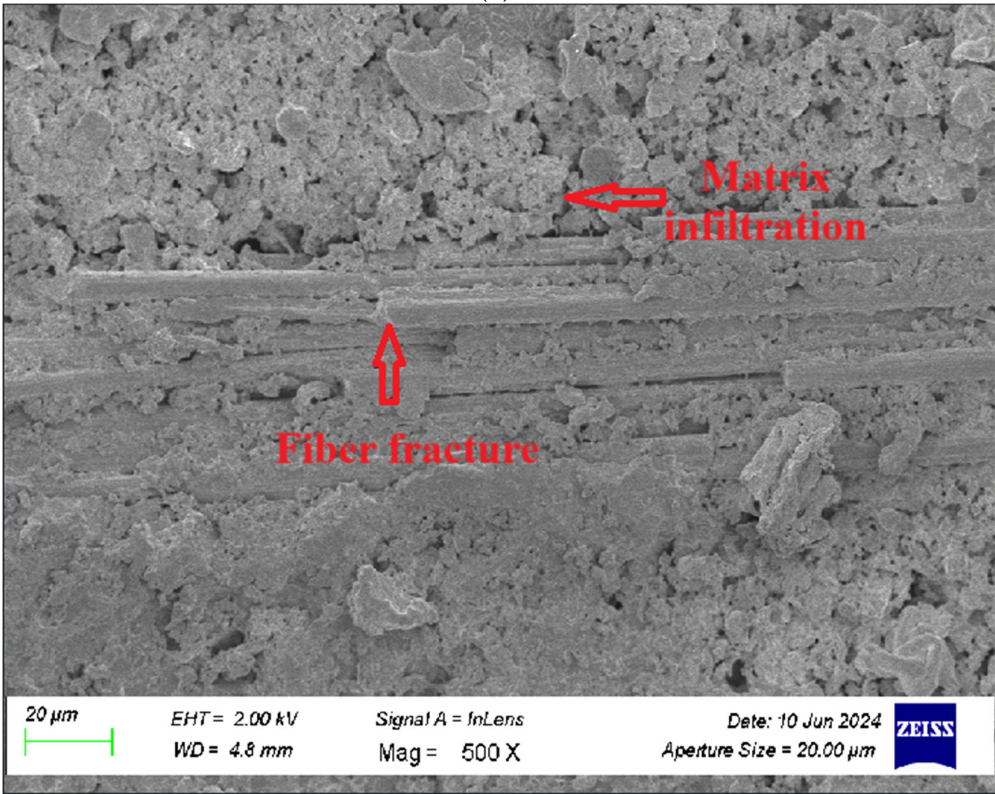


(c)

Figure 12. Cont.

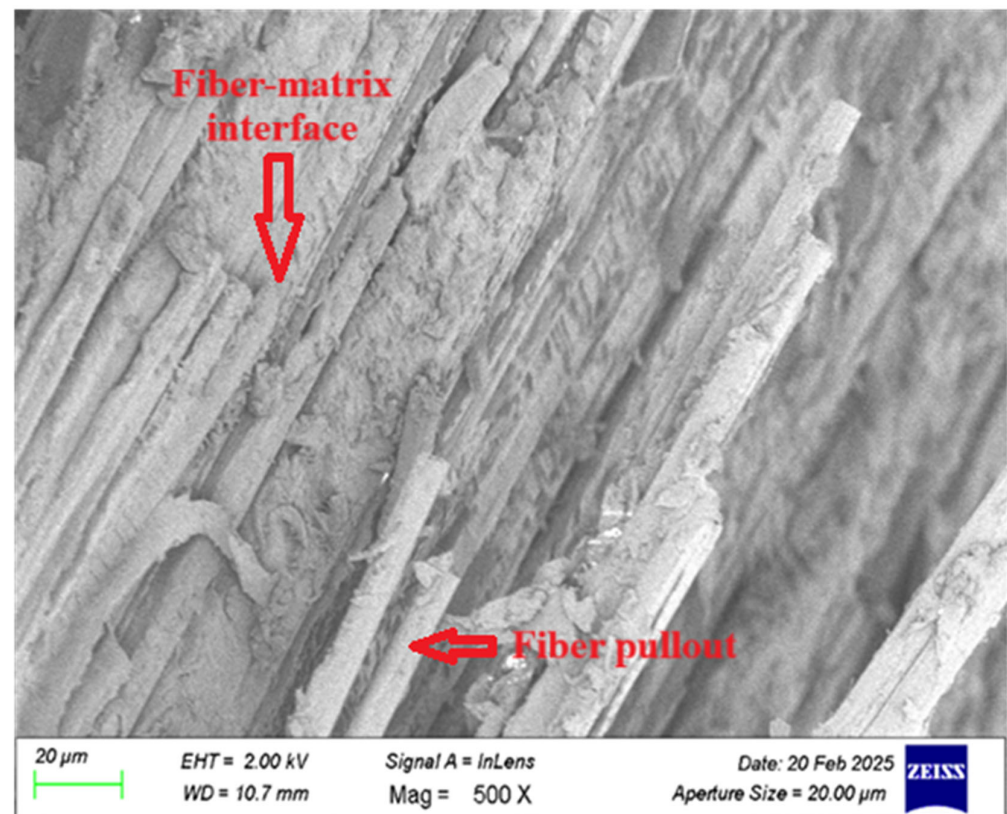


(d)



(e)

Figure 12. Cont.



(f)

Figure 12. SEM image of CFRP composite material. (a) CFRP dry environment; (b) CFRP first month; (c) CFRP second month; (d) CFRP third month; (e) CFRP sixth month; (f) CFRP 15th month.

Fiber breakage and fiber ruptures were observed in the C-8-1A sample with seawater absorption. It is observed that there is no significant change in the gaps in the fiber–matrix interface bond. This situation occurred between 1.28 J and 1.59 J (Figure 12b). In the C-8-2A sample, it was observed that the fiber breakage continued to some extent at 1.93 J, as in the sample kept in seawater for 1 month, but the fiber–matrix interface bond was not much different from the situation at 1.28–1.59 J (Figure 12c). It was observed that the breakage of the fibers and the gap between the fiber–matrix interface bond in the C-8-3A sample did not change much compared to the C-8-2A sample (Figure 12d). Here, fiber breakage was observed at 1.85 J, and the increase in the gap between the fiber–matrix interface bond was not different from 1.93 J. Fiber breakage and matrix infiltration were observed in the C-8-6A sample (Figure 12e). This occurred between 1.85 J and 2.45 J. It was observed that there was no significant separation in the fiber pullout and fiber–matrix interface bond in the C-8-15A sample (Figure 12f). This occurred between 2.45 J and 3.59 J.

If GFRP and CFRP single-lap connection samples are compared, fiber fractures and fiber breaks were detected in SEM images (Figure 11a). It was determined that the most intense fiber breaks were seen in Figure 11a. More voids were observed at the fiber–matrix interface in GFRP samples stored in seawater for the first month compared to CFRP samples. If GFRP and CFRP single-lap connected samples for dry samples are compared in SEM images, when the impact load is applied, the bond between the fiber and matrix in both connections is weakened, which can lead to fiber breakages and fractures. It was observed that the breakage was concentrated in the regions close to the connection point where the load was applied. However, it was observed that fiber breakages and fractures were more intense in GFRP dry samples compared to CFRP (Figures 11a and 12a).

The first crack formed by the impact effect spreads rapidly within the composite and causes the load-carrying fibers to break.

In the GFRP samples that were kept in seawater for the first month due to the effect of salt water, more voids were formed at the fiber–matrix interface compared to the CFRP samples. The reason for this is that glass fibers are more sensitive to salt water and have a higher water absorption tendency than carbon fibers (Figures 11b and 12b). After two months, fiber breakage, matrix leakage, and voids at the interface were detected in the GFRP specimens. This is due to the high water absorption capacity of glass fibers and their greater sensitivity to chemical deterioration (Figure 11c). On the other hand, no significant change was observed in the interface bond in the CFRP samples that were kept for two months. This can be associated with the lower water absorption capacity, high chemical resistance and mechanical strength of carbon fibers (Figure 11c).

In GFRP samples kept in seawater for 3 months, it was observed that the gaps between the fiber–matrix interface increased compared to the previous months, while there was no significant change in CFRP samples. More fiber breaks were observed in CFRP samples (Figures 11d and 12d). In GFRP samples kept in seawater for 6 months, fiber breaks and fiber ruptures increased even more. This is due to the erosion of glass fibers in GFRP samples with seawater absorption over time (Figure 11e). Matrix cracking was observed in CFRP samples. Matrix cracking is generally a progressive type of damage and tends to weaken the fiber–matrix interface over time, but this situation alone may not constitute a critical damage (Figure 12e). As it is known, fiber breaks are more dangerous because they directly affect the load-carrying capacity of the material [40].

In GFRP samples that were stored in seawater for 15 months, as the storage time in seawater increased, the internal stresses in the GFRP samples increased, leading to the growth of microscopic cracks at the fiber–matrix interface. This weakened the fiber–matrix interface in the GFRP samples, and the samples broke when the impact load occurred (Figure 11f). In CFRP samples, since they are more resistant to seawater absorption thanks to their chemical resistance properties, the formation of microscopic cracks and because gaps at the fiber–matrix interface are fewer. Here, most of the samples did not break (Figure 12f).

4. Discussion and Conclusions

Composite adhesive joints have generally been studied on a single material and a specific joint structure. However, the effects of different composites and environmental factors remain uncertain. These uncertainties constitute a significant problem in terms of reliability and durability in applications. Examining the behavior of the material after impact helps to evaluate the degree of damage and its effect on mechanical properties. Scanning electron microscope (SEM) images were used to examine the moisture retention rates (%) and the behavior of the material after impact. Thus, matrix cracks, fiber fractures, fiber–matrix interface separations and delaminations were observed in detail. The degree of damage and crack propagation mechanisms were examined, and the weak points of GFRP and CFRP single-lap adhesive joint composite samples were determined. Changes in mechanical properties and the post-impact strength of GFRP and CFRP composite samples were evaluated.

Axial impact tests and moisture retention rates (%) of GFRP and CFRP single-lap adhesively bonded joint samples were measured. The holding times of GFRP and CFRP samples in dry conditions and in seawater were evaluated by comparing them with dry samples at the end of 1, 2, 3, 6 and 15 months.

The results are as follows:

In single-lap adhesive bonded joints, GFRP samples retained 0.66% moisture under dry conditions, while this rate increased to 6.84% in seawater for up to 15 months. In CFRP samples, the moisture retention rate was 0.57% under dry conditions and reached 1.16% after 15 months. GFRP showed more moisture absorption compared to CFRP.

GFRP single-lap adhesive-bonded samples retained more moisture compared to CFRP. Higher porosity and microcrack formation increased water penetration. Since CFRP has higher chemical resistance, seawater absorption was limited. In GFRP, water penetration into the matrix material caused swelling, polymer weakening and deterioration at the fiber–matrix interface, reducing mechanical strength.

As a result of axial impact tests performed using 30 J of impact energy, the fracture toughness of single-lap adhesive joints increased depending on the retention time in seawater in both GFRP and CFRP samples. The fracture toughness in GFRP samples was measured as 4.6% in dry environment and reached 9.1%, 14.7%, 11.23%, 16.36% and 27.96% when stored in seawater for 1, 2, 3, 6 and 15 months, respectively. In CFRP samples, these rates were 4.2% in dry environment and 5.3%, 6.4%, 6.1%, 8.16% and 11.96% when stored in seawater for 1, 2, 3, 6 and 15 months, respectively. These data show that exposure to seawater increases the fracture toughness of both materials, but this effect is more pronounced in GFRP samples.

According to the results, seawater absorption increased the impact energy of GFRP compared to CFRP single-lap adhesive connection. The reason is that seawater penetrated into the polymer matrix, made the material more flexible and delayed sudden fractures by filling the micropores. It also weakened the fiber–matrix interface. This allowed more energy to be absorbed during the impact. Thus, it reduced the mechanical strength of GFRP and accelerated the formation of cracks. As a result of the moisture retention rates (%) and axial impact tests in the seawater environment, it was found that CFRP single-lap adhesive connection samples exhibited longer durability compared to GFRP. This situation shows in SEM images that the fiber and matrix bond weakens under impact load, which causes fractures and cracks. While fractures are concentrated near the load point, it was observed that the damage in GFRP samples was greater than in CFRP. The main reasons for this situation are low water absorption, chemical resistance and strong matrix–material compatibility. In addition, the degree of damage at the connection point in single-lap adhesive connection GFRP and CFRP samples after the impact test helps to understand how it affects the structural integrity and strength of the composite material. Thus, single-lap adhesive bonding plays a critical role in predicting the service life of GFRP and CFRP composite materials and developing necessary strengthening or repair strategies.

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