HITTITE JOURNAL OF SCIENCE AND ENGINEERING

e-ISSN: 2148-4171
Volume: 12 • Number: 2
June 2025

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Özkan Özbek[1] | Zeynal Abidin Oğuz[*2] | Ahmet Erkliğ[3] | Ömer Yavuz Bozkurt[3]

[1]Pamukkale University, Faculty of Engineering, Mechanical Engineering Department, 20160 Denizli, Türkiye.
[2]Adıyaman University, Besni Ali Erdemoğlu Vocational School, Mechatronics Department, 02040 Adıyaman, Türkiye.
[3]Gaziantep University, Faculty of Engineering, Mechanical Engineering Department, 27310 Gaziantep, Türkiye.

Corresponding Author

Zeynal Abidin Oğuz

E-mail: zoguz@adiyaman.edu.tr Phone: +90 554 845 42 05
RORID[1]: https://ror.org/01etz1309 RORID[2]: https://ror.org/02s4gkg68 RORID[3]: https://ror.org/020vvc407

Article Information

Article Type: Research Article
Doi: https://doi.org/10.17350/HJSE19030000352
Received: 27.02.2025
Accepted: 09.04.2025
Published: 30.06.2025

Cite As

Özbek Ö, et al. Performance analysis of environmental conditioning effect on crush character of hybrid composite pipes with different winding angles . Hittite J Sci Eng. 2025;12(2):59-67.

Peer Review: Evaluated by independent reviewers working in at least two different institutions appointed by the field editor.
Ethical Statement: Not available.
Plagiarism Checks: Yes - iThenticate
Conflict of Interest: Authors declare no conflict of interest.

CRediT AUTHOR STATEMENT

Özkan Özbek: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Supervision, Writing – review and editing. **Zeynal Abidin Oğuz:** Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Supervision, Visualization, Writing – original draft & editing. **Ahmet Erkliğ:** Conceptualization, Data Curation, Formal Analysis, Methodology, Validation, Writing. **Ömer Yavuz Bozkurt:** Conceptualization, Data Curation, Formal Analysis, Methodology, Validation, Writing.

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[1]Pamukkale University, Faculty of Engineering, Mechanical Engineering Department, 20160 Denizli, Türkiye.
[2]Adıyaman University, Besni Ali Erdemoğlu Vocational School, Mechatronics Department, 02040 Adıyaman, Türkiye.
[3]Gaziantep University, Faculty of Engineering, Mechanical Engineering Department, 27310 Gaziantep, Türkiye.

Abstract

The effects of hydrothermal aging in distilled water (DW) and seawater (SW) environments on the water absorption behavior and crush characteristics of hybrid glass/carbon fiber-reinforced composite pipes with ±55° and ±70° winding angles were evaluated. Specimens were kept for 120 days at 30°C, and water absorption was analyzed experimentally and theoretically. Results revealed that distilled water-aged samples exhibited higher maximum water absorption rates (2.5% for DW55 and 2.62% for DW70) compared to seawater-aged samples (2.37% for SW55 and 2.44% for SW70), attributed to the inhibitory role of ionic components in seawater. Lower winding angles consistently showed greater water absorption due to increased microstructural voids, facilitating water diffusion. Quasi-static axial compression tests demonstrated significant degradation in crush performance after aging. Unconditioned samples with 70° winding angles achieved the highest initial peak load (56.9 kN) and specific energy absorption (28.89 J/g). However, aging reduced these values, with seawater-aged samples (SW55) showing a 12.32% decrease in specific energy absorption compared to unconditioned counterparts. Crushing force efficiency (CFE) also declined, correlating with matrix plasticization and fiber/matrix interface weakening. Notably, hybrid pipes with 55° winding angles exhibited superior energy absorption (30.44 J/g for U55), emphasizing the role of fiber orientation in load distribution.

Keywords: Hybrid composites, Hydrothermal aging, Winding angle, Fickian diffusion, Crush performance, Energy absorption

INTRODUCTION

Composites have numerous better qualities compared to conventional materials. Since these materials are formed by combining different components, they can simultaneously carry opposing properties such as high strength and lightness. In particular, high specific strength (strength/density ratio) and specific stiffness (stiffness/density ratio) values make composites indispensable in sectors where lightweight and durable materials are critical, such as aerospace, automotive and construction. In addition, their properties such as corrosion resistance, fatigue life and chemical resistance are superior to traditional metals and alloys [1,2]. For this reason, composite materials are widely preferred in order to increase performance and efficiency in modern engineering applications. Composite pipes offer significant advantages over pipes manufactured with traditional materials in industrial and industrial applications. These pipes stand out with their features such as high corrosion resistance, lightness, long life and low maintenance costs. Especially in sectors such as petrochemical, energy, water and wastewater management, composite materials provide a more durable and economical solution than metal pipes in pipelines exposed to aggressive chemicals and harsh environmental conditions. In addition, the high mechanical strength and low thermal conductivity of composite pipes minimize energy losses and increase system efficiency. Therefore, composite pipes are of great importance in terms of the sustainability and performance of modern industrial infrastructures. Testing the sensitivity of composite pipes to environmental aging is critical to assessing the long-term performance and reliability of these materials. Environmental factors (humidity, water, UV rays, temperature changes, chemical exposure, etc.) can affect the mechanical properties of composite materials, causing structural changes. Such aging effects can change the load-bearing capacity, leak-tightness, and overall service life of pipes [3,4]. Therefore, accelerated aging tests performed in laboratory environments help predict the durability and performance of composite pipes by simulating their behavior under different environmental conditions. These tests enable improvements in the design and material selection of pipes, ensuring their safe and sustainable use in industrial applications.

Zuo et al. [5] evaluated the crashworthiness of carbon fiber reinforced plastic (CFRP) composite tubes under thermal and hydrothermal aging conditions were experimentally investigated. CFRP tubes were subjected to thermal aging at temperatures of 25°C, 70°C, 100°C and 160°C and to hydrothermal aging at 25°C and 70°C. As a result of the experiments, it was observed that the impact strength of CFRP tubes decreased significantly with increasing temperature. For example, specific energy absorption (SEA) decreased by 35% at 70°C, 86% at 100°C and 94% at 160°C. As a result of hydrothermal aging, water absorption reached 1.4118% at 70°C, and this reduced the average crushing load of CFRP tubes by 25%. Microscopic examinations showed that temperature and humidity significantly affected the bonding state between the fiber and the resin.

The behavior of glass reinforced epoxy (GRE) composite pipes with [±55°]4 winding angle at multiaxial stress rates under accelerated hydrothermal aging conditions was experimentally investigated by Krishnan et al. [6]. The pipes were aged by exposure to water at 80°C for 1500 h and then subjected to multiaxial cyclic loading tests at five different stress rates. Axial and circumferential strength reductions of up to 14% were observed in the aged pipes. Scanning electron microscope (SEM) images revealed a significant separation between the epoxy resin and glass fibers in the aged samples. The results show that hydrothermal aging significantly affects the mechanical properties of GRE pipes, and especially the axial strength is damaged more.

Fitriah et al. [7] investigated the effects of hydrothermal aging on the compressive strength of glass fiber reinforced epoxy (GRE) composite pipes. Pipes with three different winding angles (±45°, ±55°, ±63°) were aged for 500, 1000 and 1500 hours in tap water at 80°C and compression tests were conducted at different temperatures such as 25°C, 45°C and 65°C in accordance with ASTM standard. The results showed that the strength of the pipes decreased significantly as temperature and aging time increased, but the strength increased as the winding angle decreased. For example, the strength of the pipes with ±45° angle at 25°C decreased from 118.9 MPa to 64.6 MPa, while the strength of the pipes with ±63° angle decreased from 59.4 MPa to 37.2 MPa. The experimental results were predicted by the Berbinau model and agreement was achieved with a maximum deviation of 25%.

Sepetçioğlu et al. [8] searched the effect of hydrothermal aging on the mechanical properties was investigated by adding 0.25% graphene nanoplatelets (GnP) to basalt fiber reinforced epoxy composite pipes (BFRP). Mechanical properties such as water absorption, hardness, density and environmental tensile strength were tested in accordance with ASTM standards in samples aged in distilled water at 80 °C for 15, 30, 45 and 60 days. Aging showed that the mechanical properties of BFRPs decreased significantly due to water absorption and temperature-induced stresses; for example, the environmental tensile strength of unaged unreinforced samples decreased from 677.9 MPa to 430.6 MPa at the end of 60 days, while this decrease was from 694.7 MPa to 449.1 MPa in GnP reinforced samples. GnP reinforcement reduced mechanical losses by strengthening the fiber-matrix interfacial bonds. Additionally, the hydrophobic properties of GnP reduced water absorption and contributed to the preservation of mechanical properties.

Kara et al. [9] assessed the impact character and mechanical properties of hydrothermally aged multiwalled carbon nanotube (MWCNT) reinforced carbon composite pipes with ±55° winding angle were investigated. For aging conditions, fluid, temperature and aging time were selected as distilled water, 80°C and 3 weeks, respectively. The samples subjected to ring tensile test (ASTM D 2290) and low-velocity impact tests at 5, 10, 15 J energy levels after aging. The results showed that MWCNT reinforcement increased the tangential tensile strength of the composite pipes, but this strength decreased with the aging process. For example, after 3 weeks of aging, the tangential tensile strength decreased by 17% in MWCNT-reinforced samples and by 13% in samples without MWCNT reinforcement. In low-velocity impact tests, MWCNT reinforcement increased the impact resistance, but the aging process negatively affected this resistance. In particular, the maximum contact force decreased by 26% in particulated pipes after 3 weeks of aging. The aging process increased the damage mechanisms such as delamination and matrix cracks in the samples and decreased the impact durability of the material. It was discovered that MWCNT reinforcement increased the mechanical characteristics of pipes, however aging largely removed this benefit.

Oğuz et al. [10] studied the the crushing character of hybrid and non-hybrid composite pipes under hydrothermal aging process. Composite pipes are created using glass, basalt and carbon fibers. For aging conditions, fluid, temperature and aging time were selected as purified water/seawater, 30°C and four months. The water absorption data were defined both theoretically and experimentally. The results revealed that basalt pipes had the highest water absorption rate (10.45% in distilled water, 8.44% in seawater), while glass pipes had the lowest water gain rate (1.45% in distilled water, 1.29% in seawater). The mass change rates of hybrid samples remained between these values depending on the fiber types they contained. The aging process adversely affected the crushing character of the samples, and especially the load carrying capacity and energy absorption decreased significantly because of the deterioration at the fiber/matrix interface. For example, while unaged carbon fiber reinforced pipes showed a specific energy absorption of 35.3 J/g, this value decreased by 24-29.3% in aged hybrid CB pipes. Hybrid pipes were particularly effective in improving the performance of pipes with low crushing properties. Hybrid constructions were therefore proposed as a potential advantage for pipelines that may be subjected to severe environmental conditions.

Özbek et al. [11] investigated the different aging conditions effect on the mechanical properties of glass/basalt hybrid pipes after 2500 h aging exposure. Aging negatively affected the mechanical properties; specific energy absorption values decreased by 3.26–11% (distilled water) and 7.31–18.23% (seawater) in glass fiber reinforced samples. The highest specific energy absorption value of 32.9 J/g was observed in the unaged 55% angle glass fiber sample. Aging decreased the load carrying capacity and increased the brittleness of the material, but hybrid samples exhibited a more stable crushing behavior.

In this study, hybrid glass/carbon fiber reinforced composite pipes with ±50° and ±70° winding angles were subjected to hydrothermal aging in both distilled water and seawater environments for 120 days at 30°C, and the effects of water absorption behaviors on the crush properties were investigated. Although there are various studies in the literature on water absorption mechanisms and mechanical performances of composite pipes after aging, most studies have focused on structures containing only single fiber type or short-term aging conditions. In this study, experimental and theoretical water absorption models were derived by considering hybrid fiber content and different winding angles, and their effects on specific energy absorption, load carrying capacity and fracture mechanisms were investigated in detail. In particular, the role of fiber type and winding angle on mechanical weakening due to water absorption was revealed, and the effects of long-term hydrothermal aging on the crush properties of hybrid composite pipes were evaluated more comprehensively. In this respect, the study provides an original contribution to the literature by providing important engineering data for maritime, pipelines and applications requiring structural safety.

MATERIALS & METHODS

Materials

In this study, the fiber reinforcements in the pipe samples were used as carbon roving fiber with a 7 µm filament diameter (Dost Kimya A. Ş., Turkey) and glass fiber roving having a 17 µm filament diameter (Plasto A. Ş., Turkey). To create the matrix phase of the samples, EPIKOTE MGS LR160 resin (Dost Kimya A. Ş., Turkey), and EPIKURE MGS LH260S

Curing Agent (Dost Kimya A. Ş., Turkey) were considered and they were mixed in a stoichiometric weight ratio of 100:35, respectively. The mechanical and physical properties of these materials are given in Table 1.

Table 1 The properties of raw materials [17]

Material	Linear Density (tex)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Elongation at Break (%)	Specific Density (g/cm³)
Carbon Fiber	800	3950	238	1.5	1.77
Glass Fiber	2400	1970	79	3.5	2.56
Epoxy (neat)	-	70-80	3.2-3.5	5.0-6.5	1.18-1.20

Sample Preparation

For all sample fabrication, the filament winding technique which is schematically seen in Figure 1 was used. Interply fiber hybridization is the presence of different fibers in different layers and offers non-homogeneous performance between layers. However, intraply fiber hybridization means winding more than one different filament on the same layer and means having the same fibers in each layer. Therefore, intraply fiber hybridization was planned in the study. Firstly, the fiber reinforcements passing through rollers and resin bath were oriented with the desired parameters. To create intraply fiber hybridization, fiber bundles were stacked side by side. Then, wet fibers were wrapped around a mandrel with the help of motion codes given to the machine. After the winding process, a release agent film was covered, and curing at room temperature was applied for a day. After this period, the pipes were kept at 40°C for 2 hours to perform post-curing [21]. Finally, the samples by cutting with a diamond sawing process were prepared at the desired dimensions with 49.5±1 mm in length. Additionally, their inner and outer diameters were measured as 46.3±0.2 mm and 54.4±0.6 mm, respectively. Five composite pipes were tested for each sample group.

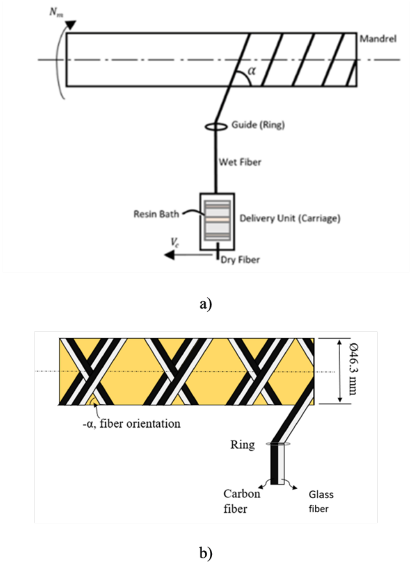

Figure 1 Fabrication of composite pipes; a) filament winding technique [22], b) intraply fiber hybridization [20]

Hydrothermal aging

In this work, pipes were hydrothermally aged for 120 days at 30°C in both saltwater and distilled water. In compliance with ASTM D5229/D5229M-14, the aging procedure was conducted. Purchased sea salts were used to create a seawater solution with a salinity of 3.5%. A 400 L/h circulation pump and an adjustable thermostat with a ±1°C tolerance was used to maintain temperature uniformity in the aging chamber. In this manner, it was ensured that the samples were exposed to identical circumstances at every stage of the aging process and that the ambient temperature stayed constant. Prior to aging, the specimens had been dried until their weight remained consistent. The hybrid glass/carbon fiber tubes used for every specimen group were then submerged in saltwater and distilled water. Throughout the age procedure, specimens were removed from the aging chamber at specific times, their weights were determined using an accurate analytical scale, and the water droplets on their surfaces were meticulously wiped. Weight change calculation was done with two different methods. First, the amount of water present at a certain aging time is calculated:

$$M_f = \frac{(m_t - m_i)}{m_i} \times 100 \qquad (1)$$

where m_t, and m_i are the sample's initial weights before and after aging, respectively, and M_f is the percentage of water at that time t.

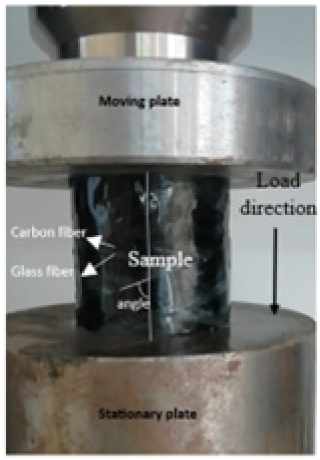

Figure 2 Quasi-static axial compression on Shimadzu AG-X Series testing machine

Fickian's law is used in this work to calculate the sorption of water of the aged samples since it establishes the amount of water uptake in composite materials. The formula is written as:

$$\frac{M_{\%}}{M_m} = 1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(\frac{-(2n+1)^2 \pi^2 D t}{h^2}\right) \qquad (2)$$

where D is the diffusion coefficient, h is the sample thickness, $M_{\%}$ is the water amount at time, t, and M_m is the amount of water saturation. The following formula can be used to determine D's value:

$$D = \pi\left(\frac{h}{4M_m}\right)^2\left(\frac{M_2 - M_1}{\sqrt{t_2} - \sqrt{t_1}}\right)^2 \quad (3)$$

where denotes the linear part of the line and M_2 - M_1 is the slope of the graph of the water intake throughout the first ageing phase.

Quasi-static Axial Compression

The unconditioned and aged pipes were exposed to the quasi-static axial compression loads to define the crushing properties of glass/carbon intraply fiber hybrid reinforced composite pipes. The tests were conducted on the Shimadzu AG-X Series universal testing machine with a frame capacity of 300 kN as shown in Figure 2. 5 mm/min stroke movement was applied for loading rate. The compression amount was adjusted to 35 mm which means approximately 70% stroke efficiency. During the ex periments, the samples we re photographed at various stages (after initial peak (5 mm), during crush (15 mm and 25 mm) and before densification (35 mm)) to examine fracture behaviors under crushing.

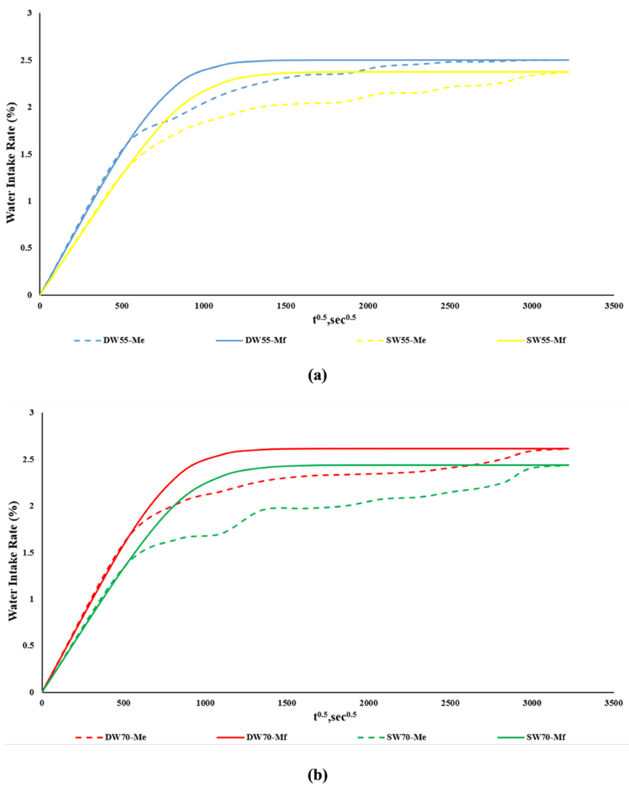

Figure 3 Water intake ratio of pipes different environment conditions a) 55° b) 70° winding angle

The load and displacement values taken by the test device were used for the calculation of the crushing parameters such as mean crushing load, initial peak load, crushing force efficiency, and energy absorption [14]. The total energy absorption, E which is the area under the load-displacement diagram from starting of the test to the end (s_f = 35 mm) was calculated by Eqn. (4):

$$E = \int_0^{S_f} P(s)\,ds \quad (4)$$

Mean crushing load, P_m which is a useful indicator to make a reliable comment on crushing was calculated by Eqn. (5):

$$P_m = \frac{\int_0^{S_f} P(s)\,ds}{S_f} \quad (5)$$

Crushing force efficiency, CFE is the ratio of mean crushing load to initial peak load (P_i) as seen in Eqn. (6):

$$\mathrm{CFE} = 100(P_m/P_i) \quad (6)$$

The specific energy absorption considering the mass of the samples is seen as the most reliable parameters in crushing experiments. It was calculated by Eqn. (7):

$$E_s = \frac{E}{m_c} \quad (7)$$

RESULTS & DISCUSSIONS

Water Gain Character

Experimental (M_e) and theoretical (M_f) water absorption models obtained after aging of composite pipes in different environments for 55° and 70° winding angle are shown in Figure 3 a) and b) respectively, showing the water uptake rates versus time. In general, the water absorption trend shows a rapid increase at the beginning and then tends to reach saturation. This shows that the material absorbs water rapidly at the beginning, but the amount of water it can absorb becomes limited over time. This behavior also coincides with the theoretical model in accordance with Fick's law. Although there is a general agreement between the experimental results and the theoretical model, there are also differences at some points. These differences may be due to variations in the microstructure of the material or small deviations in the experimental conditions. Further, the differences can be associated with the factors such as microstructure, fiber/matrix interface, and voids of hybrid composite materials may affect the water sorption behavior. The theoretical model may not fully reflect these heterogeneities [9-11].

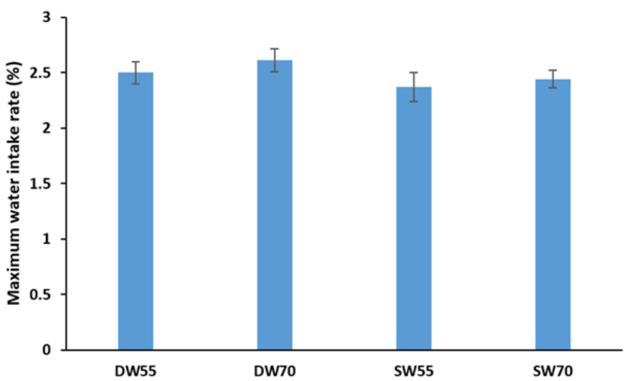

Figure 4 Maximum water intake rate of pipes under different conditions with winding angle

Maximum water intake rates based on aging conditions and winding angles is illustrated in Figure 4. This graph makes it evident that varying aging circumstances and winding angles have a direct impact on the maximum water intake rates of pipes. The maximum water absorption rates of the hybrid composite samples were measured as 2.5%, 2.62%, 2.37%, and 2.44% for DW55, DW70, SW55, and SW70, respectively. Samples aged in distilled water exhibited higher water absorption rates compared to samples aged in seawater. This can be explained by the purity of distilled water and its ability to penetrate the internal structure of the material more effectively. Salt and other ionic components in seawater affected the structure of the material and limited water absorption. Seawater may have reduced the water absorption capacity by creating chemical interactions on the polymer matrix and fiber/matrix interface of the material [12,13]. In addition, samples with a winding angle of 55° exhibited higher water absorption rates compared to samples with a winding angle of 70°. This can be explained by the fact that the lower winding angle causes the formation of more voids and pores in the microstructure of the material. These voids allow easier diffusion of water molecules within the material [10,11]. The main differences between seawater and pure water are due to the presence of ionic components, especially sodium chloride (NaCl). In this study, the lower water absorption of samples aged in seawater (3.5% salinity) compared to pure water (Figure 4) is consistent with the findings in the literature. Oğuz et al. [10] reported that salt ions interact with the polymer matrix as a result of aging hybrid composite pipes in seawater, causing changes in osmotic balance and inhibiting water diffusion. Similarly, Sepetçioğlu et al. [8] stated that ions in seawater accumulate in the microcavities of the composites, physically limiting the penetration of water into the internal structure, thus reducing the maximum water absorption rate by 15-20%. This mechanism explains the low water absorption observed in samples aged in seawater in this study. The high water absorption in samples aged in pure water (DW55: 2.5%, DW70: 2.62%) is related to the freer occurrence of Fickyen diffusion due to the absence of ionic inhibitors. Fitriah et al. [7] showed that the high polarity of pure water increased the swelling of the epoxy matrix, triggered the formation of microcracks, and this accelerated water absorption. In addition, the increased microvoid density in samples with low winding angle (55°) [10,11] shortened the diffusion path of water and increased the absorption rate. These findings are consistent with the effect of fiber orientation on microstructural heterogeneities emphasized by Miki et al. [18] and Wang et al. [19] in the literature.

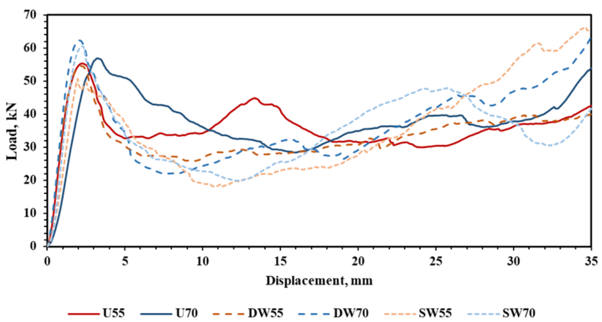

Figure 5 Load-displacement curves of the samples

Crushing Test Results

Load-displacement response and failure modes

The load-displacement graph of the unconditioned and aged pipes with varying winding angles are depicted in Figure 5. The load values initiated with a linear increase up to the first peak point where the short inter/intralaminar crack begins. Then, dramatic decreases were seen, particularly in aged samples. Here, the unconditioned samples showed a better load-bearing capability against crushing loads. So, it can be said that the aging process had a negative effect in the post-crushing zone. This can be associated with the lower interaction between fiber and matrix [15]. According to the literature, aging might be the reason for the matrix fragmentations and weakening fiber/matrix interphases which decreases the mechanical performance of the samples [11,12]. Examining the winding angle revealed that increases in angle led to increases in the first elastic region's load responses. However, a complicated behavior was seen in the post-crushing stage due to intraply fiber hybridization.

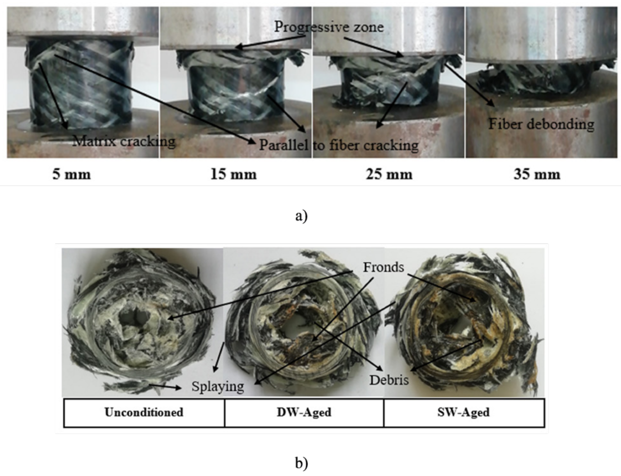

Figure 6 Fracture characteristics; a) crushing history, b) crushed samples

The crushing history of the samples is seen in Figure 6(a). As a result of intraply fiber hybridization, a parallel to fiber cracking because of the presence of glass fiber was seen in the samples. This was the reason for the sharp drop in load values after the first peak load. Also, progressive crushing mode which starts from one end of the sample to the other end is observed. The failures began with matrix fragmentations and were followed by delamination. Then, fiber cracking was observed as a failure mode. The samples exposed to crushing loads are given in Figure 6(b). Outer fiber splaying behaviors are observed due to the debonding of the fibers. Aged samples exhibited more debris as a result of weak fiber/matrix interphase. Additionally, frond formations, especially inner region of the samples, occurred due to parallel fiber cracking. As seen in Figure 6(b), aged samples showed more destructive fracture characteristics because of the degradation of the matrix phase. This may be attributed to the matrix plasticization due to the effects of different environmental conditions [11].

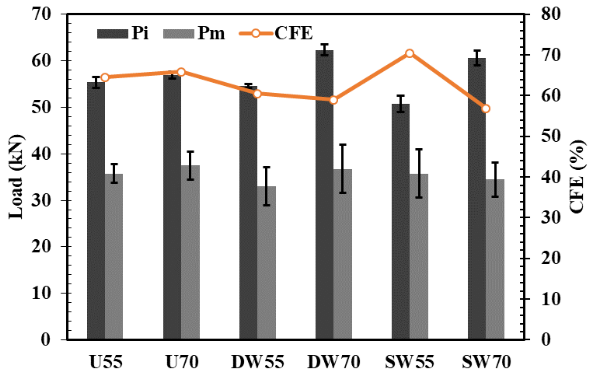

Figure 7 Loading responses of the samples

Loading Characteristics

Figure 7 shows the samples' loading characteristics in terms of initial peak load, mean crushing load, and crushing force efficiency. While the U70 samples had a maximum initial peak load of 56.9 kN, SW55 exhibited a minimum of 50.7 kN. At the same winding angle, U55 with 55.36 kN showed 1.4% and 9.2% more initial load response than DW55 and SW55, respectively. Additionally, the maximum mean crushing load of 37.5 kN was achieved from U70 samples which is 1.9% and 8.7% higher than DW70 and SW70, respectively. So, it can be said that exposure to distilled, and seawater environments decreased the load-bearing capabilities of the unconditioned glass/carbon intraply fiber-reinforced composite pipes. This may be explained by the water absorption of the samples led to matrix fragmentations, non-homogeneity in load distribution, and so local stress concentrations [16]. The performance loss in the samples aged in pure water (SEA in DW55: 28.49 J/g) is related to the polar structure of water causing matrix swelling and microcrack formation. Fitriah et al. [7] showed that pure water creates thermal stresses in the epoxy resin, leading to internal structural heterogeneities, which trigger sudden load drops during crushing. In addition, the high SEA value (30.44 J/g) obtained in the unaged samples (U55) can be explained by the fact that the fiber orientation (55°) optimizes the load distribution and increases energy dissipation. Wang et al. [19] emphasized that low winding angles provide more effective response of the fibers to axial load and this supports the progressive crushing mode. As a result, the corrosion and chemical degradation effects of seawater and the physical swelling mechanisms of pure water affect the crushing behavior of composites in different ways. Studies in the literature [6,10,16] provide critical clues on how these processes can be modulated depending on the design parameters (e.g. fiber orientation, hybridization). In particular, since low wrapping angles (55°) optimize energy absorption but increase the risk of water exposure, the integration of hybrid strategies such as protective coatings or nano-filler reinforcements [8] can be recommended in marine applications. This study provides the experimental and theoretical basis of this balance and provides guidance for industrial optimization.

Energy absorption

Figure 8 displays the unconditioned and aged pipe samples' overall and specific absorbance of energy values. While the maximum value in absorbance of energy was observed from the U70 samples (1311.56 J), the best specific energy absorption of 30.44 J/g was achieved from the U55 samples. These results indicated the importance of mass in the determination of the crushing characteristics of the composites. As seen in Table 2, which shows the crushing indicators of the samples, the mass values of the samples were different due to aging, water absorption, and the content of the composites. So, specific energy absorption was accepted as the main parameter in crushing parameters and was the best way to make a reliable discussion on the results [17]. U55 showed 6.84% and 12.32% higher specific energy absorption than DW55 and SW55, respectively. Also, it was 5.36% more than U70 (28.89 J/g). It was seen that an increase in winding angle cause to drop of the specific energy absorption because of the fiber orientation's closeness to the loading direction [17]. In literature, many studies devoted to fiber orientation had serious effects on the mechanical behaviors of the composites [18,19]. In addition, it is known that salt in seawater creates a partial "barrier effect" on the polymer matrix and reduces the mobility of water molecules [12,13]. Krishnan et al. [6] experimentally proved that NaCl in seawater reduces the plasticization tendency of epoxy resin and provides a more stable structure at the fiber/matrix interface, which slows down water absorption. However, it is also emphasized that salt can also lead to corrosion and chemical degradation [16]. This contradictory effect can be interpreted as the main reason for the mechanical performance loss observed in the samples aged with seawater in this study. The effects of hydrothermal aging in seawater and pure water environments on the crushing performance of hybrid composite pipes are shaped by the synergistic interactions of both ionic components and fiber orientation. In the study, a decrease of 12.32% in specific energy absorption (SEA) of samples aged in seawater (SW55) is consistent with the findings in the literature related to corrosion and fiber/matrix interface deterioration. For example, Sebaey [16] reported that NaCl in seawater triggers galvanic corrosion in composites, weakening the fiber/matrix bond, and this situation increases delamination during crushing. Similarly, Oğuz et al. [10] stated that salt ions accelerate hydrolysis reactions in the epoxy matrix, leading to plasticization, and this process reduces the load carrying capacity. These mechanisms explain the low CFE (70.44%) and SEA (27.10 J/g) values observed in SW55 samples.

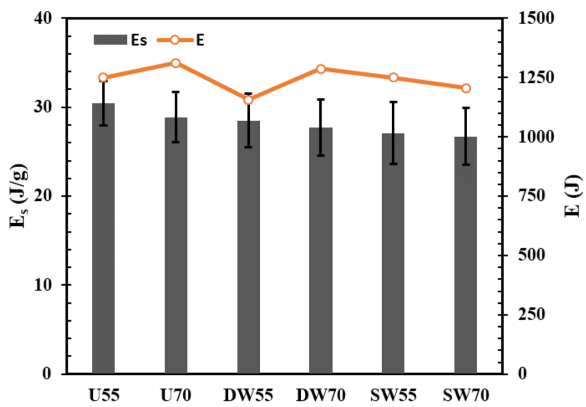

Figure 8 Energy absorption values of the samples subjected to different environmental conditions

Table 2 Summarization of the crushing indicators

	Angle (°)	P_m (kN)	P_i (kN)	CFE (%)	m_{crush} (g)	E (J)	E_s (J/g)
Unconditioned	55	35.7	55.4	64.52	28.52	1250.26	30.44
	70	37.5	56.9	65.83	32.10	1311.56	28.89
DW Aged	55	33.1	54.6	60.53	28.09	1156.90	28.49
	70	36.8	62.3	58.99	33.52	1287.31	27.72
SW Aged	55	35.7	50.7	70.44	32.29	1250.00	27.10
	70	34.5	60.6	56.89	32.27	1206.37	26.70

CONCLUSION

The water adsorption performance and crushing durability of hybrid glass/carbon fiber reinforced composite pipes with ±55° and ±70° winding angles under the impacts of hydrothermal aging in distilled water (DW) and seawater (SW) environments were thoroughly assessed in this work. Peak intake of water percentages was greater in specimens aged in distilled water than in samples aged in seawater (DW55: 2.5%, DW70: 2.62%; SW55: 2.37%, SW70: 2.44%). It was found that the primary cause of this discrepancy was the ionic elements in seawater, which inhibit water transport by generating chemical reactions at the fiber/matrix interface. Because of the increased microstructural voids, specimens with a smaller winding angle (55°) exhibited greater water absorption. The effect of microstructural heterogeneities (void distribution, interfacial distortions) was demonstrated by variations of up to 0.5%, despite the fact that theoretical Fickian models generally agreed with experimental trends. Mechanical characteristics were significantly lost as a result of hydrothermal aging. The maximum initial peak load (56.9 kN) and average crushing load (37.5 kN) were obtained from unaged 70° winding angle samples. These results, however, declined with aging, in samples aged in seawater (SW55), specific energy absorption dropped from 30.44 J/g to 27.10 J/g, a 12.32% decrease. In aged specimens, the CFE dropped (DW55: 60.53%, SW55: 70.44%), which was linked to matrix plasticization and a compromised fiber/matrix interaction. The maximum specific energy absorption (30.44 J/g, U55) was obtained by hybrid tubes with a winding angle of 55°, underscoring the crucial role that fiber orientation plays in load distribution and energy dissipation. The findings emphasize how crucial it is to optimize winding angles and hybrid designs in order to minimize mechanical losses brought on by aging, particularly in harsh settings like pipelines and ships. Low winding angles (55°) boost energy absorption but increase water exposure, therefore design decisions must be balanced.

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