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Towards Sustainable Concrete Infrastructure: Durability of Full-Scale BFRP Dowel Bars Under Seawater and Alkaline Exposure

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Abstract

Basalt fibre-reinforced polymer (BFRP) dowel bars offer a corrosion-resistant alternative to steel dowels for jointed concrete infrastructure, particularly in aggressive marine environments. However, the durability of full-scale BFRP dowels remains insufficiently understood because their shear-dominated behavior differs from that of conventional small-diameter FRP reinforcement. This study investigates the durability of 25-mm epoxy-based BFRP dowel bars exposed separately to artificial seawater and alkaline solution at 60 °C under accelerated continuous-immersion conditions. Mechanical performance was evaluated through flexural strength, transverse shear strength, and interlaminar shear strength (ILSS), while chemical and microstructural changes were examined using Fourier-transform infrared spectroscopy (FTIR) and scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM/EDS). At the common 2- and 4-week exposure durations, seawater caused greater flexural-strength losses (10.0% and 11.5%) than alkaline exposure (1.3% and 8.5%), whereas alkaline exposure caused greater reductions in transverse shear strength (7.3% and 8.3% vs. 2.5% and 5.5%) and ILSS (7.0% and 10.0% vs. 1.3% and 2.4%). FTIR and SEM/EDS observations provided complementary evidence of matrix modification and fibre–matrix interfacial deterioration. Overall, the investigated BFRP dowel system showed limited mechanical degradation under the accelerated conditions, indicating promising material-level durability performance within the investigated exposure durations.

Keywords: BFRP dowel bars; durability; marine environment; alkaline exposure; degradation mechanisms

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1. Introduction

The use of fibre-reinforced polymer (FRP) composites as alternatives to conventional steel reinforcement has attracted substantial international interest due to their inherent corrosion resistance and improved durability in aggressive service environments. In reinforced concrete structures exposed to chloride ingress, sustained moisture, and cyclic wet–dry conditions, corrosion of steel reinforcement remains a dominant cause of structural degradation and reduced service life, driving extensive investigation of FRP materials to enhance the long-term performance of concrete infrastructure [1,2]. Recent research has also provided complementary insights into the protective performance of FRP systems for concrete exposed to chloride environments [3]. However, the widespread adoption of FRP reinforcement remains challenging. While carbon fibre-reinforced polymer (CFRP) composites provide excellent mechanical and durability performance, their high production and life cycle costs limit practical implementation. Conversely, conventional E-glass fibre-reinforced polymer (GFRP) systems are more cost-effective but may experience durability concerns when exposed to the highly alkaline pore solution of concrete [4].

These constraints have motivated the development of alternatives to CFRP and GFRP that balance durability, cost effectiveness, and sustainability. Within this context, basalt fibre-reinforced polymer (BFRP) composites have emerged as promising next-generation FRP materials, providing favorable mechanical properties, enhanced chemical resistance, improved thermal stability, and lower material costs compared with CFRP and GFRP. Basalt fibres are considered environmentally friendly materials because they are produced from naturally abundant basalt rock, a non-toxic and widely available raw material [5]. The production of basalt fibres does not require the incorporation of special additives, resulting in a simpler manufacturing process and potentially lower production costs compared with other fibre types, such as glass fibres [6]. Recent life cycle assessment (LCA) studies have reported that the Global warming potential, excluding transportation (measured as kg CO2eq) of BFRP bars, is 74%, 49%, 88%, and 44% lower than that for carbon steel, galvanized steel, stainless steel, and GFRP, respectively [7].

While extensive research has focused on FRP as longitudinal reinforcement in concrete structures, their application as load-transfer elements, specifically dowel bars, has received comparatively limited attention. Dowel bars play a critical structural role in jointed concrete systems by transferring shear forces across joints while allowing controlled relative movements induced by temperature variations, shrinkage, and cyclic mechanical loading. Such systems are widely used in jointed concrete pavements, industrial ground-bearing slabs, precast deck panels, and infrastructure exposed to aggressive environmental conditions, including coastal roads, port pavements, seawall deck slabs, flood-defense structures, and other marine and flood-resilience applications. In these structures, dowel bars are typically positioned at construction and movement joints, which often serve as preferential pathways for the ingress of moisture, chlorides, and other deleterious agents, thereby increasing the risk of corrosion-related deterioration in conventional steel dowels [8].

In marine and coastal environments, these durability challenges become even more critical, as dowel bars are frequently exposed to chloride-rich seawater through direct contact, splash action, and cyclic wet–dry regimes. Traditionally, carbon steel dowel bars have been used due to their high stiffness and ductility; however, both laboratory investigations and field observations have confirmed their pronounced susceptibility to corrosion under such conditions. Corrosion-induced section loss and expansive corrosion products significantly reduce load-transfer efficiency and accelerate joint deterioration. Although stainless steel dowels offer improved corrosion resistance, their high initial and life cycle costs limit their practicality in large-scale infrastructure, thereby motivating the search for alternative corrosion-resistant materials [9,10].

In response to these challenges, FRP dowel bars have been proposed and increasingly investigated as viable substitutes for conventional steel systems. Existing research on FRP dowels has focused predominantly on GFRP systems, with studies examining shear capacity, bearing behavior, load-transfer efficiency, fatigue performance, structural response, and long-term durability in jointed concrete pavements [11–14]. Overall, GFRP dowels have demonstrated promising structural performance under both laboratory and field conditions, and their durability behavior under alkaline and seawater environments is relatively well understood. In particular, Won et al. [15] reported that seawater and alkaline conditioning caused only limited degradation in the mechanical properties of GFRP dowels, indicating good durability under conditions representative of marine exposure and concrete pore solutions.

In contrast, BFRP dowel bars remain significantly under-researched despite increasing interest in BFRP as a sustainable and cost-effective reinforcement material. Recent studies have therefore focused on understanding the durability performance of BFRP bars under aggressive environmental conditions, particularly alkaline solutions simulating concrete pore water and marine-related exposures [16]. These studies consistently indicate that the long-term performance of BFRP is governed by resin matrix degradation, fibre–matrix interfacial debonding, and moisture or ion ingress, with temperature and exposure duration acting as dominant accelerating factors. Al Rifai et al. [17] observed that BFRP bars exposed to alkaline solution at temperatures up to 60 °C for periods up to 9 months experienced tensile strength losses reaching approximately 29%. Elgabbas et al. [18] investigated the durability of small-diameter BFRP reinforcing bars of different manufacturers exposed to an alkaline solution at 60 °C for up to 3000 h. The results showed progressive deterioration in mechanical properties with increasing exposure time. Tensile strength retention decreased to approximately 61–77%, transverse shear strength retention ranged from 82% to 90%, interlaminar shear strength retention varied between 60% and 90%, and flexural strength retention remained between 82% and 99%, depending on the bar type. Wu et al. [19] further demonstrated that BFRP bars maintain more than 60% of their initial strength after 9 weeks in alkaline solution at 55 °C. Lu et al. [20] also showed that alkaline environments generally induce more severe degradation in BFRP compared to tap water and seawater, although the severity depends on resin chemistry and fibre architecture. Lu et al. [21] reported that BFRP bars immersed in ocean water and simulated seawater for up to 360 days exhibited significant reductions in tensile strength, with the most severe degradation observed at elevated temperature (60 °C), where strength retention dropped by approximately 81.6%. Wang et al. [22] reported that BFRP bars exposed to simulated seawater–sea sand concrete pore solutions exhibited progressive tensile strength degradation with increasing temperature and exposure duration, with strength retention decreasing to approximately 85%, 71%, and 50% after 180 days at 30 °C, 45 °C, and 60 °C, respectively. Ali et al. [23] investigated the influence of bar diameter on the long-term durability of sand-coated BFRP bars conditioned in an alkaline solution at 60 °C for 90 days. The results demonstrated that durability is strongly size-dependent, with tensile strength retention ranging from approximately 67% to 85%, while flexural and shear strength retention remained between 80% and 91%. The study highlighted that bar diameter plays an important role in the long-term durability of BFRP bars under alkaline exposure. However, it is important to note that these findings were obtained from sand-coated BFRP bar systems under alkaline exposure only, without considering seawater environments.

Previous studies have also examined the influence of exposure mode on the durability of FRP systems. Wet–dry cycling has been used to represent the moisture fluctuations encountered in chloride-containing and marine environments, while continuous immersion has been adopted as a controlled accelerated conditioning method. Liu et al. [24] directly compared continuous immersion and wet–dry cycling for BFRP bars exposed to an alkali–salt solution and reported greater degradation under continuous immersion. Similar observations have been reported for FRP systems exposed to saline and alkaline environments [25,26]. These findings indicate that continuous immersion can provide a controlled accelerated condition for comparative durability assessment.

Despite these valuable contributions, the available literature remains largely restricted to conventional small-diameter reinforcing bars subjected predominantly to uniaxial tensile loading under either alkaline or seawater exposure conditions. Even the limited studies addressing size effects are confined to specific material systems (sand-coated BFRP bars) and alkaline environments, without incorporating marine exposure scenarios [23]. Consequently, there remains a critical lack of understanding regarding the durability behavior of large-diameter BFRP dowels, which operate under fundamentally different shear-dominated, flexural, and bearing stress conditions within jointed concrete systems. This represents a significant research gap, as existing durability data for small-diameter rebar cannot be reliably extrapolated to full-scale dowel applications, particularly under seawater and alkaline environmental exposure. Recent studies on cementitious materials have demonstrated the value of relating microstructural evolution to macroscopic mechanical performance [27,28]. These studies highlight the potential of microstructure–mechanical correlations for interpreting material degradation. However, such relationships remain insufficiently explored for environmentally conditioned BFRP dowel bars, particularly in relation to flexural and shear-related mechanical responses.

To address these gaps, the present study investigates the durability performance of BFRP dowel bars under separate seawater and alkaline exposure conditions to distinguish their individual effects on dowel behavior. Dowel bars embedded in concrete are inherently exposed to highly alkaline pore solutions, while those used in marine and coastal infrastructure may additionally experience seawater exposure through chloride ingress, splash action, and cyclic wet–dry conditions. The study evaluates changes in flexural, transverse shear, and interlaminar shear strength as the primary mechanical indicators of environmental degradation, which are relevant to the load-transfer and shear-dominated behavior of BFRP dowel bars in jointed concrete systems. Microstructural and chemical changes are further examined using SEM/EDS and FTIR to provide complementary evidence for interpreting the observed mechanical degradation. The separate exposure approach does not reproduce the coupled alkaline-chloride environment that may occur in marine concrete and is therefore considered a limitation of the study. The findings provide an environment-specific durability assessment of BFRP dowel bars and support informed material selection and the design of durable jointed concrete systems for marine and coastal infrastructure.

2. Experimental Program

The experimental program was designed to evaluate the durability performance of epoxy-based basalt fibre-reinforced polymer (BFRP) dowel bars under separate seawater and alkaline exposure conditions. The program included baseline characterization of unconditioned dowel bars, followed by controlled environmental conditioning under standardized immersion protocols and post-exposure evaluation of flexural strength, transverse shear strength, and interlaminar shear strength (ILSS). Complementary chemical and microstructural characterization using FTIR and SEM/EDS was also conducted to support the interpretation of changes observed in the mechanical properties. The experimental design enabled a controlled comparison of the effects of seawater and alkaline exposure on the mechanical and physicochemical performance of BFRP dowel bars under accelerated laboratory conditioning.

2.1. Materials

The experimental program employed basalt fibre-reinforced polymer dowel bars with a nominal diameter of 25 mm, supplied by Orlimex CZ s.r.o. (Osík, Czech Republic) and manufactured using an industrial pultrusion process. Continuous basalt fibres were fully impregnated with an epoxy-based thermoset matrix, resulting in a composite reinforcement with a manufacturer-reported composite density of approximately 2.1 g/cm^3, a basalt-fibre content of approximately 83 wt%, and a glass-transition temperature of approximately 113 °C. The bars were manufactured with a nominally smooth external surface, without additional surface treatment or deformation, such that load transfer in dowel action is governed primarily by bearing and shear mechanisms rather than bond enhancement. Specimens were cut to the required lengths using a diamond saw, and both ends of each dowel bar were sealed with epoxy resin to isolate radial environmental exposure through the external surface of the dowel bars and minimize the potential contribution of longitudinal solution ingress through the exposed fibre ends during environmental conditioning.

2.2. Environmental Conditioning

To evaluate the durability performance of the BFRP dowel bars, two separate environmental conditioning regimes were considered: alkaline exposure representing the highly alkaline environment of concrete, and artificial seawater exposure representing marine conditions. The environmental exposures were conducted using continuous immersion rather than wet–dry cycling. This protocol was selected to provide controlled and accelerated conditioning while minimizing variations associated with repeated wetting and drying. Continuous immersion also facilitates direct comparison of the mechanical, chemical, and microstructural responses under the two exposure media. Previous comparative studies have reported that continuous immersion can produce more severe degradation than wet–dry cycling under certain accelerated conditions [24–26]. Therefore, the continuous-immersion protocol adopted in this study is considered an accelerated laboratory conditioning method and does not directly reproduce field wet–dry exposure conditions.

2.2.1. Alkaline Exposure

The alkaline solution was prepared in accordance with ISO 10406-1:2015 [29] using 8.0 g/L NaOH and 22.4 g/L KOH dissolved in deionized water, producing an initial pH greater than 13, representative of the highly alkaline environment of mature concrete pore solution. The pH of the solution was monitored periodically throughout the environmental exposure. The environmental exposure was conducted at 60 ± 3 °C, as specified in ISO 10406-1:2015 [29] for accelerated alkaline durability assessment of FRP reinforcement. The elevated temperature was adopted to accelerate environmental degradation processes and enable measurable changes in mechanical and microstructural properties within a practical laboratory exposure period. Therefore, the results obtained under this condition are interpreted as accelerated laboratory durability trends and are not directly converted into equivalent field exposure durations or service-life predictions. Specimens were exposed for 1, 2, and 4 weeks. These exposure periods were selected to monitor the progression of degradation up to the one-month exposure duration specified in ISO 10406-1:2015 [29]. Accordingly, the 4-week condition represents the endpoint of the standard-based accelerated alkaline exposure duration adopted in this study.

2.2.2. Seawater Exposure

Artificial seawater was prepared in accordance with ASTM D1141-98(2021) [30] using 24.54 g/L NaCl, 4.09 g/L Na_2SO_4, 5.20 g/L $MgCl_2$, 1.16 g/L $CaCl_2$, and 0.69 g/L KCl, producing a solution with a pH of approximately 7.1, representative of natural seawater conditions. The exposure containers were maintained under controlled laboratory conditions, and solution levels were periodically adjusted to compensate for evaporation losses throughout the conditioning period. Unlike alkaline durability testing, no internationally recognized standard currently specifies accelerated environmental exposure conditions for FRP reinforcement in seawater. Therefore, an exposure temperature of 60 °C was adopted based on previous BFRP durability studies conducted under marine environments [21,22,31], where elevated temperature has been used to accelerate moisture diffusion and salt ingress and to obtain measurable degradation within a practical laboratory period. The present seawater results are therefore interpreted as accelerated laboratory durability trends rather than direct equivalents of field exposure durations or service-life predictions. Specimens were exposed in artificial seawater for 2, 4, and 8 weeks. The 2- and 4-week exposure durations were selected to provide common conditioning periods with the alkaline exposure, thereby enabling direct comparison of the degradation response at identical exposure durations. The additional 8-week condition was included to characterize the continued evolution of seawater-induced degradation beyond the common 4-week comparison period.

2.3. Mechanical Testing

The mechanical performance of the conditioned and unconditioned BFRP dowel bars was evaluated through standardized tests of flexural behavior, transverse-shear resistance, and interlaminar-shear capacity. These tests were selected as material-level indicators of environmental degradation relevant to dowel-bar behavior and are sensitive to degradation of the polymeric matrix and fibre–matrix interface. However, they do not directly reproduce the combined effects of shear, bending, concrete bearing, and dowel–concrete interaction that govern the response of an actual dowel embedded across a concrete joint. All tests were conducted using consistent procedures for both unconditioned and conditioned specimens to ensure reliable comparison of strength retention.

2.3.1. Flexural Testing

Flexural testing was employed primarily for quality control and specification verification, as bending response represents a secondary but relevant action for dowel bars subjected to joint rotation and differential displacements under service conditions. In addition, flexural properties of FRP bars are known to be sensitive to variations in specimen diameter, temperature, and environmental conditions [23]. The tests were performed in accordance with the relevant ISO 10406-1:2015 [29]. Unconditioned BFRP specimens were tested using a simply supported configuration with a clear span equal to 40 times the nominal bar diameter and an overhang of twice the bar diameter at each support. Testing was conducted using a universal testing machine equipped with a 150 kN load cell to ensure accurate load measurement. Five replicate specimens were tested for each experimental condition in this study. The load was applied at mid-span through a circular loading nose, while the specimens were supported on two circular rollers to allow free bending, as illustrated in Figure 1a. All tests were conducted under displacement control at a constant rate of 3.0 mm/min. Load and mid-span deflection were continuously recorded using a computer-controlled data acquisition system. The flexural strength of the BFRP bars was subsequently calculated in accordance with Equation (1).

$$F_u = \frac{PLC}{4I} \quad (1)$$

where P is the failure load, L is the clear span, C is the distance to the centroid of the extreme-most fibres, and I is the moment of inertia.

2.3.2. Transverse-Shear Testing

Transverse shear is an important material-level mechanical response associated with load transfer by dowel bars across joints in concrete structural systems. To characterize the transverse-shear capacity of the BFRP dowel bars, tests were conducted in accordance with the relevant ISO 10406-1:2015 [29]. The test configuration employed a standardized double-shear setup designed to promote shear-dominated failure of the bar, with loading applied through a centrally positioned blade between two reaction planes. All tests were performed using a universal testing machine equipped with a 150 kN load cell, as illustrated in Figure 1b. Five replicate specimens were tested for each experimental condition in this study. Specimens were loaded under displacement control at a constant rate of 1 mm/min until failure, ensuring smooth load application without impact or shock. The transverse-shear strength of the BFRP bars was subsequently calculated in accordance with Equation (2).

$$\tau_u = \frac{P_s}{2A} \tag{2}$$

where τ_u is the transverse-shear strength (MPa); P_s is the failure load (N); and A is the bar cross-sectional area (mm^2).

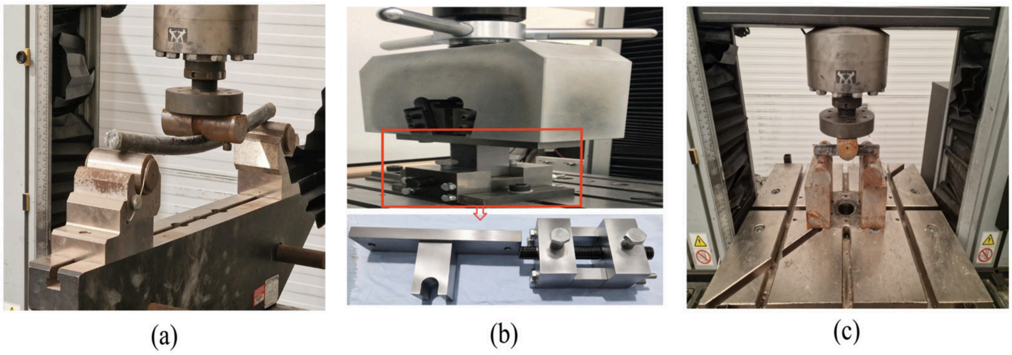


Figure 1. Test setup: (**a**) flexural strength; (**b**) transverse shear; (**c**) interlaminar shear.

2.3.3. Interlaminar Shear Testing

In pultruded FRP dowel bars, where fibres are predominantly aligned in the longitudinal direction and bonded by a polymeric matrix, horizontal shear stresses are more effective in promoting fibre–matrix interfacial degradation than transverse-shear stresses [32]. Accordingly, short-beam shear tests were conducted to evaluate the interlaminar shear strength (ILSS) of the BFRP dowel bars in accordance with the relevant ASTM D4475/D4475M-16 [33]. The tests were performed using a universal testing machine equipped with a 250 kN load cell, as illustrated in Figure 1c. Five replicate specimens were tested for each experimental condition in this study. The distance between the shear planes was fixed at five times the nominal bar diameter to ensure interlaminar shear-dominated failure. All specimens were loaded under displacement control at a constant rate of 1 mm/min until failure. The applied load and corresponding displacement were continuously recorded using a computer-controlled data acquisition system. The ILSS of the BFRP bars was subsequently calculated in accordance with Equation (3).

$$S_u = \frac{0.849P}{d^2} \tag{3}$$

where P is the shear failure load (N); and d is the bar diameter (mm).

2.4. Chemical Testing

Chemical and microstructural characterization techniques were employed to examine changes in the epoxy matrix and fibre–matrix interface following environmental conditioning. Fourier-transform infrared spectroscopy (FTIR) was used to identify changes in the chemical structure and functional groups of the epoxy matrix. Scanning electron microscopy (SEM) was used to examine microstructural features associated with environmental deterioration, while energy-dispersive X-ray spectroscopy (EDS) provided additional information on the elemental composition at selected locations. The results from these techniques were used as complementary evidence to support the interpretation of the observed mechanical degradation, rather than as direct confirmation of specific degradation mechanisms.

2.4.1. Fourier-Transform Infrared Spectroscopy (FTIR)

Fourier-Transform Infrared Spectroscopy was employed to investigate changes in the chemical bonding and functional groups of the epoxy matrix of BFRP dowel bars after exposure to seawater and alkaline environments, compared with the control specimens. FTIR analysis was carried out using a PerkinElmer Spectrum One FTIR spectrometer (PerkinElmer, Shelton, CT, USA). Following environmental conditioning, BFRP samples were extracted using a diamond saw, then dried and cleaned with isopropyl alcohol prior to FTIR analysis. FTIR spectra were recorded using an ATR configuration over a wavenumber range of 600–4000 cm^{-1}, while frequencies below 600 cm^{-1} were excluded in accordance with the sensitivity limits of the FTIR detector used in this study. Because the FTIR response in the investigated spectral region is dominated by the polymeric matrix, the spectra were interpreted primarily in terms of epoxy-related chemical changes. The spectra were baseline-corrected prior to interpretation, and the same spectral processing procedure was applied consistently to the control and conditioned specimens. The FTIR results were evaluated primarily by comparing changes in peak position, intensity, broadening, and disappearance between the control and conditioned specimens. Because no quantitative calibration was established for the individual chemical constituents, the FTIR analysis was used as qualitative/semi-quantitative supporting evidence of chemical changes rather than as a direct quantitative measure of degradation. Particular attention was given to characteristic absorption bands associated with epoxy ring and C-O-C-related vibrations ($\approx$915–1100 cm^{-1}), aliphatic C-H stretching ($\approx$2800–3000 cm^{-1}), carbonyl (C=O) stretching ($\approx$1710–1730 cm^{-1}), and hydroxyl (O-H) stretching ($\approx$3200–3600 cm^{-1}). Changes in these functional groups have been associated in previous studies with environmental effects such as moisture uptake, hydrolysis, oxidation, and plasticization in epoxy-based FRP composites [34–36]. In the present study, these spectral changes are therefore interpreted as evidence consistent with chemical modification of the epoxy matrix rather than as direct confirmation of a specific degradation mechanism.

2.4.2. Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy was employed to examine the microstructural changes in the BFRP dowel bars before and after environmental conditioning using a JSM-IT200 scanning electron microscope (JEOL Ltd., Tokyo, Japan). Small cross-sectional specimens were cut from the BFRP dowel bars using a diamond saw. The specimens were dried and cleaned with isopropyl alcohol and mounted on aluminum stubs prior to analysis. A thin carbon coating (~10 nm) was applied to minimize surface charging during imaging. Five SEM specimens were examined, representing the five investigated conditions: the unconditioned control, seawater exposure for 2, 4, and 8 weeks, and alkaline exposure for 4 weeks. For each specimen, two sampling locations were examined, corresponding to the outer surface and core regions of the BFRP dowel bar. One representative field of view was examined at each sampling location. The field of view was selected to represent the typical microstructural condition observed at the corresponding location rather than an isolated or anomalous feature. The same sampling and imaging procedure was applied to all investigated conditions to ensure consistent comparison of the observed microstructural changes. SEM observations were performed using secondary electron (SE) and back-scattered electron (BSE) detectors at accelerating voltages ranging from 5 to 15 kV. EDS was also performed at selected representative locations to characterize the elemental composition and identify changes in elemental distribution associated with environmental exposure. The examination focused on identifying microstructural changes such as resin cracking, fibre–matrix interfacial condition, fibre surface morphology, and surface roughness, which are widely reported as key indicators of degradation mechanisms in FRP composites exposed to marine and alkaline environments [37–39].

3. Results and Discussion

This section presents and discusses the mechanical and chemical characterization results of BFRP dowel bars subjected to seawater and alkaline environments. Mechanical performance is first assessed through flexural, transverse shear, and interlaminar shear tests, followed by chemical and microstructural analyses to interpret the observed degradation mechanisms.

3.1. Mechanical Performance of BFRP Dowel Bars

Table 1 summarizes the flexural, transverse shear, and interlaminar shear strength of BFRP dowel bars subjected to seawater and alkaline conditioning at different exposure durations. For each environmental condition and mechanical property, five replicate specimens were tested, and the results are presented as mean ± standard deviation (SD) to quantify the variability among the tested specimens. Figure 2 presents representative failure modes observed during flexural, transverse shear, and interlaminar shear testing. The statistical significance of the differences between the investigated conditioning conditions was evaluated using one-way analysis of variance (ANOVA), followed by Tukey's HSD post hoc test, as detailed in Section 3.1.4.

Table 1. Means ± standard deviations of the flexural, transverse shear and interlaminar shear strength of BFRP dowel bars under different environmental conditioning regimes.

Environmental Condition	Exposure Duration	Flexural Strength (MPa)	Transverse Shear Strength (MPa)	Interlaminar Shear Strength (MPa)
Control	Unconditioned	943 ± 2.74	219 ± 2.12	59.8 ± 0.89
Seawater	2-Weeks	850 ± 2.75	213.5 ± 3.20	59.0 ± 1.53
	4-Weeks	835 ± 4.95	207 ± 2.75	58.4 ± 1.93
	8-Weeks	807 ± 4.94	200 ± 2.74	55.7 ± 1.50
Alkaline	1-Week	939 ± 2.55	210 ± 2.12	57.3 ± 1.10
	2-Weeks	931 ± 4.18	203 ± 4.06	55.7 ± 1.68
	4-Weeks	863 ± 3.81	201 ± 1.87	53.8 ± 1.66

(a) (b) (c)

Figure 2. Representative failure modes of BFRP dowel bars after mechanical testing: (**a**) flexural failure; (**b**) transverse shear failure; (**c**) interlaminar shear failure.

3.1.1. Flexural Behavior

The flexural capacity of BFRP dowel bars after exposure to seawater and alkaline environments is presented in Figure 3 in terms of strength retention relative to the unconditioned specimens. Flexural strength provides an indication of the overall bending performance of the BFRP dowel bars and is influenced by the integrity of the fibre–matrix system, particularly in the outer regions subjected to higher bending stresses.

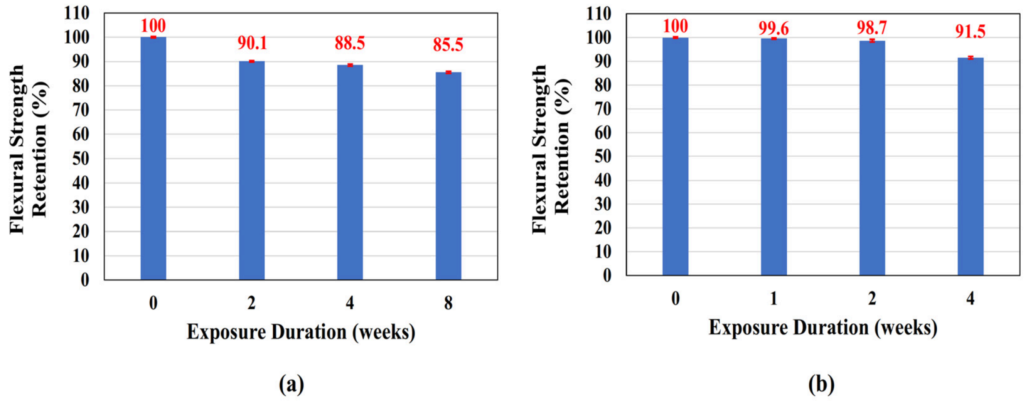


Figure 3. Flexural strength retention of BFRP dowel bars after environmental conditioning: (**a**) seawater exposure; (**b**) alkaline exposure. Error bars represent ±SD calculated from five replicate specimens ($n = 5$).

Under seawater exposure, flexural strength exhibited a gradual reduction with increasing immersion duration. Compared with the unconditioned reference specimens, flexural strength decreased by approximately 10% after 2 weeks and reached a total reduction of about 14.5% after 8 weeks. This gradual reduction is consistent with diffusion-controlled degradation, whereby moisture and dissolved ions may progressively penetrate the polymer matrix and affect regions contributing to flexural resistance. However, because direct moisture-uptake or diffusion measurements were not conducted, this interpretation provides supporting rather than direct evidence of a diffusion-controlled process. In contrast, alkaline conditioning resulted in a distinctly different degradation pattern. Flexural strength under alkaline exposure remained nearly unchanged during the early exposure stage, with a reduction of less than 1% after 1 week and approximately 1.3% after 2 weeks, followed by a more pronounced decrease with prolonged conditioning. After 4 weeks of alkaline exposure, flexural strength decreased by approximately 8.5%.

At the common exposure durations of 2 and 4 weeks, seawater conditioning resulted in greater flexural strength reductions than alkaline conditioning. After 2 weeks, the reduction was approximately 10% under seawater exposure compared with 1.3% under alkaline conditioning. At 4 weeks, the corresponding reductions were approximately 11.5% and 8.5%, respectively. Thus, seawater exposure produced a greater early reduction in flexural performance than alkaline conditioning within the common exposure periods investigated.

3.1.2. Transverse Shear Behavior

The transverse shear strength retention of BFRP dowel bars following exposure to seawater and alkaline environments is illustrated in Figure 4. Transverse shear resistance is a key performance parameter for dowel bars in jointed concrete systems, where shear and bearing actions play an important role in load transfer across joints. Consequently, transverse shear behavior is particularly relevant for evaluating the environmental durability of BFRP dowel bars used in load-transfer applications.

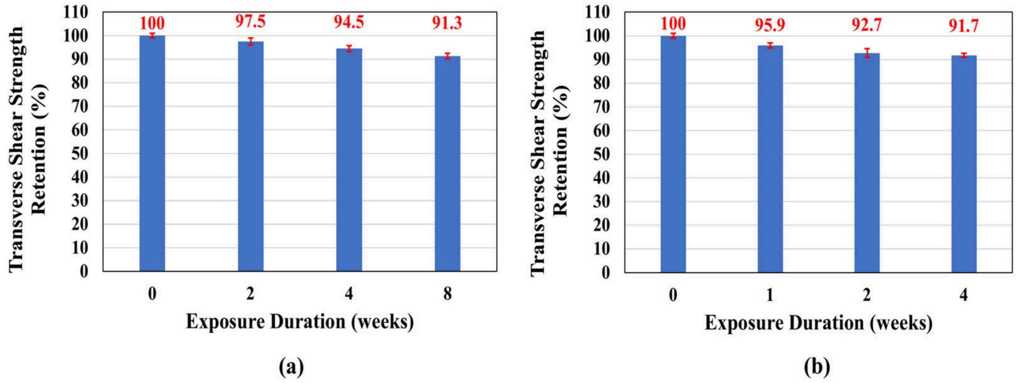


Figure 4. Transverse shear strength retention of BFRP dowel bars after environmental conditioning: (**a**) seawater exposure; (**b**) alkaline exposure. Error bars represent ±SDs calculated from five replicate specimens (n = 5).

Under seawater exposure, the transverse shear strength exhibited a gradual and consistent reduction with increasing immersion duration. Compared with unconditioned specimens, transverse shear strength decreased by approximately 2.5% after 2 weeks, followed by a cumulative reduction of about 8.7% after 8 weeks. This gradual reduction is consistent with the diffusion-controlled degradation trend observed under seawater exposure. In contrast, alkaline conditioning resulted in a distinctly different degradation pattern in transverse shear performance. Transverse shear strength under alkaline exposure exhibited a noticeable early decline, with a reduction of approximately 4.1% after 1 week and about 7.3% after 2 weeks, followed by a continued decrease with prolonged conditioning. After 4 weeks of alkaline exposure, transverse shear strength decreased by approximately 8.3%.

At the common exposure durations of 2 and 4 weeks, alkaline conditioning induced a greater reduction in transverse shear strength than seawater conditioning. After 2 weeks, alkaline exposure resulted in an approximate 7.3% reduction in transverse shear strength, compared with about 2.5% under seawater exposure. Similarly, after 4 weeks, the reduction under alkaline conditioning was approximately 8.3%, compared with about 5.5% under seawater exposure. These results indicate that alkaline conditioning caused greater transverse shear degradation than seawater exposure within the common conditioning periods investigated.

3.1.3. Interlaminar Shear Behavior

The interlaminar shear strength (ILSS) retention of BFRP dowel bars after exposure to seawater and alkaline environments is presented in Figure 5. ILSS is a matrix-dominated mechanical property and is particularly sensitive to changes in the polymer matrix and fibre–matrix interface. Therefore, it provides a useful measure of the effects of environmental conditioning on pultruded BFRP composites.

Under seawater exposure, ILSS exhibited a relatively stable response during the initial conditioning stage, with a marginal reduction of approximately 1.3% after 2 weeks. With prolonged immersion, ILSS showed a gradual but measurable decline, reaching a total reduction of approximately 7.0% after 8 weeks. In contrast, alkaline conditioning resulted in a distinctly different degradation pattern in interlaminar shear strength (ILSS). Under alkaline exposure, ILSS exhibited a pronounced early decline, with a reduction of approximately 4.2% after 1 week, followed by a continued decrease with increasing conditioning duration. After 4 weeks of alkaline exposure, ILSS decreased by approximately 10.0%.

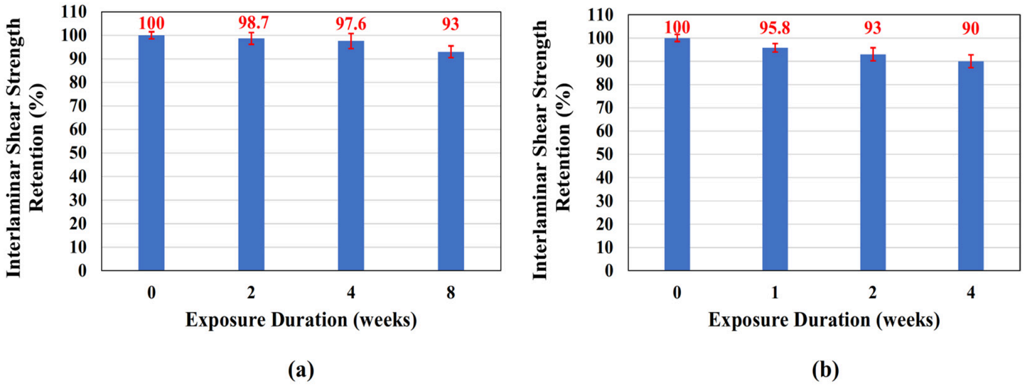


Figure 5. Interlaminar shear strength retention of BFRP dowel bars after environmental conditioning: (**a**) seawater exposure; (**b**) alkaline exposure. Error bars represent ± SDs calculated from five replicate specimens (n = 5).

At the common exposure durations of 2 and 4 weeks, alkaline conditioning induced a greater reduction in interlaminar shear strength than seawater exposure. After 2 weeks, alkaline exposure resulted in an approximate 7.0% reduction in ILSS, compared with only about 1.3% under seawater conditioning. Similarly, after 4 weeks, the reduction under alkaline conditioning was approximately 10.0%, compared with about 2.4% under seawater exposure. These results indicate that alkaline conditioning caused greater ILSS degradation than seawater exposure within the common conditioning periods investigated.

3.1.4. Statistical Analysis of Mechanical Performance

To assess the variability of the experimental measurements and determine whether the observed changes in mechanical performance were statistically significant, the five replicate measurements obtained for each conditioning condition were statistically analyzed. The results in Table 1 are reported as means ± standard deviations (SDs), and the corresponding coefficients of variation (CV) ranged from 0.27 to 0.61% for flexural strength, 0.93–2.00% for transverse shear strength, and 1.48–3.30% for interlaminar shear strength. These relatively low CV values indicate low specimen-to-specimen variability and good consistency among the replicate measurements.

One-way analysis of variance (ANOVA) was performed separately for flexural strength, transverse shear strength, and interlaminar shear strength. Significant overall differences among the conditioning conditions were obtained for all three mechanical properties, with F-values of 1057.67, 31.54, and 10.10 for flexural, transverse shear, and interlaminar shear strength, respectively ($p < 0.001$). Tukey's honestly significant difference (HSD) post hoc test was subsequently performed at a significance level of $p < 0.05$ to identify the specific differences between the selected conditioning conditions. The statistically significant and non-significant pairwise comparisons are summarized in Table 2.

For flexural strength, seawater exposure resulted in statistically significant reductions relative to the control at all investigated durations (2, 4, and 8 weeks), whereas the 1-week alkaline exposure did not produce a statistically significant difference from the unconditioned condition. Significant reductions were observed after 2 and 4 weeks of alkaline exposure. Furthermore, the direct comparison between the two environments showed statistically significant differences at both 2 and 4 weeks, with seawater exposure resulting in significantly greater reductions in flexural strength than alkaline conditioning at both exposure durations.

For transverse shear strength, the reduction after 2 weeks of seawater exposure was not statistically significant (p = 0.056), despite the numerical reduction observed in the mean strength. In contrast, the reductions after 4 and 8 weeks of seawater exposure were statistically significant relative to the control. All alkaline exposure durations produced statistically significant reductions relative to the control. Moreover, the comparison between seawater and alkaline exposure was statistically significant at both 2 weeks ($p < 0.001$) and 4 weeks ($p = 0.029$), supporting the greater deterioration in transverse shear strength under alkaline conditioning at the common exposure durations.

Table 2. Summary of Tukey HSD pairwise comparisons for mechanical performance.

Property	C–SW2	C–SW4	C–SW8	C–AK1	C–AK2	C–AK4	SW2–AK2	SW4–AK4
Flexural strength	<0.001 ***	<0.001 ***	<0.001 ***	0.651 NS	<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ***
Transverse shear strength	0.056 NS	<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ***	<0.001 ***	0.029 *
Interlaminar shear strength	0.978 NS	0.759 NS	0.003 **	0.156 NS	0.003 **	<0.001 ***	0.025 *	<0.001 **

where C denotes the unconditioned control; SW2, SW4, and SW8 denote seawater exposure for 2, 4, and 8 weeks, respectively; AK1, AK2, and AK4 denote alkaline exposure for 1, 2, and 4 weeks, respectively. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; NS denotes not statistically significant. Values represent Tukey HSD-adjusted p-values.

For interlaminar shear strength, the early seawater exposure stages (2 and 4 weeks) did not result in statistically significant reductions relative to the control, whereas the reduction after 8 weeks became statistically significant ($p = 0.003$). Similarly, 1-week alkaline exposure did not produce a statistically significant difference from the control, while significant reductions were observed after 2 and 4 weeks. The direct comparison between seawater and alkaline conditioning further showed significant differences at both 2 weeks ($p = 0.025$) and 4 weeks ($p < 0.001$), confirming the greater sensitivity of ILSS to alkaline exposure at the common conditioning durations.

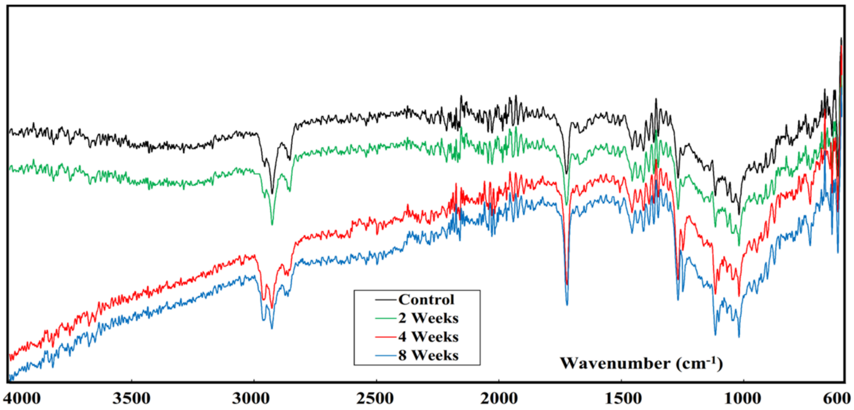
Overall, the statistical analysis confirms that the observed differences in mechanical performance are associated with the environmental conditioning conditions rather than specimen-to-specimen variability. The Tukey HSD results also distinguish statistically significant degradation from numerical changes observed during the early stages of exposure.

3.2. Chemical and Microstructural Characterizations

This section presents the chemical and microstructural characterization results of BFRP dowel bars after seawater and alkaline conditioning. FTIR and SEM/EDS analyses were conducted to examine changes in the epoxy matrix, fibre–matrix interface, and elemental composition, providing complementary evidence to support the interpretation of the mechanical performance trends discussed in Section 3.1.

3.2.1. FTIR Analysis

Fourier-transform infrared spectroscopy (FTIR) was used to examine environmentally induced chemical changes in the epoxy matrix of BFRP dowel bars following seawater and alkaline conditioning. As FTIR primarily probes the chemical structure of the polymer matrix, the analysis was used to assess matrix-level changes associated with environmental conditioning. The FTIR spectra corresponding to all conditioning durations under seawater and alkaline exposure are presented in Figure 6a and Figure 6b, respectively. Prior to interpretation, the spectra were baseline-corrected and processed using the same procedure for all specimens, including the unconditioned control. No additional intensity normalization or peak-ratio analysis was performed; therefore, the FTIR results were interpreted qualitatively based on changes in peak position, intensity, broadening, and disappearance. The observed spectral changes were considered supporting evidence of chemical modification rather than a direct quantitative measure of degradation.



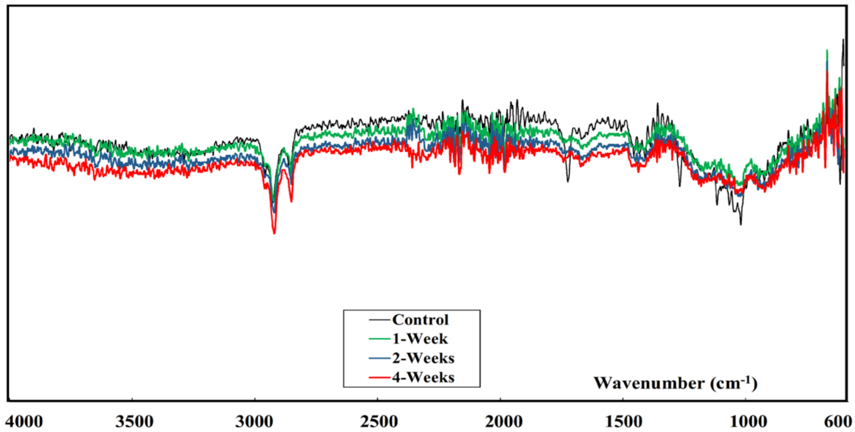


Figure 6. FTIR spectra of BFRP dowel bars after environmental conditioning: (**a**) seawater exposure, and (**b**) alkaline exposure.

The characteristic absorption bands identified in the FTIR spectrum of the unconditioned control specimen included the bands around 2800–2950 cm^{-1}, which are attributed to -CH_2 and -CH_3 stretching vibrations [40]. A distinct peak around 1710 cm^{-1} corresponds to carbonyl (C=O) stretching [41]. The peaks around 1225–1266 cm^{-1} are associated with asymmetric stretching vibrations, while those around 1000–1150 cm^{-1} are attributed to symmetric C-O-C stretching vibrations [41]. Moreover, a peak around 1038 cm^{-1} was associated with aromatic ring stretching [42]. These characteristic bands were used as reference features for qualitative comparison of the spectra obtained after environmental conditioning.

The FTIR spectra of specimens subjected to seawater conditioning displayed progressive deviations from the unconditioned reference spectrum with increasing exposure duration. In particular, the absorption band in the range of approximately 3200–3600 cm^{-1}, associated with O-H stretching vibrations, exhibited increased intensity and noticeable broadening. This change is consistent with increased moisture uptake and hydrogen-bonding interactions within the epoxy matrix and may indicate matrix plasticization. The peaks around 2900–2950 cm^{-1} also showed slight broadening and increases in intensity, indicating changes in the chemical environment of the epoxy matrix. Additionally, the intensity of the peak around 1710 cm^{-1} increased with exposure duration [41]. This increase is consistent with the formation or enhancement of carbonyl-containing groups and may be associated with chemical ageing of the epoxy matrix; however, the FTIR results alone cannot conclusively distinguish between hydrolysis and oxidative processes. The peaks attributed to asymmetric and symmetric C-O-C stretching in the ranges of 1225–1266 cm^{-1} and 1000–1150 cm^{-1}, respectively, also showed increases in intensity, particularly after 4 and 8 weeks of exposure. These changes indicate progressive chemical modification of the epoxy matrix with increasing seawater exposure duration, while the specific degradation mechanisms cannot be established from FTIR analysis alone.

In contrast, the FTIR spectra of the alkaline-conditioned specimens exhibited a different response, despite the chemically aggressive nature of the exposure medium. Compared with seawater conditioning, the overall spectral deviations from the reference spectrum were less pronounced. The peak corresponding to the carbonyl (C=O) group at around 1710 cm^{-1} disappeared after the first week of exposure compared with the control, which is consistent with chemical modification or degradation of carbonyl-containing groups under alkaline conditions [43]. No clear increase was observed in the bands associated with the C-O-C region, while the peaks within the range of 1000–1266 cm^{-1} showed a noticeable reduction in intensity. These changes indicate modification of the epoxy network under alkaline exposure; however, the FTIR spectra alone cannot conclusively determine whether the observed changes resulted from hydrolysis, leaching, or other concurrent chemical processes. The relatively close similarity between the spectra of alkaline-conditioned specimens at different exposure durations and the unconditioned control suggests that the bulk chemical modification detected by FTIR remained relatively limited and did not increase substantially with exposure duration. Overall, the alkaline-conditioned spectra indicate chemical modification of the epoxy matrix, but the extent and specific mechanism of this modification cannot be quantified from the FTIR results alone.

An important observation from the mechanical testing program is that flexural strength exhibited greater degradation under seawater exposure than under alkaline conditioning at comparable exposure durations. This difference is broadly consistent with the more pronounced spectral changes observed in the seawater-conditioned specimens, particularly in the O-H, C-H, carbonyl, and C-O-C regions. These changes suggest greater chemical modification of the epoxy matrix under seawater exposure, which may have contributed to reduced stress-transfer efficiency and the greater reduction in flexural performance. Conversely, alkaline exposure produced comparatively smaller changes in the bulk FTIR spectra, despite the more pronounced reductions observed in transverse shear and interlaminar shear strength. This difference may indicate that part of the degradation under alkaline exposure occurs in localized matrix-dominated or fibre–matrix interfacial regions that may not be fully captured by bulk FTIR measurements. Therefore, the FTIR results are considered complementary evidence for the observed mechanical trends rather than definitive proof of specific degradation mechanisms.

Since FTIR primarily reflects bulk chemical changes in the epoxy matrix, localized fibre damage and fibre–matrix interfacial degradation cannot be fully resolved from the spectra alone. Therefore, SEM analysis was used to provide complementary microstructural evidence by examining matrix cracking, fibre surface morphology, and fibre–matrix interfacial condition, as discussed in the following section.

3.2.2. SEM/EDS Microstructural Analysis

Scanning electron microscopy (SEM) combined with energy-dispersive X-ray spectroscopy (EDS) was used to characterize the microstructural evolution and local elemental changes in the BFRP dowel bars after seawater and alkaline conditioning. SEM observations focused on microstructural features associated with environmental degradation, including small cracks, fibre exposure, and fibre–matrix interfacial debonding, while EDS provided complementary semi-quantitative information on the local elemental composition. For each investigated condition, five representative EDS spot measurements were obtained at comparable microstructural locations, and the results are reported as means ± standard deviations (n = 5) in Table 3. Only the major and discussion-relevant elements detected by EDS are reported in Table 3; therefore, the reported elemental percentages do not represent the complete elemental composition. Because EDS measurements are sensitive to the local fibre–matrix geometry and sampling location, the elemental compositions are interpreted as supporting evidence of microstructural changes rather than as direct quantitative measures of matrix loss or environmental ion penetration. Representative SEM micrographs and corresponding EDS spectra are presented in Figures 7 and 8 for seawater and alkaline exposure, respectively.

Table 3. Selected EDS elemental composition of BFRP specimens under seawater and alkaline exposure.

Condition	C (wt%)	Si (wt%)	Al (wt%)	Na (wt%)	Mg (wt%)	Ca (wt%)	K (wt%)
Control	89.7 ± 3.80	5.8 ± 0.50	2.2 ± 0.60	0.45 ± 0.10	0.50 ± 0.10	0.85 ± 0.15	0.15 ± 0.03
Seawater-2W	87.2 ± 3.25	6.0 ± 0.90	2.4 ± 0.50	0.55 ± 0.15	0.64 ± 0.15	1.00 ± 0.10	0.25 ± 0.07
Seawater-4W	62.1 ± 4.30	22.3 ± 1.90	8.1 ± 1.00	1.73 ± 0.25	1.95 ± 0.20	3.05 ± 0.15	0.50 ± 0.12
Seawater-8W	40.8 ± 4.60	33.3 ± 2.25	12.5 ± 1.50	2.45 ± 0.30	3.00 ± 0.35	4.80 ± 0.30	0.65 ± 0.15
Alkaline-4W	78.7 ± 4.20	10.7 ± 1.10	4.2 ± 0.80	0.85 ± 0.15	0.50 ± 0.10	1.75 ± 0.12	0.35 ± 0.05

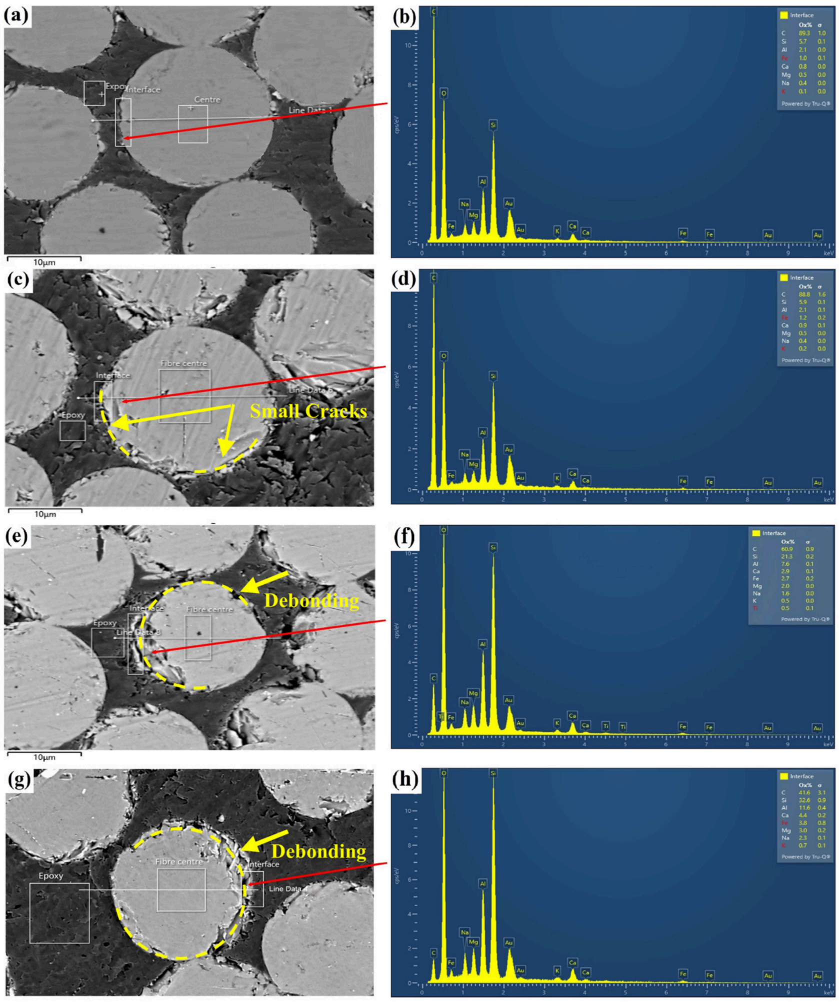


Figure 7. Representative SEM micrographs and corresponding EDS spectra for (**a**,**b**) Control sample; (**c**,**d**) 2 weeks exposure; (**e**,**f**) 4 weeks exposure; (**g**,**h**) 8 weeks exposure to seawater.

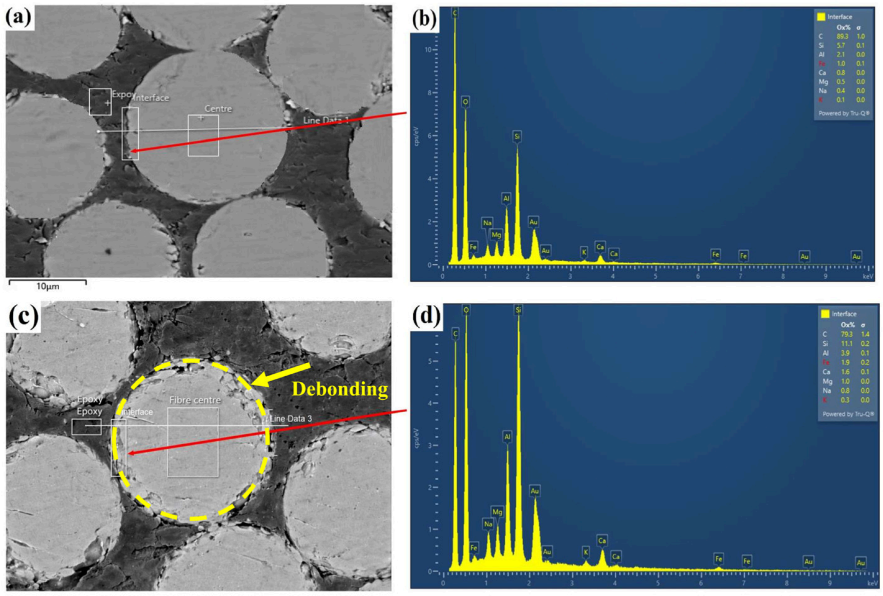


Figure 8. Representative SEM micrographs and corresponding EDS spectra for (**a**,**b**) Control sample; (**c**,**d**) 4 weeks exposure to alkaline solution.

1. Seawater Exposure

Figure 7 presents representative SEM micrographs and corresponding EDS spectra of the BFRP dowel bars before and after seawater exposure. The unconditioned specimen exhibited a dense and relatively homogeneous epoxy matrix with basalt fibres well embedded in the surrounding matrix and no evident cracking or interfacial gaps. The corresponding EDS measurements showed a predominantly carbon-rich composition (89.7 wt%), with lower Si and Al contents associated with the basalt-fibre phase. The selected elemental composition of the control and conditioned specimens is summarized in Table 3. These observations provide the microstructural and elemental reference for evaluating the changes induced by seawater exposure.

After 2 weeks of seawater conditioning, the SEM images showed the initial development of small matrix microcracks and localized fibre–matrix interfacial gaps, while the fibres remained largely embedded and no extensive matrix loss was observed. As shown in Table 3, the carbon content decreased slightly from 89.7 wt% in the control to 87.2 wt%, accompanied by small increases in Si and Al contents. This local compositional shift is consistent with limited exposure of the basalt-fibre phase associated with early matrix deterioration. Small increases in Na, Mg, and Ca were also detected in Table 3, indicating increased local detection of these elements at the analyzed locations following seawater exposure. These early microstructural changes were accompanied by an approximately 10% reduction in flexural strength, whereas transverse shear and interlaminar shear strength decreased by only about 2.5% and 1.3%, respectively. The relatively limited changes in the SEM/EDS observations and shear-related properties suggest that the early degradation remained localized while the overall fibre–matrix stress-transfer structure was largely maintained.

After 4 weeks of seawater exposure, the SEM images revealed a more pronounced deterioration of the epoxy matrix, characterized by increased surface roughness, matrix fragmentation, and more visible fibre–matrix interfacial gaps, as shown in Figure 7. Localized matrix detachment from the fibre surfaces was also observed, indicating progressive interfacial debonding. As reported in Table 3, the carbon content decreased markedly to 62.1 wt%, while the Si and Al contents increased to 22.3 and 8.1 wt%, respectively. This substantial shift in local elemental composition is consistent with increased exposure of the basalt-fibre phase in the analyzed regions as the surrounding epoxy matrix deteriorated. The concentrations of Na, Mg, and Ca also increased relative to the control, indicating increased local detection of these elements following seawater exposure, as shown in Table 3. These compositional changes provide complementary evidence of the progressive environmental alteration observed by SEM but should not be interpreted as direct measurements of ion penetration or matrix loss. The observed microstructural deterioration was accompanied by reductions of approximately 11.5%, 5.5%, and 2.4% in flexural, transverse shear, and interlaminar shear strengths, respectively. The observed matrix fragmentation and interfacial debonding are consistent with the reductions in shear-related properties, although the larger reduction in flexural strength indicates that flexural performance was also substantially affected at this exposure stage.

After 8 weeks of seawater exposure, the SEM images showed further deterioration of the epoxy matrix, with extensive matrix cracking, enlarged interfacial gaps, and more pronounced exposure of the basalt fibres, as shown in Figure 7. More pronounced local matrix deterioration was also observed in several regions, indicating advanced deterioration of the matrix in the examined areas. Consistent with these observations, Table 3 shows a substantial decrease in carbon content to 40.8 wt%, accompanied by marked increases in Si and Al contents to 33.3 and 12.5 wt%, respectively. This shift in local elemental composition is consistent with increased exposure of the basalt-fibre phase in the analyzed regions as the surrounding epoxy matrix deteriorated. The concentrations of Na, Mg, and Ca also reached their highest values at this exposure duration, as shown in Table 3, indicating increased local detection of these elements following prolonged seawater conditioning. These EDS results provide complementary evidence of the progressive environmental alteration observed by SEM, but do not represent direct measurements of ion penetration or matrix loss. The advanced microstructural deterioration was accompanied by reductions of approximately 14.5%, 8.7%, and 7.0% in flexural, transverse shear, and interlaminar shear strengths, respectively, compared with the control specimens. The pronounced matrix cracking and fibre–matrix debonding observed at this stage are consistent with the reductions in shear-related properties, while the larger reduction in flexural strength reflects the substantial overall deterioration of the conditioned specimens.

Overall, the SEM/EDS observations indicate a progressive, exposure-dependent deterioration of the epoxy matrix and fibre–matrix interface under seawater conditioning. The gradual development of matrix cracking, fibre exposure, and interfacial debonding is consistent with the progressive reductions observed in flexural, transverse shear, and interlaminar shear strengths. The corresponding changes in local elemental composition, particularly the decrease in carbon content and increase in Si and Al contents, provide complementary evidence of increased exposure of the basalt-fibre phase in the analyzed regions. Similarly, the increasing detection of Na, Mg, and Ca with exposure duration is consistent with environmental alteration associated with prolonged seawater conditioning. However, because direct moisture-uptake and diffusion measurements were not performed, these observations should be interpreted as microstructural evidence consistent with diffusion-controlled degradation under seawater exposure rather than as direct measurements of moisture transport.

2. Alkaline Exposure

Figure 8 presents representative SEM micrographs and corresponding EDS spectra of the control BFRP specimen and the specimen after 4 weeks of alkaline exposure. The control specimen exhibited a dense epoxy matrix with basalt fibres well embedded in the surrounding resin, with no apparent interfacial gaps or significant surface damage. After 4 weeks of alkaline conditioning, localized microstructural deterioration was observed, particularly at the fibre–matrix interface. The exposed specimen showed interfacial gaps and localized debonding around several fibres, together with matrix roughening and partial exposure of the basalt fibres. These features indicate localized deterioration of the epoxy matrix and changes at the fibre–matrix interface under the alkaline conditioning environment.

The EDS results presented in Table 3 provide complementary evidence of the compositional changes observed in the SEM micrographs. The carbon content decreased from 89.7 wt% in the control specimen to 78.7 wt% after 4 weeks of alkaline exposure, while the Si and Al contents increased from 5.8 and 2.2 wt% to 10.7 and 4.2 wt%, respectively. This shift in local elemental composition is consistent with increased exposure of the basalt-fibre phase in the analyzed regions as the surrounding epoxy matrix deteriorated. The concentrations of Na, K, and Ca also increased after alkaline conditioning, as shown in Table 3, indicating greater local detection of these elements at the analyzed locations. However, because EDS measurements are localized and sensitive to fibre–matrix geometry and sampling location, these compositional changes should be interpreted as supporting evidence of environmental alteration rather than as direct quantitative measurements of matrix loss or ion penetration.

The observed microstructural deterioration is consistent with the mechanical response after 4 weeks of alkaline exposure. Transverse shear and interlaminar shear strengths decreased by approximately 8.3% and 10.0%, respectively, whereas flexural strength decreased by approximately 8.5% compared with the control specimens. The greater reduction in ILSS compared with flexural strength and the comparable reduction in transverse shear strength are consistent with the observed matrix deterioration and fibre–matrix interfacial debonding, particularly because these features can affect stress transfer under shear loading. In contrast, the SEM images showed no clear evidence of extensive fibre damage in the examined regions, indicating that the observed microstructural changes were primarily localized within the matrix and fibre–matrix interfacial regions.

Overall, the SEM/EDS results indicate that alkaline conditioning primarily affected the epoxy matrix and fibre–matrix interface in the examined regions, with no clear evidence of extensive fibre damage. The observed interfacial debonding, matrix roughening, and partial fibre exposure provide microstructural support for the observed reductions in shear-related mechanical properties, particularly ILSS, under alkaline exposure. The accompanying changes in local elemental composition, including the decrease in carbon content and increases in Si and Al contents, are consistent with increased exposure of the basalt-fibre phase following matrix deterioration. The increases in Na, K, and Ca detected after alkaline conditioning further indicate environmental alteration at the analyzed locations. However, because the EDS measurements were localized and only the 4-week alkaline condition was examined by SEM/EDS, these results should be interpreted as supporting evidence of environmental degradation rather than as direct quantitative measures of matrix loss, ion penetration, or the temporal progression of alkaline-induced degradation.

The combined FTIR, SEM/EDS, and mechanical results provide complementary evidence supporting an association between environmental exposure to chemical modification of the epoxy matrix, fibre–matrix interfacial deterioration, and changes in mechanical performance. Under seawater exposure, progressive changes in the O-H, C-H, carbonyl, and C-O-C regions of the FTIR spectra were accompanied by increasing matrix cracking, fibre exposure, and interfacial debonding in the SEM observations. These changes were associated with progressive reductions in flexural, transverse shear, and interlaminar shear strengths with increasing exposure duration. Under alkaline exposure, changes in characteristic epoxy-related FTIR bands and localized matrix and fibre–matrix interfacial deterioration observed by SEM/EDS were similarly accompanied by reductions in the corresponding mechanical properties. At the common 2- and 4-week exposure durations, the combined mechanical results indicate greater flexural degradation under seawater exposure, whereas the shear-related properties showed greater deterioration under alkaline exposure. Overall, the combined results support an association between environmental conditioning, matrix and fibre–matrix interfacial changes, and the observed mechanical degradation. However, because the microscopic observations were qualitative and were not converted into quantified damage indices, a statistically robust relationship between specific microstructural features and mechanical strength retention could not be established. Therefore, the present correlation should be regarded as mechanistic rather than predictive, and quantitative microstructural–mechanical modelling is recommended for future work.

The degradation trends observed in the present study are generally consistent with those reported in previous durability investigations of BFRP materials under seawater and alkaline exposure conditions. Previous studies have reported progressive changes in mechanical performance with increasing exposure duration and temperature, with the severity of degradation depending strongly on the specific BFRP material system and environmental conditions [17–23]. Similarly, the present study showed progressive reductions in flexural, transverse shear, and interlaminar shear strengths with increasing exposure duration. The observed degradation was more pronounced for flexural strength under seawater exposure, whereas the shear-related properties showed greater sensitivity under alkaline conditioning. These general trends are consistent with degradation mechanisms reported in previous studies, including epoxy matrix degradation, fibre–matrix interfacial deterioration, and moisture-assisted degradation and environmental ion transport [17–23]. However, direct quantitative comparison of strength-retention values is not appropriate because the previous studies differed substantially from the present work in terms of bar/dowel diameter, fibre and resin systems, exposure medium, temperature, exposure duration, and mechanical testing procedures. Therefore, the previous literature is used primarily to contextualize the degradation trends and mechanisms observed in the present study rather than to establish a quantitative durability ranking among different BFRP systems.

4. Conclusions

This study evaluated the durability performance of 25-mm smooth, epoxy-based pultruded basalt fibre-reinforced polymer (BFRP) dowel bars under separate seawater and alkaline exposure conditions using accelerated conditioning at 60 °C. The study aimed to quantify the effects of these environments on flexural, transverse shear, and interlaminar shear strength and to provide complementary evidence of the associated chemical and microstructural changes using FTIR and SEM/EDS analyses. Based on the experimental results, the following conclusions can be drawn:

- BFRP dowel bars exhibited generally stable mechanical performance under both environmental conditions over the investigated exposure periods, with reductions in all measured mechanical properties remaining below 15%.
- Under seawater exposure (up to 8 weeks), gradual reductions were observed in all mechanical properties, with flexural strength showing the highest reduction (≈14.5%), followed by transverse shear strength (≈8.7%) and ILSS (≈7.0%).
- Under alkaline exposure (up to 4 weeks), reductions were also observed in all mechanical properties, with ILSS showing the highest reduction (≈10.0%), followed by flexural strength (≈8.5%) and transverse shear strength (≈8.3%).
- At the common exposure durations of 2 and 4 weeks, seawater exposure led to greater reductions in flexural performance, while alkaline exposure resulted in greater reductions in shear-related properties (transverse shear strength and ILSS).
- FTIR analysis showed changes in characteristic epoxy-related absorption bands following environmental conditioning. Under seawater exposure, increased intensity

and broadening of hydroxyl- and carbonyl-related bands were observed with increasing exposure duration, whereas alkaline exposure resulted mainly in reductions in characteristic epoxy-related absorption bands.
- SEM observations revealed progressive matrix cracking, fibre exposure, and fibre–matrix interfacial debonding with increasing seawater exposure duration. After 4 weeks of alkaline exposure, localized fibre–matrix interfacial debonding was observed, accompanied by matrix surface roughening and partial erosion.
- EDS analysis detected changes in the local elemental composition of conditioned specimens, including increased local detection of Na, Mg, Ca, and K at the analyzed locations. The observed reductions in carbon content and corresponding increases in Si and Al contents were consistent with increased local exposure of basalt fibres as the surrounding matrix deteriorated. Because EDS measurements were localized, these compositional changes are interpreted as semi-quantitative supporting evidence rather than direct quantitative measurements of ion penetration or matrix loss.

Overall, the investigated BFRP dowel system showed limited reductions in mechanical performance under the accelerated seawater and alkaline conditioning regimes adopted in this study, indicating promising material-level durability performance under the investigated exposure conditions. However, these results represent accelerated laboratory durability trends and should not be interpreted as direct predictions of field service life or equivalent field exposure durations. The findings are limited to the specific 25-mm smooth, epoxy-based pultruded BFRP dowel system investigated in this study and should not be generalized to BFRP dowels with different diameters, resin systems, fibre contents, surface treatments, or manufacturing processes.

Future work should incorporate gravimetric moisture-uptake measurements and/or diffusion-based characterization to quantitatively evaluate moisture transport and its relationship with mechanical degradation, as well as investigations of unsealed or field-damaged dowel ends to evaluate the potential effects of longitudinal solution ingress. Environmentally conditioned joint-level testing should also be conducted to assess the combined effects of shear, bending, concrete bearing, and dowel–concrete interaction under realistic joint conditions. Additional studies should consider wet–dry cycling, combined alkaline–chloride exposure, different dowel diameters, longer exposure periods, cyclic and fatigue testing under environmentally conditioned states to evaluate the effects of repeated traffic-induced loading, and deformation-based indicators. Such studies should also consider validated time–temperature relationships, predictive durability models, design reduction factors, and service-life assessment.

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References

1. Benmokrane, B.; Wang, P.; Ton-That, T.M.; Rahman, H.; Robert, J.F. Durability of Glass Fiber-Reinforced Polymer Reinforcing Bars in Concrete Environment. *J. Compos. Constr.* **2002**, *6*, 143–153. [CrossRef]
2. Micelli, F.; Nanni, A. Durability of FRP Rods for Concrete Structures. *Constr. Build. Mater.* **2004**, *18*, 491–503. [CrossRef]
3. Shahmansouri, A.A.; Lei, Z.; Shi, X. *Protective Performance of Externally-Bonded, Nano-Modified FRP for Concrete in Chloride Environments*; Final Report; National Center for Transportation Infrastructure Durability & Life-Extension (TriDurLE), Washington State University: Pullman, WA, USA, 2025.
4. Hollaway, L.C. A Review of the Present and Future Utilization of FRP Composites in the Civil Infrastructure with Reference to Their Important In-Service Properties. *Constr. Build. Mater.* **2010**, *24*, 2419–2445. [CrossRef]
5. Wu, Z.; Wang, X.; Wu, G. Advancement of Structural Safety and Sustainability with Basalt Fiber Reinforced Polymers. In Proceedings of the 6th International Conference on FRP Composites in Civil Engineering (CICE 2012), Rome, Italy, 13–15 June 2012.
6. Shamass, R.; Cashell, K.A. Experimental Investigation into the Flexural Behavior of Basalt FRP Reinforced Concrete Members. *Eng. Struct.* **2020**, *220*, 110950. [CrossRef]
7. Pavlović, A.; Donchev, T.; Petkova, D.; Staletović, N. Sustainability of Alternative Reinforcement for Concrete Structures: Life Cycle Assessment of Basalt FRP Bars. *Constr. Build. Mater.* **2022**, *334*, 127424. [CrossRef]
8. Larson, R.M.; Smith, K.D. Alternative Dowel Bars for Load Transfer in Jointed Concrete Pavements. In *Proceedings of the 8th International Conference on Concrete Pavements, Colorado Springs, CO, USA, 14–18 August 2005*; International Society for Concrete Pavements: East Lansing, MI, USA, 2025; Volume 1, pp. 415–439. [CrossRef]
9. Wang, R.; Hu, Z.; Li, Y.; Wang, K.; Zhang, H. Review on the Deterioration and Approaches to Enhance the Durability of Concrete in the Freeze-Thaw Environment. *Constr. Build. Mater.* **2022**, *321*, 126371. [CrossRef]
10. Lee, S.K. *Technical Review of FHWA-HRT-15-079: Laboratory Evaluation of Corrosion Resistance of Various Metallic Dowel Bars*; Federal Highway Administration, U.S. Department of Transportation: Washington, DC, USA, 2018.
11. Montaigu, M.; Ahmed, E.; Benmokrane, B.; Thebeau, D. Newly Developed GFRP Dowel Bars for Jointed Plain Concrete Pavement. In *Proceedings of the 10th International Conference on Concrete Pavements, Québec City, QC, USA, 8–12 July 2012*; International Society for Concrete Pavements: East Lansing, MI, USA, 2025; Volume 10, p. 1. [CrossRef]
12. Windisch, A. Performance Evaluation of Glass Fiber-Reinforced Polymer Shear Reinforcement for Concrete Beams. *ACI Struct. J.* **2010**, *107*, 738–740. [CrossRef]
13. Li, L.K.; Tan, Y.Q.; Gong, X.B.; Li, Y.L. Load Transfer Characteristics and Durability Study of GFRP Dowels in Jointed Concrete Pavement. In *Advances in Engineering Forum*; Trans Tech Publications: Bäch SZ, Switzerland, 2012; Volume 5, pp. 277–282. [CrossRef]
14. Li, L.; Li, Y.; Tan, Y.; Xue, Z. Research on Load Transfer Efficiency of GFRP Dowel in Jointed Plain Concrete Pavement. *Appl. Mech. Mater.* **2012**, *178–181*, 1152–1155. [CrossRef]
15. Won, J.P.; Cho, Y.C.; Jang, C.I. The Durability of Glass Fibre-Reinforced Polymer Dowel after Accelerated Environmental Exposure. *Polym. Polym. Compos.* **2006**, *14*, 719–730. [CrossRef]
16. Zhang, K.; Zhang, Q.; Xiao, J. Durability of FRP Bars and FRP Bar Reinforced Seawater Sea Sand Concrete Structures in Marine Environments. *Constr. Build. Mater.* **2022**, *350*, 128898. [CrossRef]
17. Al Rifai, M.; El-Hassan, H.; El-Maaddawy, T.; Abed, F. Durability of Basalt FRP Reinforcing Bars in Alkaline Solution and Moist Concrete Environments. *Constr. Build. Mater.* **2020**, *243*, 118258. [CrossRef]
18. Elgabbas, F.; Ahmed, E.A.; Benmokrane, B. Physical and Mechanical Characteristics of New Basalt-FRP Bars for Reinforcing Concrete Structures. *Constr. Build. Mater.* **2015**, *95*, 623–635. [CrossRef]
19. Wu, G.; Wang, X.; Wu, Z.; Dong, Z.; Xie, Q. Degradation of Basalt FRP Bars in Alkaline Environment. *Sci. Eng. Compos. Mater.* **2015**, *22*, 649–657. [CrossRef]
20. Lu, C.; Ni, M.; Chu, T.; He, L. Comparative Investigation on Tensile Performance of FRP Bars after Exposure to Water, Seawater, and Alkaline Solutions. *J. Mater. Civ. Eng.* **2020**, *32*, 04020170. [CrossRef]
21. Lu, Z.; Li, Y.; Xie, J. Durability of BFRP Bars Wrapped in Seawater Sea Sand Concrete. *Compos. Struct.* **2021**, *255*, 112935. [CrossRef]
22. Wang, T.; Razaqpur, A.G.; Chen, S. Durability of GFRP and BFRP Reinforcing Bars in Simulated Seawater Sea Sand Calcium Sulfoaluminate Cement Concrete Pore Solution. *J. Build. Eng.* **2023**, *80*, 107954. [CrossRef]
23. Ali, A.H.; Mohamed, H.M.; Benmokrane, B. Bar Size Effect on Long-Term Durability of Sand-Coated Basalt-FRP Composite Bars. *Compos. Part B Eng.* **2020**, *195*, 108059. [CrossRef]
24. Liu, J.; Li, N.; Chen, M.; Yang, J.; Long, B.; Wu, Z. Durability of Basalt Fiber-Reinforced Polymer Bars in Wet-Dry Cycles Alkali-Salt Corrosion. *Sci. Eng. Compos. Mater.* **2019**, *26*, 43–52. [CrossRef]
25. Chen, Y.; Davalos, J.F.; Ray, I.; Kim, H.Y. Accelerated Aging Tests for Evaluations of Durability Performance of FRP Reinforcing Bars for Concrete Structures. *Compos. Struct.* **2007**, *78*, 101–111. [CrossRef]
26. Dong, Z.; Wu, G.; Xu, Y. Experimental Study on the Bond Durability between Steel-FRP Composite Bars (SFCBs) and Sea Sand Concrete in Ocean Environment. *Constr. Build. Mater.* **2016**, *115*, 277–284. [CrossRef]

27. Lin, H.; Jiang, Y.; Li, S.; Li, W.; Zhu, D.; Chen, J.; Teng, T.; Xue, Y.; Cao, Z. In Situ Study on High-Temperature Performance and Structural Deterioration Mechanism of Concrete. *Processes* **2026**, *14*, 1753. [CrossRef]
28. Wang, L.; Xue, Y.; Wang, X.; Zhu, L.; Cao, X.; Ge, R. Effect of Aggregate Gradation on Pore Structure Evolution and Mechanical Performance of Coal Gangue-Fly Ash Cemented Backfill: Insights from NMR. *Powder Technol.* **2026**, *482*, 122775. [CrossRef]
29. *ISO 10406-1:2015*; Fibre-Reinforced Polymer (FRP) Reinforcement of Concrete—Test Methods—Part 1: FRP Bars and Grids. International Organization for Standardization: Geneva, Switzerland, 2015.
30. *ASTM D1141-98(2021)*; Standard Practice for the Preparation of Substitute Ocean Water. ASTM International: West Conshohocken, PA, USA, 2021.
31. Lu, Z.; Su, L.; Xian, G.; Lu, B.; Xie, J. Durability Study of Concrete-Covered Basalt Fiber-Reinforced Polymer (BFRP) Bars in Marine Environment. *Compos. Struct.* **2020**, *234*, 111650. [CrossRef]
32. Patnaik, A. Applications of Basalt Fiber Reinforced Polymer (BFRP) Reinforcement for Transportation Infrastructure. *Dev. Res. Agenda Transp. Infrastruct.* **2009**, 1–5.
33. *ASTM D4475/D4475M-16*; Standard Test Method for Apparent Horizontal Shear Strength of Pultruded Fiber-Reinforced Plastic Rods. ASTM International: West Conshohocken, PA, USA, 2021.
34. Al-Sabagh, A.; Taha, E.; Kandil, U.; Awadallah, A.; Nasr, G.A.M.; Taha, M.R. Monitoring Moisture Damage Propagation in GFRP Composites Using Carbon Nanoparticles. *Polymers* **2017**, *9*, 94. [CrossRef]
35. Zhao, C.; Wen, R.; Dai, Y.; Al-Mansour, A.; Fu, C.; Zeng, Q. Hydrolysis Degradation Mechanisms of Epoxy Resin Coatings on Concrete in Hydrothermal Environment Resolved by Molecular Dynamic Simulations. *Constr. Build. Mater.* **2025**, *479*, 141463. [CrossRef]
36. Pannico, M.; Mensitieri, G.; Musto, P. In-Situ FTIR Spectroscopy of Epoxy Resin Degradation: Kinetics and Mechanisms. *Front. Chem.* **2024**, *12*, 1476965. [CrossRef]
37. Mai, G.; Xiong, Z.; Zhu, H.; Zhou, L.; Zhou, H.; Li, L. Durability of GFRP Bars Embedded in Seawater Sea Sand Concrete in Marine Environments. *Constr. Build. Mater.* **2025**, *458*, 139488. [CrossRef]
38. Dong, Z.; Wu, G.; Lian, J. Experimental Study on the Durability of FRP Bars Reinforced Concrete Beams in Simulated Ocean Environment. *Sci. Eng. Compos. Mater.* **2018**, *25*, 1123–1134. [CrossRef]
39. Wang, Z.; Zhao, X.L.; Xian, G.; Wu, G.; Singh Raman, R.K.; Al-Saadi, S. Durability Study on Interlaminar Shear Behaviour of Basalt-, Glass- and Carbon-Fibre Reinforced Polymer (B/G/CFRP) Bars in Seawater Sea Sand Concrete Environment. *Constr. Build. Mater.* **2017**, *156*, 985–1004. [CrossRef]
40. Salasinska, K.; Barczewski, M.; Aniśko, J.; Hejna, A.; Celiński, M. Comparative Study of the Reinforcement Type Effect on the Thermomechanical Properties and Burning of Epoxy-Based Composites. *J. Compos. Sci.* **2021**, *5*, 89. [CrossRef]
41. Yang, Y.; Xian, G.; Li, H.; Sui, L. Thermal Aging of an Anhydride-Cured Epoxy Resin. *Polym. Degrad. Stab.* **2015**, *118*, 111–119. [CrossRef]
42. Idrisi, A.H.; Mourad, A.H.I.; Abdel-Magid, B.M.; Shivamurty, B. Investigation on the Durability of E-Glass/Epoxy Composite Exposed to Seawater at Elevated Temperature. *Polymers* **2021**, *13*, 2182. [CrossRef]
43. Sun, Y.; Jin, Z.; Zhang, X.; Zhang, S.; He, S.; Pang, B. Initial Stage Degradation of GFRP Bars Based on Functional Group Ratio Change Using FTIR in High Temperature and Alkaline Solution. *J. Build. Eng.* **2023**, *68*, 106190. [CrossRef]