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[Review Article](#)



Durability and Long-Term Performance of Fiberglass Reinforced Polymer Composites: A Review of Environmental Effects and Degradation Mechanisms

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Abstract

Glass fiber reinforced polymer (GFRP) composites are increasingly adopted in civil infrastructure, marine, transportation, and energy applications due to their high strength-to-weight ratio, corrosion resistance, and design flexibility. Despite these advantages, the long-term durability of GFRP composites under sustained environmental exposure remains a critical concern governing their structural reliability and service life. Environmental factors such as moisture ingress, temperature fluctuations, ultraviolet radiation, and chemically aggressive conditions can induce complex physical and chemical changes within the composite system, ultimately leading to progressive degradation and performance loss. This review provides a comprehensive and mechanism-driven synthesis of the environmental effects and degradation processes that control the long-term behavior of GFRP composites. Emphasis is placed on clearly distinguishing environmental exposure conditions, observable material responses, and the underlying degradation mechanisms affecting the polymer matrix, glass fibers, and fiber–matrix interface. The resulting implications for mechanical performance, damage tolerance, thermal stability, and failure evolution are critically examined in the context of long-term service conditions. Furthermore, current durability assessment methodologies and accelerated aging approaches are reviewed, with particular attention to their ability to capture realistic degradation pathways and predict in-service performance. Key limitations in existing experimental practices and the challenges associated with extrapolating laboratory results to real environments are highlighted. The review concludes by identifying critical research gaps and outlining future directions toward mechanism-based durability modeling and performance-oriented design of GFRP composites. By integrating environmental exposure, degradation mechanisms, and engineering performance, this review aims to support more reliable durability assessment and long-term application of GFRP materials in demanding environments.

Keywords: Glass fiber reinforced polymer (GFRP), Durability, Environmental exposure, Degradation mechanisms, Long-term performance and Accelerated aging

1. Introduction

Glass fiber reinforced polymer (GFRP) composites have gained widespread interest in modern engineering applications due to their high strength-to-weight ratio, corrosion resistance, and adaptability to complex structural forms. Because of these properties, GFRP materials are increasingly used in infrastructure, marine structures, pipelines, and load-bearing structural elements where conventional materials such as steel and concrete may suffer from corrosion or excessive weight penalties (Tatar and Milev, 2021; Călin *et al.*, 2024). Despite their advantages, environmental exposure remains a fundamental concern that limits the reliable long-term performance of GFRP composites. Studies have demonstrated that prolonged exposure to moisture, thermal fluctuations, alkaline conditions, and ultraviolet (UV) radiation can significantly alter the physical and mechanical behaviour of GFRP materials, often with detrimental effects (Tatar and Milev, 2021; Călin *et al.*, 2024; Liu *et al.*, 2025).

Moisture has been shown to be one of the most aggressive environmental agents affecting GFRP composites because water uptake modifies matrix behaviour and weakens the fiber matrix interface. In polymer-based composites, moisture absorption leads to plasticization of the matrix, elevated swelling stresses, and microcracking that facilitate further ingress of water and accelerate degradation processes (Tatar and Milev, 2021; Tefera *et al.*, 2022; Thomason, J. and Xypolias, 2023). This behaviour is particularly pronounced in humid and marine environments where the diffusion of water follows either Fickian or non-Fickian patterns depending on temperature and exposure duration (Liu *et al.*, 2025). Elevated temperatures further intensify these effects because increased thermal energy enhances molecular mobility and swelling within the polymer matrix, leading to reduced stiffness, lowered glass transition temperatures, and compromised load transfer between fibers and matrix (Tefera *et al.*, 2022). Taken together, these phenomena underscore the complexity of environmental ageing and the need for a detailed mechanistic understanding.

Ultraviolet radiation and alkaline conditions also contribute to environmental degradation, albeit through different pathways. UV exposure initiates photochemical reactions on polymer surfaces, leading to chain scission, surface embrittlement, and discoloration that precede deeper material breakdown under combined stressors (Liu *et al.*, 2025). Likewise, alkaline environments common in concrete contact scenarios can attack the silica component of glass fibers, weakening the reinforcing phase and reducing composite strength (Tatar and Milev, 2021). The interaction between thermal, hygral, and chemical exposures often results in synergistic effects where the combined damage is greater than the sum of individual stressors, further challenging simple life prediction models. These coupled ageing processes are difficult to replicate accurately through conventional accelerated testing methods due to the intricate interdependencies among environmental factors, material composition, and manufacturing conditions.

A central issue in current research is the translation of laboratory-based accelerated ageing data into reliable estimations of field performance. Many accelerated ageing protocols which involve high humidity chambers, salt spray, or elevated temperatures aim to simulate long-term exposure within shorter time frames, but they may not accurately reflect the multi-factorial nature of real service environments (Shrikant *et al.*, 2024). Furthermore, material characteristics such as void content, fiber sizing, and resin chemistry influence how moisture, heat, and chemical agents penetrate and interact within the composite structure. Voids formed during manufacturing act as pathways for moisture ingress, exacerbating matrix damage and weakening interfacial regions (Thomason and Xypolias, 2023; Shrikant *et al.*, 2024). Similarly, the degradation of fiber sizing layers reduces the strength of the fiber–matrix interface, directly impacting stress transfer efficiency and contributing to early failure mechanisms. Because of these complexities, predictive models for lifetime performance that rely solely on single-stress ageing data often fail to capture the true ageing behaviour of GFRP composites in service.

Given these challenges, there is a clear need for a comprehensive review that systematically addresses not only the effects of environmental exposures but also the underlying degradation mechanisms and their impacts on long-term mechanical performance. This review aims to bridge that knowledge gap by synthesizing current research on environmental exposure conditions, elucidating the physico-chemical mechanisms driving degradation, and linking these processes to changes in structural performance over time. The review will explore moisture absorption behavior, thermal and UV effects, alkaline interactions, and their combined influences on material durability. It will also critically assess the strengths and limitations of existing accelerated ageing methodologies and propose directions for more robust predictive frameworks. By integrating environmental effects with mechanistic insights and performance outcomes, this review seeks to provide a coherent and actionable understanding of GFRP durability that supports future research, material design improvements, and reliable service life predictions in challenging environments.

2. Environmental Exposure Conditions

Environmental exposure plays a central role in determining the long-term behaviour and durability of glass fiber reinforced polymer (GFRP) composites. The operational environments that these materials encounter in service are highly variable and often involve multiple interacting factors such as moisture, temperature fluctuations, ultraviolet radiation, and chemical or alkaline conditions. These exposures can independently and synergistically influence the physical and chemical stability of the polymer matrix, fiber–matrix interface, and reinforcing fibers, thereby affecting mechanical performance and service life. An understanding of these conditions is therefore foundational to any comprehensive durability assessment or degradation

mechanism analysis. **Table 1**, illustrates the key environmental exposure conditions affecting GFRP composites, highlighting the primary type of stress and typical

service environments. It serves as a foundation for understanding how these stressors initiate material responses and degradation mechanisms discussed in subsequent sections.

Table 1. Key environmental exposure conditions affecting GFRP composites

Environmental factors	Primary nature of exposure	Typical service environments
Moisture / Water Ingress	High humidity, immersion, or condensation	Marine structures, bridges, pipelines, coastal infrastructure
Thermal Exposure and Cycling	Elevated or fluctuating temperatures, diurnal or seasonal cycles	Outdoor structures, solar panels, industrial environments
Ultraviolet (UV) Radiation	Solar radiation, long-term outdoor exposure	Bridges, facades, exposed structural components
Alkaline / Chemical Exposure	High pH, acidic or saline environments, industrial chemicals	Concrete structures, chemical plants, wastewater treatment facilities
Coupled Exposures	Simultaneous or sequential environmental stressors	Outdoor GFRP structures under combined heat, moisture, UV, and chemical contact

2.1 Moisture and Water Ingress

Moisture exposure, whether from sustained water immersion, high humidity, or aqueous environments such as seawater, is one of the most critical environmental factors affecting GFRP composites. Water molecules can diffuse into the polymer matrix, leading to plasticization, swelling, and weakening of interfacial bonds between fibers and matrix. This results in microcracking, reduced stiffness, and diminished load transfer efficiency in affected regions (Tatar and Milev, 2021; Zhang and Deng, 2022; Thomason and Xypolias, 2023). For example, simulations and accelerated aging tests have shown that increased seawater content combined with temperature rise significantly decreases Young's modulus, shear modulus, and bulk modulus of GFRP laminates, indicating accelerated degradation under marine conditions (Zhang and Deng, 2022). Similarly, moisture uptake in hot and humid environments increases volumetric expansion and micro-void formation, further exacerbating degradation (Thomason and Xypolias, 2023).

2.2 Thermal Exposure and Thermal Cycling

Thermal exposure affects GFRP composites through both short-term temperature extremes and long-term thermal cycling. Elevated temperatures can soften the polymer matrix, reduce glass transition temperatures, and accelerate molecular mobility, which weakens the fiber–matrix interface and reduces mechanical properties such as tensile strength and stiffness (Tefera *et al.*, 2022; Călin *et al.*, 2024). Conversely, low temperatures may induce differential contraction between fiber and matrix, generating internal stresses that can initiate microcracks. Variations in temperature, especially when

crossing glass transition thresholds, also alter moisture diffusion dynamics, often accelerating degradation under combined hygrothermal conditions (Tefera *et al.*, 2022).

2.3 Ultraviolet Radiation

Ultraviolet (UV) radiation exposure is especially relevant for GFRP components used in outdoor environments without protective coatings. UV photons can interact with the polymer matrix to initiate photo-oxidative reactions that break molecular bonds, forming free radicals and leading to surface embrittlement, cracking, and discoloration (Ortiz *et al.*, 2023; Smoleń *et al.*, 2024). Although UV degradation primarily affects the polymer near the surface, damaged regions can act as stress concentrators and facilitate deeper environmental attack. The combined influence of UV and moisture accelerates the formation of microcracks and surface deterioration, intensifying overall degradation processes (Ortiz *et al.*, 2023; Smoleń *et al.*, 2024).

2.4 Chemical and Alkaline Environments

Chemical exposures, particularly alkaline environments such as concrete pore solutions or industrial chemicals, pose another major threat to GFRP durability. Glass fibers, composed mainly of silica, are susceptible to attack by hydroxide ions in high-pH environments, causing breakage of silica chains and weakening of fibers near the surface (Tatar and Milev, 2021). This phenomenon reduces fiber strength and contributes to debonding at the fiber–matrix interface. Aside from alkalinity, exposure to salt, acidic media, or other corrosive fluids can also cause matrix degradation, resin leaching, and accelerated formation of microcracks, further compromising the mechanical integrity of the composite (Călin *et al.*, 2024).

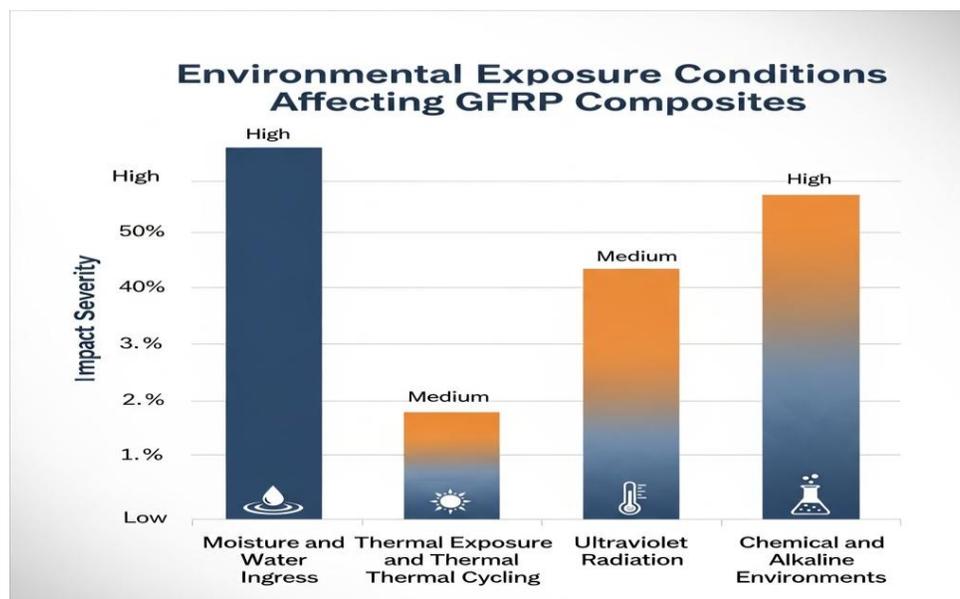


Figure 1. Key environmental exposure conditions affecting GFRP composites. This schematic illustrates how moisture, thermal cycling, ultraviolet (UV) radiation, and chemical/alkaline exposures interact with a GFRP composite.

3. Environmental Effects on GFRP Materials

Environmental exposure conditions cause distinct and measurable physical and chemical changes in glass fiber reinforced polymer (GFRP) composites. These observable effects manifest in the polymer matrix, reinforcing fibers, and especially at the fiber–matrix interface, ultimately influencing mechanical behavior, dimensional stability, and long-term performance. Below, key environmental effects such as moisture uptake, thermal stresses, UV-induced surface deterioration, and chemical attack are discussed with support from recent research findings.

3.1 Moisture Uptake, Swelling, and Physical Changes

Moisture absorption is a fundamental environmental effect on GFRP materials. When composites are exposed to humid, aqueous, or submerged environments, water molecules diffuse into the polymer matrix. This process leads to matrix plasticization, swelling, and increased void volume, which reduce adhesion at the fiber–matrix interface and elevate internal stresses (Thomason and Xypolias, 2023; Li *et al.*, 2025). Experimental long-term exposure studies on GFRP composites in seawater and other aggressive media demonstrate that moisture uptake can dramatically reduce tensile and flexural properties over time, especially at elevated temperatures (Liao *et al.*, 2024; Li *et al.*, 2025). These physical changes, including volumetric expansion and surface microcracking, are among the earliest effects observed in service environments and are often precursors to deeper degradation phenomena.

3.2 Thermal Stresses and Residual Strain Development

Exposure to elevated temperatures and thermal cycling induces thermal stresses and residual strains within GFRP composites due to differences in the coefficients of thermal expansion between glass fibers and the polymer matrix. Elevated temperatures soften the resin, decrease elastic modulus, and impair load transfer mechanisms, contributing to dimensional changes and reduced structural integrity (Călin, *et al.*, 2024; Mourad *et al.*, 2024). Thermal cycling, such as daily or seasonal temperature fluctuations, produces microcracking and residual stresses that accumulate over repeated cycles, particularly in composites used outdoors or in industrial thermal environments (Mourad *et al.*, 2024). The combined effect of temperature and moisture amplifies these changes, accelerating degradation compared with single-stress exposures (Călin, *et al.*, 2024).

3.3 Photo-oxidation and Surface Deterioration

Ultraviolet (UV) radiation affects GFRP materials primarily at the surface. Photo-oxidative reactions initiated by UV exposure break molecular bonds in the polymer matrix, leading to surface embrittlement, chalking, and microcracking (Smoleń *et al.*, 2024; Thapa *et al.*, 2025). Even when limited to a thin surface region, these changes can function as stress concentrators that facilitate deeper environmental damage under combined exposures such as moisture or heat. UV studies show that extended irradiation can lower mechanical properties (e.g., flexural strength) and increase surface roughness, especially in resin-rich regions where the polymer matrix absorbs more radiation than the reinforcing fibers (Thapa *et al.*, 2025). Surface deterioration also accelerates

water ingress, linking UV effects to more extensive environmental degradation.

3.4 Chemical Attack and Material Softening

Chemical and alkaline exposures produce material softening and surface degradation in GFRP composites. Aggressive chemical environments — such as alkaline solutions, acids, or saltwater interact with polymer chains and fiber surfaces, altering mechanical and physical responses. Recent

investigations report that GFRP exposed to saline and alkaline conditions at varied temperatures shows significant decreases in tensile and flexural strength, as well as increased diffusion rates, compared to ambient conditions (Liao *et al.*, 2024). Alkaline environments, in particular, accelerate resin softening and weaken fiber–matrix bonding, leading to greater susceptibility to moisture ingress and dimensional changes (Li *et al.*, 2024; Liao *et al.*, 2024). These chemical effects are especially relevant for composites used in concrete reinforcement or marine applications.

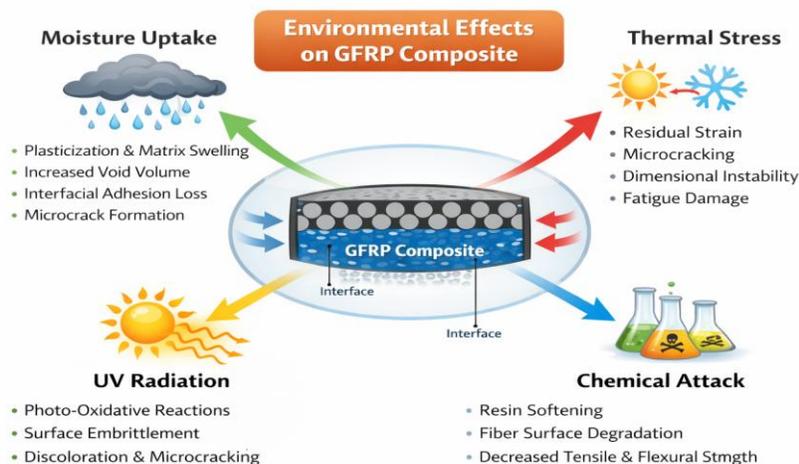


Figure 2. Schematic representation of material-level responses of GFRP to environmental Stressors. This schematic illustrates the main environmental factors impacting GFRP composites: moisture uptake, thermal stress, UV radiation, and chemical/alkaline attack. The cross-section highlights fibers, matrix, and the fiber–matrix interface, showing how each environmental stressor produces material-level effects such as microcracking, residual strain, surface embrittlement, and resin softening.

4. Resulting Degradation Mechanisms

The long-term degradation of fiberglass reinforced polymer (GFRP) composites exposed to environmental stressors is governed by a series of coupled physical and chemical mechanisms that evolve within the matrix, fibers, and fiber–matrix interface. These mechanisms explain how environmental effects such as moisture ingress, thermal cycling, ultraviolet radiation, and chemical exposure translate into irreversible mechanical performance loss. The dominant degradation pathways include matrix hydrolysis and plasticization, fiber deterioration, interfacial debonding, and microcracking with progressive damage accumulation (Hussnain *et al.*, 2023; Thomason and Xypolias, 2023).

4.1 Matrix Hydrolysis and Plasticization

Polymeric matrices in GFRP composites are highly susceptible to environmental degradation, particularly under prolonged exposure to moisture and elevated temperatures, where hydrolytic reactions progressively cleave polymer chains and reduce crosslink density (Barreira-Pinto *et al.*, 2023; Hussnain *et al.*, 2023). Water molecules diffuse into the polymer network and interact with polar functional groups, leading to matrix plasticization, reduced glass transition temperature, and increased molecular mobility, which collectively weaken the load-transfer capability of the composite (Ghabezi and Harrison, 2022; Nezafatkah, 2025). In epoxy-based GFRPs, hydrolysis is often accompanied by irreversible chemical degradation, resulting in permanent stiffness loss and embrittlement following drying cycles (Liao *et al.*, 2024). These matrix-dominated degradation processes form the primary pathway through which environmental exposure initiates long-term mechanical deterioration in GFRP systems (Shrikant *et al.*, 2024).

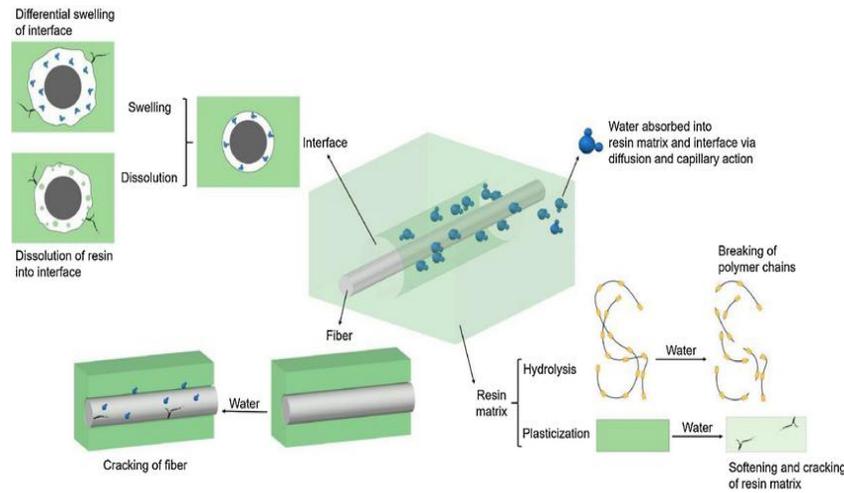


Figure 3. Degradation mechanisms from high moisture or water. This figure illustrates the key degradation mechanisms caused by high moisture or water exposure. Moisture penetrates the material through diffusion, leading to swelling and plasticization, which reduce stiffness and strength. Prolonged water exposure can trigger hydrolysis and chemical deterioration, weaken interfacial bonding, and promote microcrack formation. These processes collectively accelerate material degradation and reduce long-term durability (Wen and Cao (2023))

4.2 Fiber Degradation and Surface Deterioration

Although glass fibers are generally considered chemically stable, prolonged exposure to moisture, alkaline solutions, and aggressive chemicals can induce surface leaching and strength degradation (Ghabezi and Harrison, 2022; Călin, *et al.*, 2024). Alkali ions penetrate the silica network of glass fibers, disrupting surface integrity and reducing tensile strength, particularly in alkaline or marine environments (Hussnain *et al.*, 2023). Ultraviolet radiation further exacerbates fiber degradation indirectly by eroding the surrounding matrix, exposing fibers to environmental attack and accelerating surface flaws (Smoleń *et al.*, 2024; Nezafatkah, 2025). Over time, these mechanisms reduce the intrinsic strength of reinforcing fibers, undermining the structural reliability of GFRP components subjected to long-term outdoor service (Shrikant *et al.*, 2024).

4.3 Fiber–Matrix Interfacial Debonding

The fiber–matrix interface is a critical yet vulnerable region in GFRP composites, as environmental exposure weakens interfacial adhesion through moisture diffusion, chemical attack, and thermal mismatch (Wu *et al.*, 2023). Water ingress disrupts interfacial bonding by breaking hydrogen and covalent bonds formed during sizing and curing, thereby reducing interfacial shear strength (Barreira-Pinto *et al.*, 2023;

Mertgenç Yoldaş, 2025). Differential swelling between fibers and matrix generates localized stresses that further promote debonding under cyclic thermal or hygrothermal conditions (Ghabezi and Harrison, 2022; Hussnain *et al.*, 2023). Once interfacial degradation initiates, stress transfer efficiency declines sharply, accelerating damage propagation even when fiber and matrix constituents remain partially intact (Wu *et al.*, 2023).

4.4 Microcracking and Progressive Damage Evolution

Environmental degradation mechanisms often culminate in microcrack formation within the matrix and along fiber–matrix interfaces, driven by swelling stresses, thermal cycling, and accumulated chemical damage (Ghabezi and Harrison, 2022; Hussnain *et al.*, 2023). These microcracks act as preferential pathways for further moisture and chemical ingress, creating a self-reinforcing degradation cycle that accelerates internal damage accumulation (Shrikant *et al.*, 2024). Under sustained or cyclic mechanical loading, environmentally induced microcracks coalesce into larger cracks, leading to delamination, stiffness loss, and premature failure. Progressive damage evolution thus represents the final manifestation of coupled environmental and mechanical degradation processes governing the long-term durability of GFRP composites (Liao *et al.*, 2024; Nezafatkah, 2025).

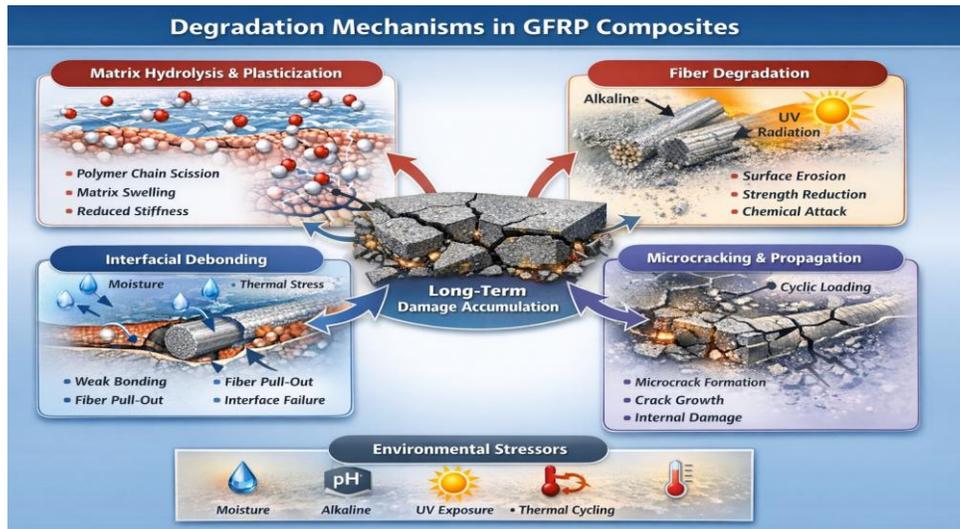


Figure 4. Schematic illustration of degradation mechanisms in GFRP composites under environmental exposure. This figure depicts the key degradation mechanisms affecting GFRP composites when exposed to environmental stressors. It shows matrix hydrolysis and plasticization due to moisture ingress, fiber surface deterioration under chemical and UV attack, fiber–matrix interfacial debonding caused by differential swelling and chemical weakening, and microcracking with progressive damage accumulation resulting from combined mechanical and environmental stresses.

5. Long-Term Performance Consequences

The long-term performance of glass fiber reinforced polymer (GFRP) composites is governed by the cumulative impact of environmental exposure and sustained loading on structural integrity, serviceability, and reliability. Over extended service

periods, degradation processes manifest as measurable reductions in mechanical properties, altered failure behavior, and compromised thermal and dimensional stability, collectively defining the durability limits of GFRP systems in civil and building applications (Karbhari *et al.*, 2003; Falahi *et al.*, 2017).

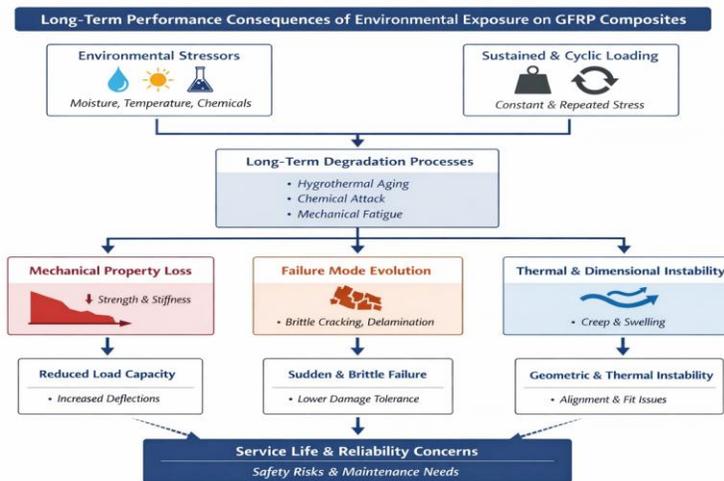


Figure 5. Long-term performance consequences of GFRP composites under environmental exposure. The figure summarizes the progressive effects of environmental exposure and sustained loading on GFRP composites, highlighting mechanical property and stiffness degradation, changes in failure behavior and damage tolerance, and loss of thermal and dimensional stability over long-term service.

A primary consequence of long-term exposure is mechanical property loss and stiffness reduction. Prolonged interaction with moisture, chemicals, and sustained stresses leads to progressive declines in tensile strength, elastic modulus, and

load-carrying efficiency, even when visible damage remains limited (Robert *et al.*, 2009; Tu *et al.*, 2020). Long-term predictive studies under acidic, alkaline, and saline environments further demonstrate that stiffness degradation

often precedes ultimate strength loss, indicating that serviceability criteria may govern design limits before catastrophic failure occurs (Zhu *et al.*, 2022). In reinforced structural systems, such reductions in stiffness translate into increased deflections and stress redistribution, thereby accelerating damage accumulation under sustained or cyclic loading (Tafsirojjan *et al.*, 2022).

Environmental ageing also induces significant changes in failure modes and damage tolerance. As exposure duration increases, GFRP components tend to transition from progressive, fiber-dominated failure toward more brittle behavior characterized by matrix cracking, interfacial debonding, and delamination (Karbhari *et al.*, 2003; Falahi *et al.*, 2017). Experimental investigations on GFRP bars embedded in moist concrete reveal that long-term exposure promotes localized damage at the fiber–matrix interface, reducing energy dissipation capacity and increasing susceptibility to sudden failure (Robert *et al.*, 2009). These changes diminish damage tolerance and reduce warning prior to failure, which is particularly critical for load-bearing and reinforced structural applications (Tafsirojjan *et al.*, 2022).

In addition to mechanical degradation, thermal and dimensional stability deteriorates during long-term service. Sustained exposure to elevated temperatures, fire-related thermal loads, and environmental cycling alters viscoelastic behavior and accelerates creep deformation, affecting stiffness retention and structural alignment (Lau *et al.*, 2016). Moisture-induced swelling and thermal expansion mismatch generate residual stresses that persist over time, influencing geometric stability and long-term deformation behavior under sustained loads (Tu *et al.*, 2020; Zhu *et al.*, 2022). These effects are especially detrimental in applications requiring tight tolerances or reliable performance under combined thermal and mechanical demands.

Overall, the long-term performance consequences of environmental exposure underscore the necessity for durability-informed design, predictive modeling, and conservative serviceability criteria when deploying GFRP composites in structural applications. Consideration of stiffness retention, evolving failure behavior, and long-term thermal stability is essential to ensure safe and reliable performance throughout the intended service life of GFRP-based systems (Karbhari *et al.*, 2003; Lau *et al.*, 2016).

Table 2. Summary of long-term performance consequences of GFRP composites

Performance aspects	Long term consequences	Service-life implication	References
Mechanical properties	Gradual reduction in strength and elastic modulus	Reduced load-carrying capacity and increased deflections	Robert <i>et al.</i> (2009); Zhu <i>et al.</i> (2022)
Stiffness retention	Progressive stiffness loss under sustained loading	Serviceability-controlled design governs performance	Tu <i>et al.</i> (2020); Tafsirojjan <i>et al.</i> (2022)
Failure behavior	Shift toward brittle and damage-controlled failure	Reduced damage tolerance and abrupt failure risk	Lau <i>et al.</i> (2016); Falahi <i>et al.</i> (2017)
Thermal stability	Degraded performance at elevated temperatures	Sensitivity to fire and thermal cycling effects	Lau <i>et al.</i> (2016)
Dimensional stability	Time-dependent swelling and residual deformation	Long-term alignment and compatibility issues	Robert <i>et al.</i> (2009); Tu <i>et al.</i> (2020)

6. Durability Evaluation and Aging Methods

Durability evaluation of glass fiber reinforced polymer (GFRP) composites relies on systematic environmental conditioning and aging methodologies designed to replicate long-term service conditions within controlled laboratory timeframes. Since polymer-based composites are inherently sensitive to moisture, temperature, and radiation, accelerated aging protocols are widely adopted to induce degradation mechanisms that would otherwise develop over extended periods in real environments. Such approaches enable the assessment of time-dependent changes in material behavior and provide critical insight into the durability limits of polymer composites (Frigione, 2022; Starkova *et al.*, 2022).

Environmental conditioning and exposure simulation typically involve hygrothermal aging, solar radiation exposure, and immersion in aggressive aqueous environments. Hygrothermal conditioning, combining elevated temperature and humidity, is particularly effective in accelerating moisture diffusion and promoting matrix plasticization and interfacial weakening in GFRP systems (Thomason and Xypolias, 2023; Narongdej *et al.*, 2025). Recent studies on pultruded GFRP composites subjected to coupled hygrothermal aging and solar radiation have demonstrated that combined stressors produce more pronounced degradation than isolated exposures, underscoring the importance of multi-factor simulation in durability assessment (Liu *et al.*, 2025). Similarly, seawater immersion tests have been widely employed to represent marine and coastal service conditions, revealing gradual reductions in

mechanical performance due to moisture uptake and salt-induced matrix degradation (Sawpan, 2018).

To establish meaningful links between environmental effects, degradation mechanisms, and long-term performance, durability evaluation employs a range of quantitative indicators. Mechanical property retention such as residual tensile strength, stiffness, and interfacial bond strength serves as a primary performance metric reflecting accumulated damage (He *et al.*, 2022; Li *et al.*, 2025). These macroscopic indicators are often complemented by measurements of moisture absorption behavior and microstructural observations, which reveal the progression of matrix cracking, fiber–matrix debonding, and interphase deterioration during aging (Thomason and Xypolias, 2023). For reinforced concrete applications, bond performance between GFRP rebars and surrounding matrices has emerged as a critical

durability indicator, particularly under aquatic exposure where combined chemical and mechanical effects govern long-term reliability (Li *et al.*, 2025).

Beyond experimental testing, durability prediction models play an increasingly important role in translating accelerated aging data into long-term performance forecasts. Modelling approaches based on diffusion kinetics, damage accumulation, and environmental rate processes enable extrapolation from laboratory exposure to anticipated service life conditions (Starkova *et al.*, 2022). When combined with experimentally derived performance indicators, these models provide a robust framework for durability assessment, supporting informed design decisions and risk mitigation strategies for GFRP composites in demanding environments (Frigione, 2022; Liu *et al.*, 2025).

Durability Evaluation and Aging Methods of GFRP Composites

Categories

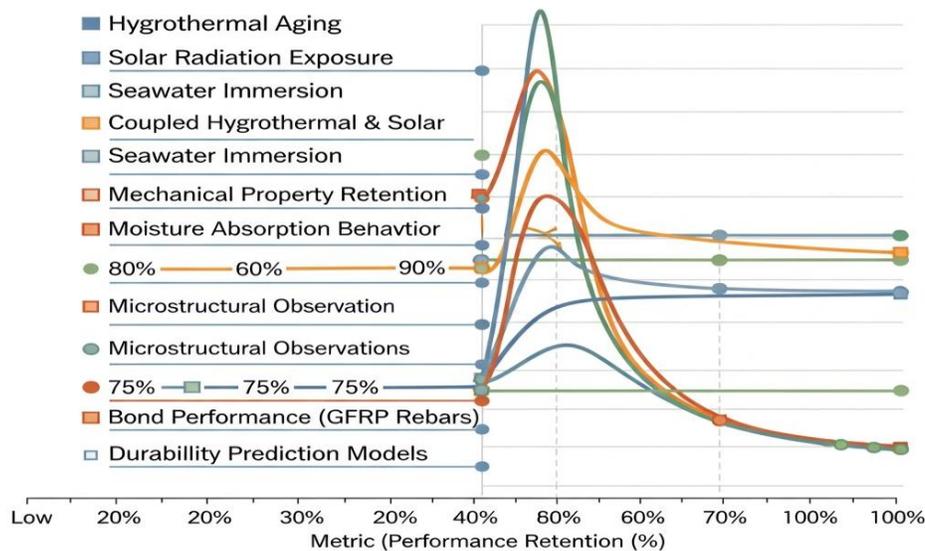


Figure 6. Durability evaluation and aging methods of GFRP composites categories. This plot presents a comparative overview of different durability evaluation and accelerated aging methods applied to GFRP composites. Each category shows the relative prevalence and reported impact of the method on long-term composite performance.

7. Conclusion

Glass-fiber reinforced polymer (GFRP) composites have demonstrated significant potential for long-term structural applications due to their high strength-to-weight ratio, corrosion resistance, and versatility. However, their durability under diverse environmental conditions remains a critical concern. Moisture ingress, thermal fluctuations, ultraviolet exposure, and chemical interactions can collectively accelerate degradation, leading to mechanical property loss, interfacial debonding, and dimensional instability. Despite advances in accelerated aging and durability evaluation methods, significant challenges persist in accurately predicting long-term performance under real-world conditions. Current

research often focuses on single environmental factors, with limited multi-factor or field-validated studies, which constrains the reliability of predictive models. Furthermore, variability in material composition, microstructure, and manufacturing processes adds complexity to understanding degradation mechanisms and structural implications. Standardized evaluation protocols and life prediction models remain underdeveloped, making it difficult to establish consistent guidelines for design and maintenance. Addressing these gaps through integrated experimental studies, robust modeling, and comprehensive performance assessment is essential to optimize GFRP applications. Future work should prioritize multi-factor exposure studies, interface behavior analysis, and the development of validated predictive tools to

ensure the safe and reliable long-term use of GFRP composites in infrastructure and industrial environments.

Authors' Contributions

The authors of this research have significantly contributed to the study's conception, data collection, and manuscript development. All authors were involved in writing the manuscript or critically reviewing it for its intellectual value. They have reviewed and approved the final version for submission and publication and accept full responsibility for the content and integrity of the work.

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Conflict of Interest

The authors declared that there are no conflicts of interest.

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