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Durability of Fiber-Reinforced Polymer (FRP) Bars: Progress, Innovations and Challenges Based on Bibliometric Analysis

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Abstract

This review systematically examines the literature on the Fiber-Reinforced Polymer (FRP) bars durability in concrete matrices using bibliometric analysis to understand progress, innovations, and challenges. The objective is to explore the durability of FRP bars, which are recognized for their strength-to-weight ratio, corrosion resistance, and non-conductivity, as a potential substitute to conventional steel reinforcement. Methods involved employing bibliometric tools such as Biblioshiny and VOSviewer to analyze trends, collaboration patterns, and the global distribution of publications. Findings reveal an increase in research activity over the past two decades, significant international collaboration, and leading contributions from key countries. Critical environmental factors like alkalinity, thermal conditions, and chemical aggressors affecting the interface of fiber-matrix mechanical properties were highlighted. Advances in predictive modeling for long-term behavior conditioned FRP bars are studied, steering future research towards improved durability and sustainable construction practices. This study contributes novelty by providing a comprehensive bibliometric perspective on FRP bar durability, identifying emerging trends, and suggesting areas for future suggested research to enhance the reliability and application of FRP bars in construction.

Keywords: Durability; Fiber-Reinforced Polymer; Bars; FRP; Environmental.

1. Introduction

Fiber-reinforced polymer (FRP) bars became a considerable substitute to ordinary steel in reinforced concrete elements, especially in harsh environments that require corrosion resistance, a high strength-to-weight ratio, and non-magnetic properties. These bars are made up of continuous fibers—such as basalt, carbon, glass, or aramid—embedded within a polymer matrix, typically epoxy, vinyl ester, or polyester resin. The unique properties of FRP bars, including their high tensile strength, corrosion resistance, and ease of installation, have made them increasingly popular in the construction industry.

Despite these advantages, the FRP bars long-term durability in harsh environments remains a critical concern. Previous studies have extensively examined various environmental conditions that can lead to the degradation of FRP

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bars. For instance, Chen et al. (2007) [1] discussed the impact of alkaline solutions on FRP bars, highlighting the susceptibility of glass fibers to alkaline attack. Similarly, Elgabbas et al. (2015) [2] emphasized the chemical stability of basalt fibers, noting their superior resistance to environmental degradation compared to glass fibers. Moreover, Feng et al. (2023) [3] reviewed the performance of different resins used in FRP bars, identifying epoxy resins as offering better durability than polyester and vinyl ester resins.

Despite significant progress, several gaps remain in the existing literature. First, there is limited understanding of the combined effects of various environmental stressors on the long-term performance of FRP bars. Most studies have focused on single-factor experiments, neglecting the complex interactions that occur in real-world conditions. Second, the variability in manufacturing processes and material properties across different FRP producers necessitates standardized testing methods and durability assessment criteria. Finally, there is a need for more comprehensive predictive models that incorporate advanced data analytics and machine learning to accurately estimate the lifespan of FRP-reinforced structures.

This review aims to address these gaps by providing a comprehensive bibliometric analysis of the existing studies on the FRP bars durability. By systematically evaluating the body of literature, this study identifies key trends, collaboration patterns, and global distribution of research efforts. The objective is to synthesize the current state of knowledge, highlight advancements, and propose future research directions to enhance the durability and application of FRP bars in sustainable construction practices.

The structure of this review is as follows: Section 2 illustrates the methodology, including the bibliometric analysis approach and data analysis tools used. Section 3 presents the bibliometric findings, including publication patterns and core research trends. Section 4 discusses the main research themes identified through co-occurrence networks. Section 5 provides a review of the progress, innovations, and challenges in the field. Section 6 outlines the remaining challenges and future directions of the research. Finally, Section 7 summarizes the review with key findings and recommendations.

2. Research Methodology

2.1. Bibliometric Analysis Approach

The objectives of this study were achieved using standard bibliometric methods for a quantitative analysis of the scientific literature on the FRP bars durability. This analysis was supplemented by text mining, that provided insights into research trends, publication trends, co-occurrences, top keywords, and the global publications distribution. The approach and analysis were informed by various bibliometric studies documented in the literature.

Bibliographic data on the durability of FRP bars was sourced from the Scopus and Web of Science platforms as of April 18th, 2024. These databases were selected for their comprehensive repositories of abstracts and citations, encompassing more than 25,000 titles from over 5,000 international publishers across various research topics. The methodology involved three primary steps: data collection, data cleaning, and data analysis, as depicted in Figure 1. The figure also illustrates the string used to gather related studies, including all terminologies and variations related to the FRP bars durability. The initial search yielded a total of 569 publications, which was reduced to 113 studies after conducting a thorough research criteria evaluation.

2.2. Selection Criteria

To ensure a comprehensive and relevant selection of references for the bibliometric analysis, the following specific criteria were followed:

- Relevance to the Topic: The primary criterion was the relevance of the publication to the durability of FRP bars in concrete structures. This was assessed based on the presence of key terms related to FRP bars and their durability in the title, abstract, and keywords of the publications. No significant studies or advancements were excluded from this review, ensuring a comprehensive analysis of the literature in this field.
- Publication Type: Only peer-reviewed journal articles were included to ensure the quality and rigor of the data. Conference papers, review articles, book chapters, and notes were excluded from the analysis.
- Language: Publications were limited to those written in English to maintain consistency and facilitate analysis.
- Time Period: The search covered publications from 1999 to April 18th, 2024. This time frame was chosen to capture both historical developments and recent advancements in the field.
- Database Inclusion: Only articles indexed in the Scopus and Web of Science databases were considered. These databases were selected for their comprehensive coverage and reliable indexing of high-quality scientific literature.
- Document Types: The search was limited to specific document types, including original research articles and comprehensive review articles. This ensured that the analysis focused on substantial contributions to the field rather than preliminary findings or non-research content.

Quality of Content: Although the analysis included all journals indexed in Web of Science and Scopus, regardless of their impact factors or quality, the relevance and depth of the content were considered. Publications that provided significant insights, data, and discussions on the durability of FRP bars were prioritized.

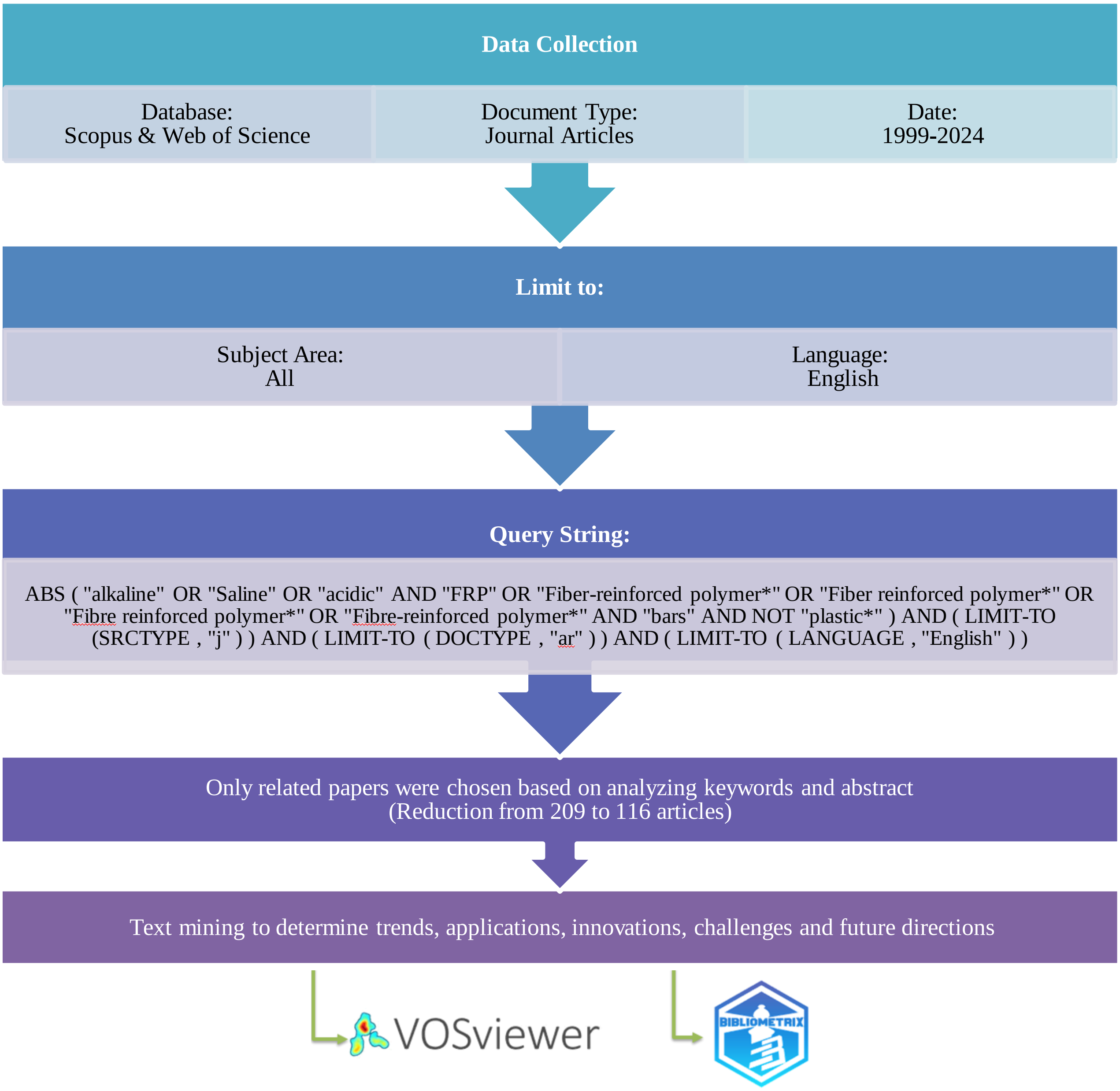


Figure 1. Data collection, search and mining methodology

2.3. Data Analysis and Visualization Tools

For the purposes of data analysis and visualization in this study, Biblioshiny and VOSviewer were utilized:

Biblioshiny, developed in the R programming language, was used for conducting quantitative analyses of data derived from collected publications. It offers visualization tools and metrics specifically designed for comprehensive analyses of large bibliographic data. Biblioshiny supports various forms of analyses, such as mapping of scientific topics, co-word and co-citation analysis, and exploring collaboration networks among researchers and institutions.

VOSviewer, by Leiden University, is a tool used for creating and visualizing bibliometric networks. It is useful for analyzing large bibliographic datasets and visualizing relationships through networks such as co-citation and co-word. VOSviewer helps identify connections between publications, authors, journals, and keywords, and its cluster analysis capabilities assist in discovering related groups within research fields.

It is worth noting that no additional weighting factors were applied beyond the inherent weights represented by the number of authored publications and count of publication output.

3. Bibliometric Findings in FRP Durability Research

This study focuses on bibliometric related aspects with detailed investigations of extracted themes. More information regarding the analyzed articles in this study including: overview, objectives, and scope, FRP type used, methods used, summarized results, limitations or future research directions can be found in Table A1 in the Appendix I [1-113].

3.1. Overview

The bibliometric analysis conducted on the literature related to the durability of FRP bars in concrete provides valuable insights into the progress, innovations, and challenges in this research field. In general, the overview of the collected studies data is summarized in Figure 2. The following key points was observed:

- The timespan covered in the analysis is 1999-2024, indicating that the research on FRP bar durability in concrete has been an active area of study for over two decades.
- The data shows there are 329 unique authors who have contributed to the publications on this topic. This suggests a substantial research community dedicated to investigate the FRP bars durability aspects.
- The average number of citations per document is 40.09, which is a relatively high citation impact. This implies that the published works on FRP bar durability have been widely recognized and referenced by the research community.
- The international co-authorship rate is 32.76%, indicating that a significant proportion of the publications involve collaborative efforts across different countries and institutions. This reflects the global nature of research on FRP bar durability and the exchange of knowledge and expertise within the research community.
- The open access percentage is 23.27%, suggesting that nearly a quarter of the published literature on FRP bar durability is freely available to the public. Emphasizing the funding received by the institutions for investigating the durability of FRP, in addition, this openness facilitates the dissemination of research findings and promotes broader access to the knowledge within this field.
- The average age of the documents is 5.56 years, indicating that the research on FRP bar durability is relatively recent and continuously evolving, with new publications contributing to the understanding and advancement of this topic.
- The annual growth rate of 13.53% suggests a steady and substantial increase in the number of publications over time. This reflects the growing interest and importance of the research on FRP bar durability in the scientific community.

Figure 2. Overview on the metrics of collected studies in FRP bars durability research

The world map (Figure 3) provides a visual representation of the global distribution of publications focused on the durability of FRP bars in concrete. China emerges as the leading contributor, producing the highest number of publications in this research domain. Other countries with significant publication outputs include Canada, the United States, Egypt, India, Italy, and Germany. This distribution highlights a widespread international interest in exploring the long-term performance of FRP reinforcement in concrete structures. However, certain regions, such as Africa, South America, and parts of Asia, remain relatively underrepresented. This underrepresentation points to potential opportunities for expanding research collaborations and enhancing knowledge sharing in these regions, which could further advance the global understanding of FRP bar durability.

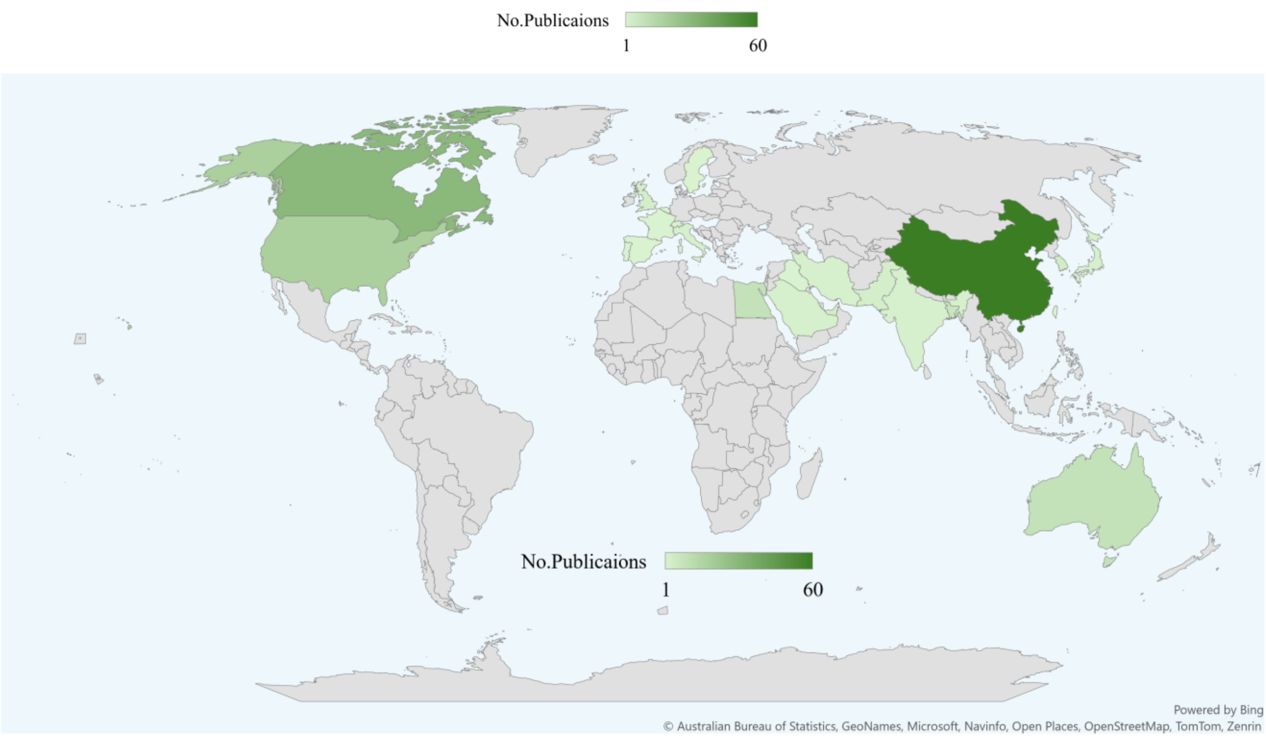


Figure 3. Worldwide distribution in FRP bars durability research

3.2. Publication Patterns

In terms of publications patterns and contributed publishers and journals, Figure 4 illustrates the number of publications across various journals within a set timeframe. Notably:

- Journals like "Journal of Composites for Construction" and "Journal of Materials in Civil Engineering" show significant publication numbers, reflecting a strong focus on the application of FRP in civil engineering contexts.
- Publishers such as Elsevier and the American Society of Civil Engineers (ASCE) lead in terms of the number of published articles, suggesting that their journals are key disseminators of research in this area.
- There is a broad distribution of publications across various journals, indicating multidisciplinary interest and applications of FRP technology.

Furthermore, Figure 5 illustrate the relationship between the publication of FRP guidelines and the number of research articles over time. The visual data indicates that the release of each guideline or code is followed by an increase in scholarly articles, signifying its impact on the research community. For instance, after the ACI 440R-07 "Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures" in 2007, there is an observable growth in the number of research articles. This report's impact suggests that researchers are responding to the comprehensive review provided by ACI by contributing additional empirical studies or by investigating new applications and implications of FRP bars as outlined in the report.

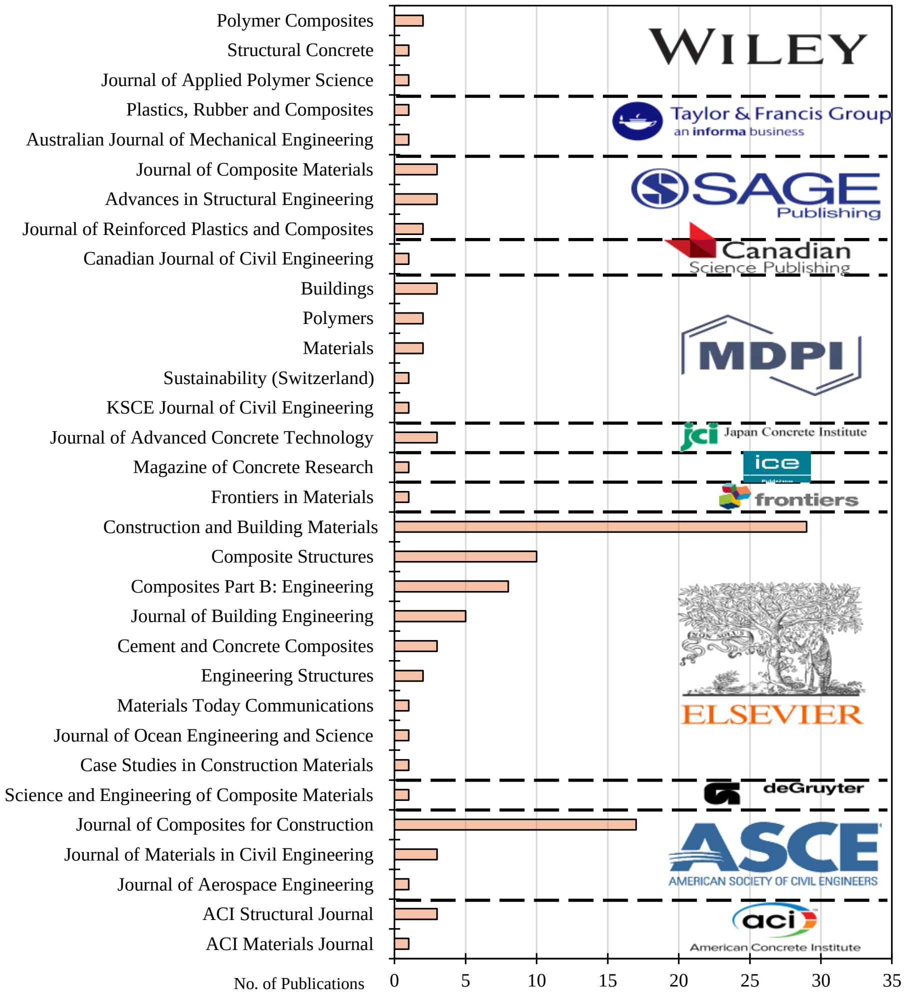
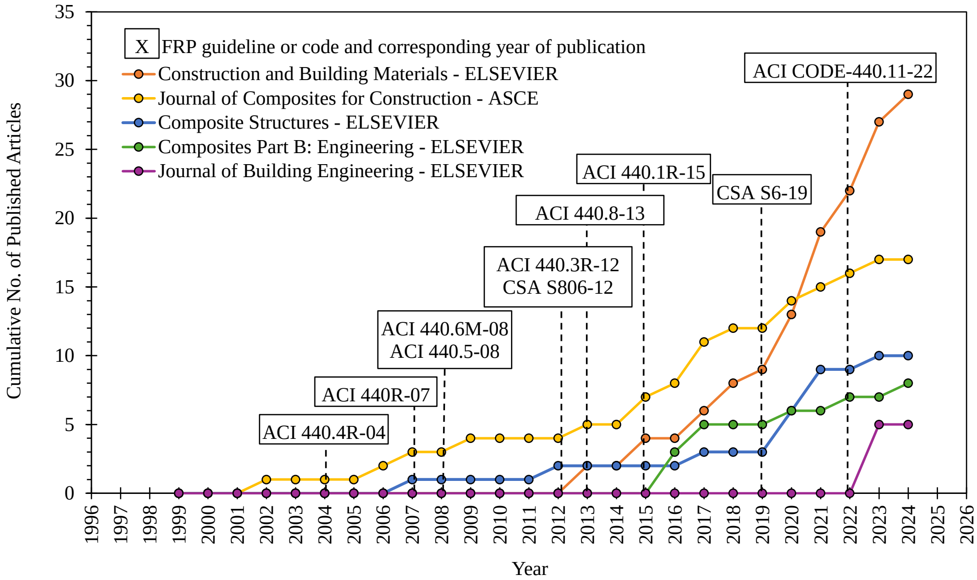


Figure 4. Distribution of publications related to durability of FRP bars in concrete across various academic journals and their publishers



ACI 440.4R-04: Guide Test Methods for Fiber-Reinforced Polymer (FRP) Cables (2004)
ACI 440R-07: Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures (2007)
ACI 440.5-08: Specification for Construction with Fiber-Reinforced Polymer Reinforcing Bars (2008)
ACI 440.6M-08: Specification for Carbon and Glass Fiber-Reinforced Polymer Bar Materials (2008)
ACI 440.3R-12: Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures (2012
ACI 440.1R-15: Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer (FRP) Bars (2015)
ACI 440.2R-17: Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures (2017)
CSA S806-12: Design and Construction of Building Structures with Fibre-Reinforced Polymers (2012)
CSA S6-19: Canadian Highway Bridge Design Code (2019)

Figure 5. Mutual impact between FRP bars guidelines and research publication trends in FRP bars durability

Similarly, the publication of the ACI 440.5-08 "Specification for Construction with Fiber-Reinforced Polymer Reinforcing Bars" in 2008, which provided specifications for the industry about the use of FRP bars, coincides with an increase in published research. This indicates a clear academic interest in exploring and validating the specifications set by the guideline. Furthermore, the CSA S806-12 "Design and Construction of Building Structures with Fibre-Reinforced Polymers" in 2012, which focuses on Canadian standards for FRP application in buildings, is mirrored by a similar trend. The ensuing increase in research reflects a desire within the academic community to expand upon the guidelines, potentially exploring the variation of FRP use in different environmental conditions and building types as specified by the Canadian context

3.3. Core Research Keywords Trends

Figures 6 and 7 summarize the core research keywords in the field of FRP bars durability, highlighting the 10 most frequent keywords (Figure 6) and the most emerging ones (Figure 7). A pronounced emphasis on Basalt Fiber Reinforced Polymer (BFRP) is evident. Basalt, a natural material known for its strength and durability, has become prominent in recent studies. This focus on basalt is due to its resilience, making it a promising material for enhancing the performance of FRP bars, particularly in demanding structural environments.

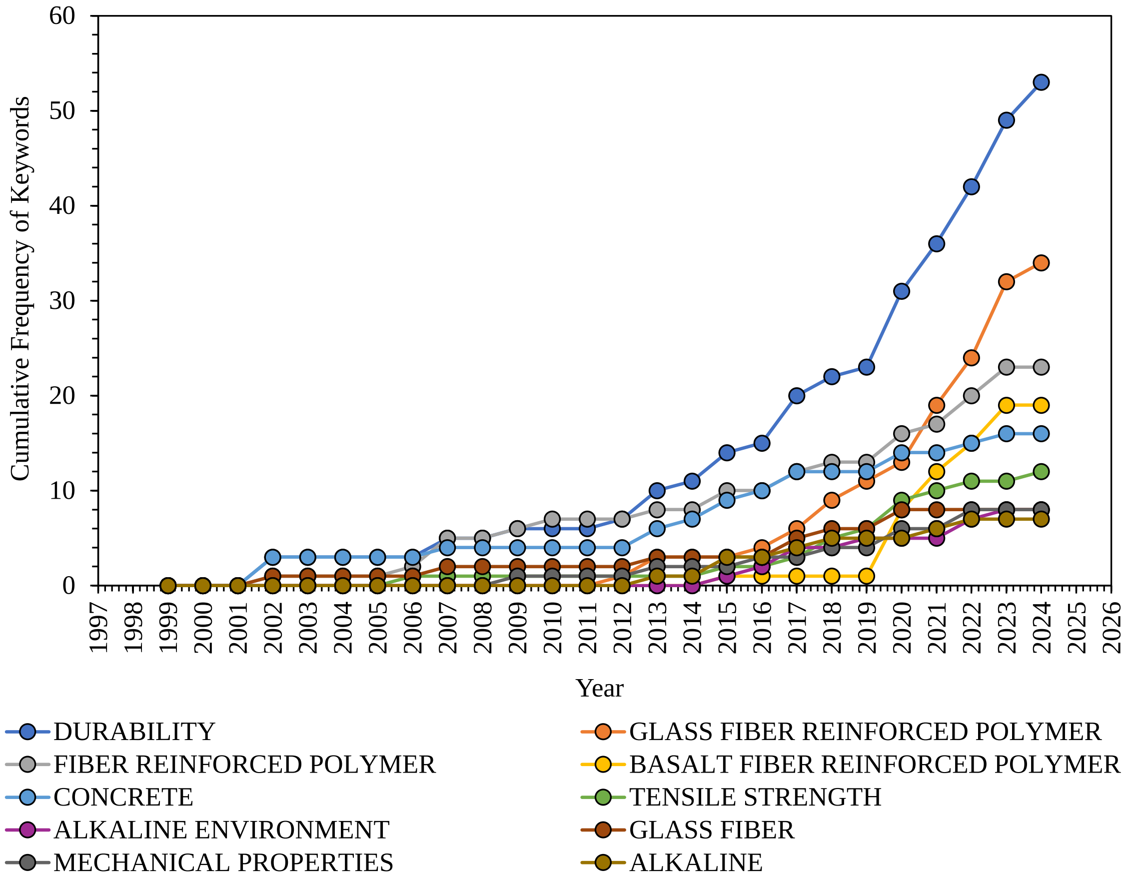


Figure 6. 10 Most frequent (overall) keywords from the collected literature on durability of FRP bars

Evaluating tensile strength, or the ability of FRP bars to resist breaking under tension, is a dominant theme in ongoing research. This test is crucial as it assesses the material's capacity to endure stresses encountered within concrete structures. Alkaline environments, which replicate the highly basic conditions within concrete, are frequently used to test the durability of these materials. Researchers immerse FRP bars in alkaline solutions to ensure they can withstand the long-term conditions of their application.

Figure 7 illustrates a surge in attention toward marine applications of FRP materials, reflecting the industry's shift toward using FRP bars in environments exposed to seawater. The innate robustness of FRP, offering greater durability compared to conventional steel, drives this research direction. By exposing FRP bars to marine conditions, scientists aim to verify their longevity and performance against the corrosive effects of seawater, an environment where steel often falters.

Moreover, accelerated aging processes are crucial for predicting the lifespan of FRP bars. By simulating years of wear and tear through controlled heating, researchers can anticipate how these materials will hold up over time, effectively fast-tracking the aging process to study potential degradation. This method is significant for understanding the long-term behavior of FRP bars, providing insights into their performance decades into the future and ensuring their reliability in infrastructure.

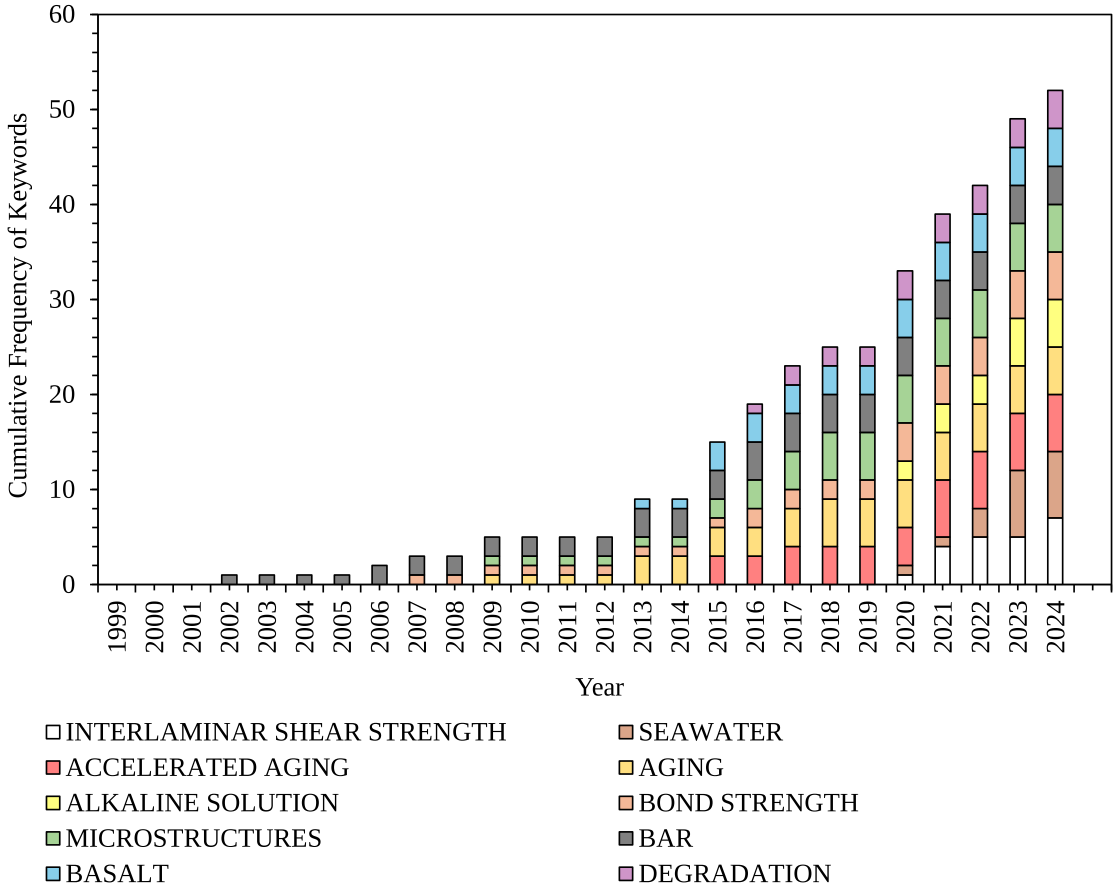


Figure 7. 10 Most trending (recent) keywords from the collected literature on durability of FRP bars

4. Research Themes Through Co-Occurrence Networks

Co-occurrence networks in bibliometrics provide a visual representation of how frequently terms or keywords appear together within a set of documents, such as academic papers. These networks map the relationship between concepts, identifying clusters that represent interconnected research themes or topics. Each node (or dot) in the network represents a keyword, and the lines (or edges) between them indicate that these keywords appear together in the literature. The strength of the connection is often indicated by the thickness of the lines, and the size of the nodes may represent the frequency of the individual terms.

From the co-occurrence network five dominant themes can be observed within the durability of FRP bars research field: 'Aging & Chemical Resilience in Alkaline Environments,' 'Seawater (Saline) Effects & Focus on Basalt FRP,' 'Durability of Epoxy and FRP,' 'Longevity and Environmental Stressors on FRP,' and 'Corrosion Mechanisms in Reinforced Polymers.'

Figure 8 presents these themes color-coded for clarity. The red cluster, 'Aging & Chemical Resilience in Alkaline Environments,' is rich with terms like 'glass fiber reinforced polymer,' 'alkaline environment conditions,' and 'bond strength.' It indicates a significant research focus on how FRP materials resist aging and maintain performance in the highly alkaline environment of concrete, which can be challenging due to the potential for chemical degradation.

The green cluster focused on 'Seawater (Saline) Effects & Basalt FRP' suggests an increasing interest in the performance of basalt FRP when exposed to saline or seawater conditions—a vital consideration for maritime and coastal applications where saltwater corrosion is a major concern. The yellow cluster, highlighting the 'Durability of Epoxy and FRP,' emphasizes investigations into the longevity of the resin systems that bind the fibers in FRP and their resistance to various degrading factors.

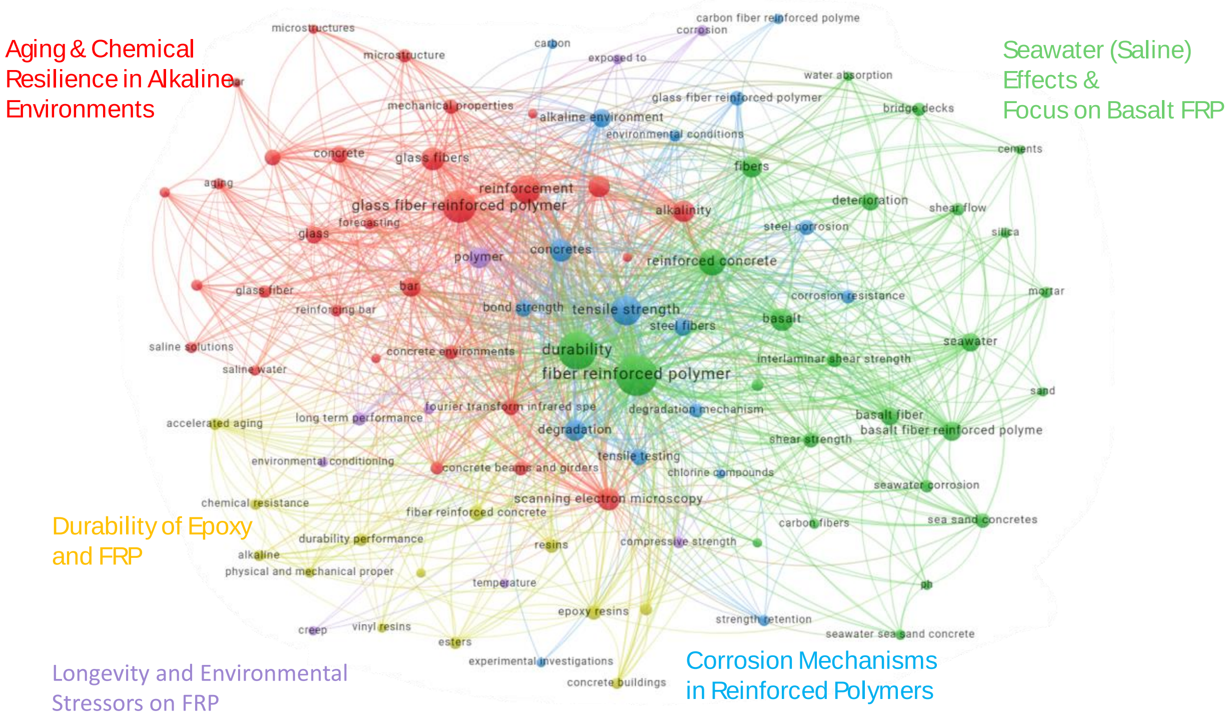


Figure 8. Co-occurrence network and observed themes in durability of FRP bars research field

5. Progress, Innovations and Challenges

This study examines bibliometric related aspects with detailed investigations of extracted themes. Additional information regarding the analyzed articles in this study, including: overview, objectives, and scope, FRP type used, methods used, summarized results, limitations, or future research directions, can be found in Table A1.

5.1. Exposure Conditions and Conditioning

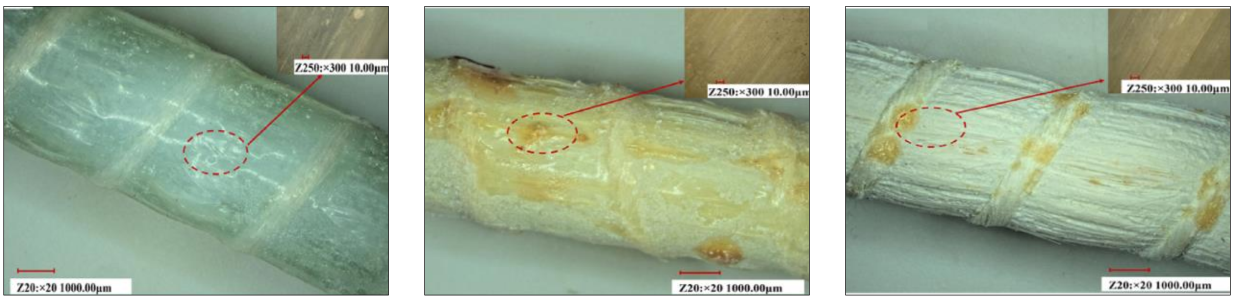
The performance of FRP bars in concrete structures is heavily influenced by the surrounding environment, which can lead to various degradation mechanisms. The most commonly studied environmental factors include alkaline solutions, chloride-induced corrosion, and elevated temperatures.

Alkaline Environment:

The high alkalinity of concrete pore solution (pH 12.5 to 13.5) is considered one of the most aggressive environments for FRP bars. The alkaline environment can cause hydrolysis of the polymer matrix, causing to the breakdown of the fiber-matrix interface and the eventual loss of mechanical properties [1–7].

Studies verified that the interlaminar shear strength, tensile strength, and bond strength of FRP bars can significantly degrade when exposed to alkaline solutions, with the extent of degradation dependent on the type of fiber, resin, and manufacturing process [8–15]. For example, glass FRP (GFRP) bars have been found to be more susceptible to alkaline attack compared to carbon FRP (CFRP) and BFRP bars [1, 4, 15].

The degradation mechanism in alkaline environments is primarily attributed to the hydrolysis of the polymer matrix and the weakening of the fiber-matrix interface (Figure 9). This can lead to the formation of microcracks, debonding, and ultimately, the loss of load-bearing capacity [2, 3, 7, 16, 17]. Additionally, the alkaline environment can trigger alkali-silica reactions (ASR) in some FRP bars, further exacerbating the degradation process [18, 19].



a) b) c)

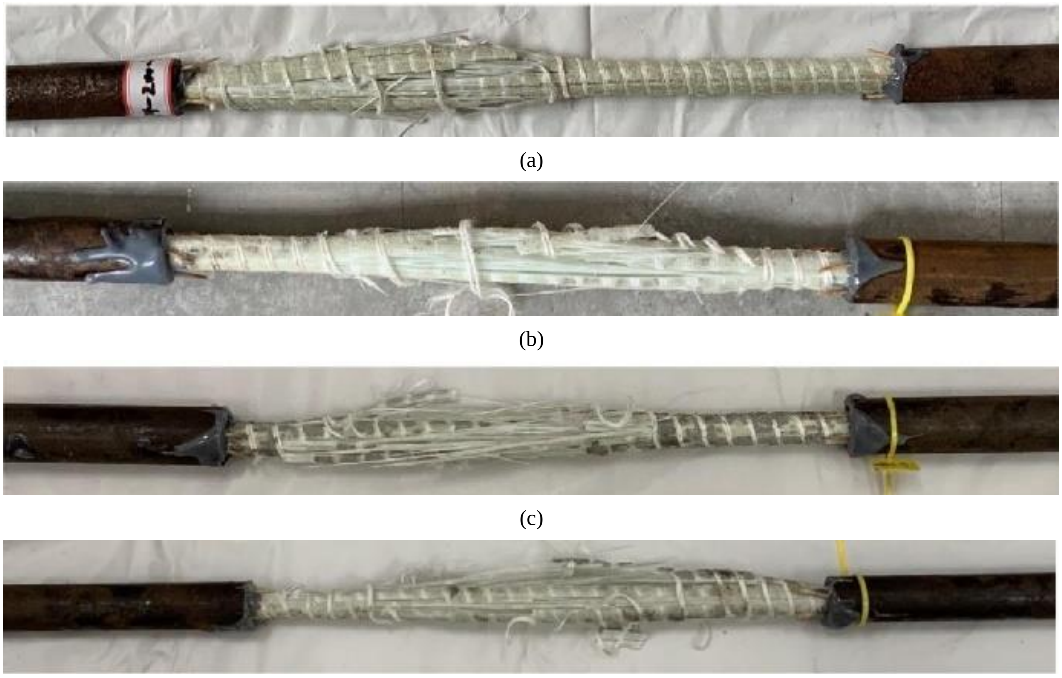
Figure 9. GFRP bars immersed in an alkaline environment at 60◦C for: (a) 7, (b) 45, (c) 105 days [7]

Chloride-Induced Corrosion

Another critical environmental factor affecting the durability of FRP bars is chloride-induced corrosion, particularly in marine environments or structures exposed to de-icing salts. Chloride ions can penetrate the concrete cover and reach the FRP reinforcement, potentially leading to the degradation of the fiber-matrix interface and the reduction of mechanical properties [2, 12, 20, 21].

The vulnerability of FRP bars to chloride-induced corrosion varies depending on the type of fibers and the resin used. CFRP bars have generally shown better resistance to chloride-induced degradation compared to GFRP and BFRP bars, as the carbon fibers are less susceptible to corrosion [1, 10]. However, the performance of FRP bars in chloride-rich environments can be improved by using appropriate concrete mix designs, such as the incorporation of supplementary cementitious materials (SCMs) like fly ash and silica fume, which can refine the pore structure and reduce the ingress of chloride ions [15, 18, 22, 23].

Recent study by Wang et al., [21] investigated the effects of exposure to a chloride environment on the durability of GFRP bars in Seawater–sea sand concrete (SWSSC) and normal concrete (NC). Figure 10 illustrates the failure modes GFRP bars that have been exposed to a chloride-rich environment. Compared to the blank group, the changes in failure modes were minimal. The specimens demonstrated a characteristic failure pattern, where the fibers and resin in the central free-form area were expelled outward in an umbrella-like shape. This is likely due to a compromised resin-fiber interface on the bar's exterior after chloride exposure, while the integrity of the bar's core was preserved.



(a)

(b)

(c)

(d)

Figure 10. Failure modes of GFRP bars a) control, b) 90 c) 180 and d) 270 days [21]

Residual tensile strength trends for GFRP bars are illustrated in Figure 11 from [21], combining data from the present test with findings from prior research [24]. A decrease in tensile strength was observed with prolonged exposure times. Retentions of tensile strength were recorded at 81%, 76%, and 76% after 90, 180, and 270 days of exposure to a chloride environment, respectively. These findings suggest that the tensile strength degradation in GFRP bars tends to slow after the initial 90-day period. Degradation is thought to be curtailed by the accumulation of Friedel's salt, which forms from the reaction of chloride ions with elements in the cement, thereby hindering further penetration of seawater and subsequent degradation of tensile strength [21]. For bars of 6 mm diameter, an increase in tensile strength retention was observed with increased NC or SWSSC cover thickness in exposure to seawater, followed by a decrease as the cover thickness continued to increase. This suggests a protective yet potentially deleterious effect of thicker concrete covers due to increased alkalinity, as supported by additional research.

Furthermore, the retained tensile strength for 14 mm diameter GFRP bars with 30 mm thick cover subjected to wet-dry seawater cycles surpassed the 6 mm GFRP bars with thinner covers. The positive influence of a greater bar diameter on the retained strength could explain this outcome. However, the defects likelihood in larger GFRP diameter bars, which could affect residual strength, has been noted and requires further examination. The impact of wet-dry cycles of seawater on retained strength was also found to be less severe than that of continuous immersion, consistent with patterns noted in the literature [21].

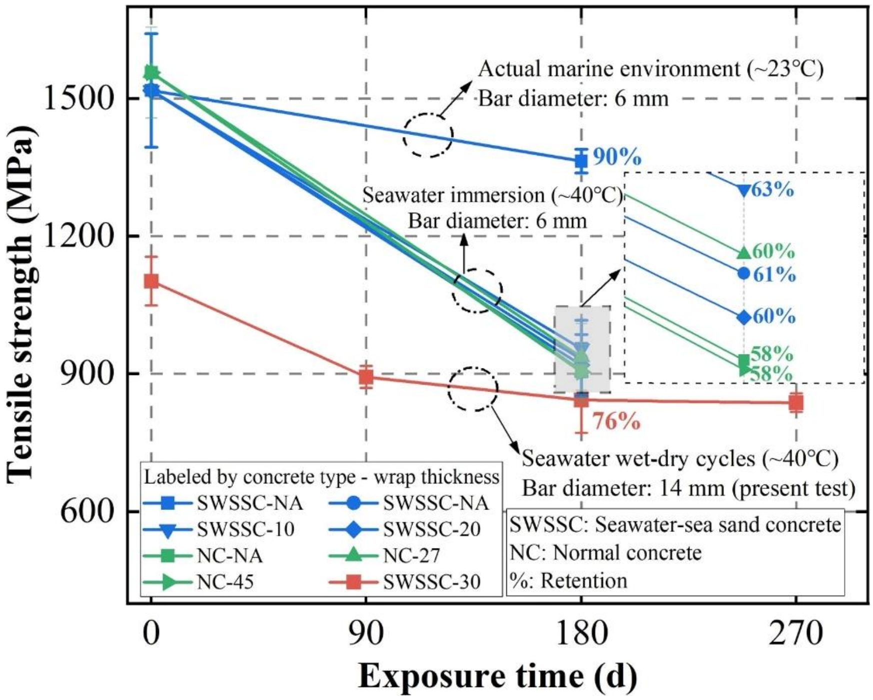


Figure 11. Effect of exposure time on tensile strength of GFRP bars [21] (SWSSC: Seawater–sea sand concrete; NC: Normal concrete; NA (0mm), 10mm and 20 mm cover thickness)

Elevated Temperatures

Elevated temperatures can also have a substantial impact on the FRP bars durability in concrete structures. Elevated temperatures can speed up the degradation of the polymer matrix, resulting in reduced mechanical performance [17, 25–28]. Additionally, the differential thermal expansion between the fibers and the matrix can cause interfacial debonding, further compromising the structural integrity of the FRP-reinforced concrete.

The extent of temperature-induced degradation is influenced by factors such as the type of resin, the fiber-matrix interface, and the manufacturing process. FRP bars formed by epoxy generally exhibit improved thermal stability compared to FRP bars with polyester or vinyl ester polymers [8, 14]. Furthermore, the use of high-performance (HP) concrete mixes, such as ultra-HP fiber-reinforced concrete (UHP-FRC), has been shown to provide better protection for FRP bars under elevated temperatures, mitigating the negative impacts on their durability [29].

Feng et al. [17] emphasized on the effect of elevated temperature on BFRPs' interlaminar shear strength (Figure 12). Results of the conditioned BFRB are shown in Figure 13 showing the decline in retained interlaminar shear strength of BFRP bars subjected to varying temperatures and pH levels , alongside actual marine field conditions. A downward trend is apparent across all scenarios, with the strength retention decreasing as exposure time increases. The steepest decline is seen at higher temperatures, with the 55°C condition causing the most rapid degradation, suggesting that elevated temperatures amplify the effects of an alkaline environment on BFRP bars. Moreover, bars exposed to the milder pH of 11.5 maintain their strength better than those at pH 12.8, indicating that a less alkaline environment preserves interlaminar strength more effectively. Interestingly, BFRP bars in real marine settings display greater resilience, retaining more strength than those in the highest temperature lab setting, hinting at the potentially overstated severity of laboratory-simulated conditions. This data highlights the nuanced interaction between environmental factors and material durability, highlighting the need for careful consideration of these variables in the application of BFRP bars in construction.

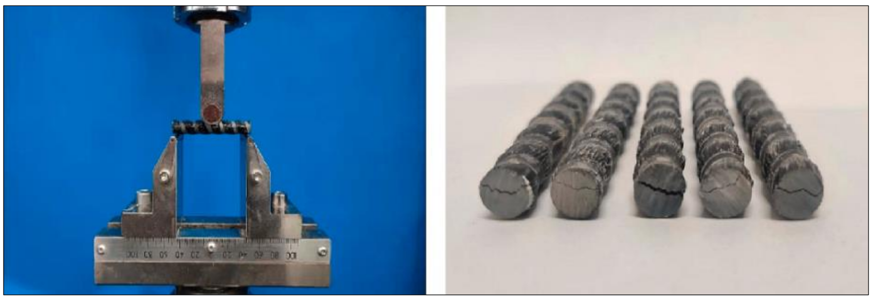


Figure 12. Typical setup for Interlaminar shear test and typical BFRP interlaminar shear failure [17]

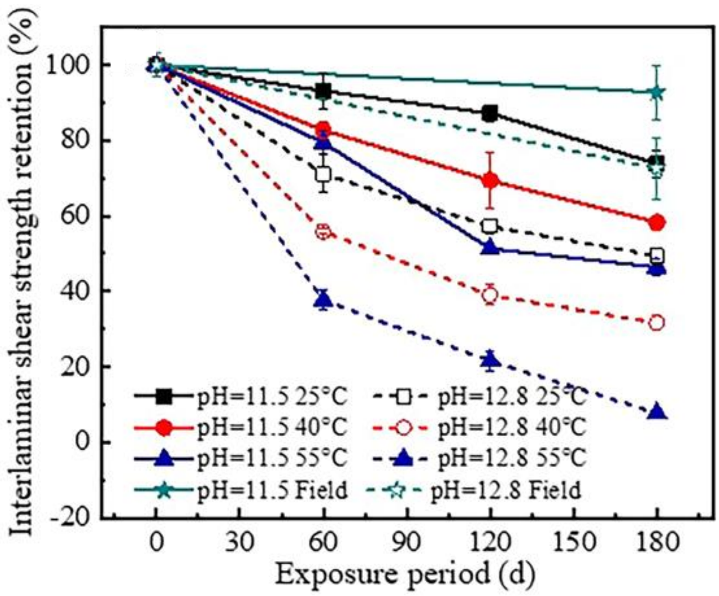


Figure 13. BFRP interlaminar retained shear strength under various temperatures and pH levels [17]

5.2. Material Composition and Manufacturing Processes

The FRP bars durability is also heavily affected by their material composition and manufacturing processes.

The overall performance of FRP bars in concrete environments is significantly influenced by the type of resin, the fibers used, and the interface between them.

Fiber Types

The most frequently utilized fibers in FRP bars include glass, carbon, basalt, and aramid, as depicted in Figure 14. Each fiber type possesses distinct properties that influence the durability of the FRP reinforcement.

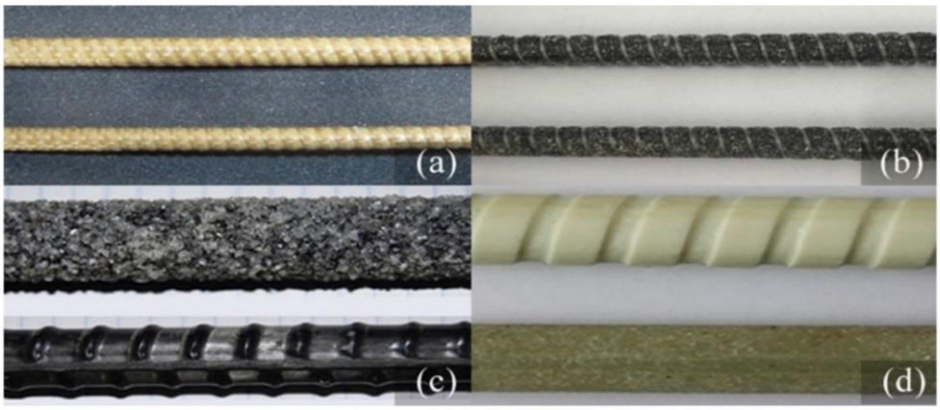


Figure 14. FRP bars and fiber types (a) Aramid; (b) Basalt ; (c) Carbon; (d) Glass [30]

GFRP bars have been extensively studied, and they are generally considered the most susceptible to environmental degradation, particularly in alkaline environments [1, 25, 31–33]. The degradation of GFRP bars mainly occurs because glass fibers are vulnerable to alkaline attack, which weakens the fiber-matrix interface and reduces the mechanical properties.

BFRP bars have gained attention as a more durable alternative to GFRP bars in concrete environments. Studies have shown that BFRP bars exhibit better resistance to alkaline attack and chloride-induced corrosion compared to GFRP bars [2, 16, 19, 20, 34–36]. The superior durability of BFRP bars is attributed to the inherent chemical stability of basalt fibers and the stronger fiber-matrix interface.

CFRP bars have demonstrated excellent durability in concrete environments, particularly in terms of resistance to alkaline attack and chloride-induced corrosion [1, 4, 10, 15]. The high chemical stability and superior mechanical properties of carbon fibers make CFRP bars a promising choice for reinforcing structures subjected l to aggressive environments.

Resin Types

Type of polymer resin utilized in the production of FRP bars greatly impacts their durability. The most common resin types include epoxy, vinyl ester, and polyester. Epoxy-based FRP bars typically exhibit superior durability compared to those made from polyester and vinyl ester, particularly in various environmental conditions [8, 14, 29, 37].

Epoxy resins are known for their superior chemical resistance, thermal stability, and adhesion to fibers, which contributes to the enhanced durability of epoxy-based FRP bars. Vinyl ester-based FRP bars have also demonstrated good durability, with performance superior to polyester-based FRP bars in alkaline and chloride-rich environments [8, 38, 39]. The chemical structure of vinyl ester resins, with fewer ester units than polyester, provides better resistance to hydrolysis and alkaline attack.

Polyester-based FRP bars have generally exhibited the poorest durability among the three resin types, particularly in alkaline environments [8, 14, 29]. The susceptibility of polyester resins to hydrolysis and the weaker fiber-matrix interface can lead to accelerated degradation of polyester-based FRP bars.

Manufacturing Processes

The manufacturing process of FRP bars can also influence their durability. The most common manufacturing methods are pultrusion, filament winding, and braiding.

Pultrusion is the most widely used method for producing FRP bars, as it allows for the continuous production of straight, uniform bars [37, 40]. The pultrusion process can affect the fiber volume fraction, resin curing, and the quality of the fiber-matrix interface, which can impact the durability of the FRP bars.

Filament winding and braiding are alternative manufacturing techniques that can produce FRP bars with different geometries and fiber orientations. These methods may influence the durability of FRP bars by affecting the fiber-matrix interface and the load transfer mechanisms [41, 42].

The optimization of manufacturing processes, including the use of specialized coatings, surface treatments, and the control of fiber-matrix interactions, can enhance the durability of FRP bars in concrete environments [3, 22, 43].

5.3. Durability Assessment and Predictive Models

To ensure the long-term performance of FRP-reinforced concrete structures, various durability assessment techniques and predictive models have been developed to evaluate the degradation of FRP bars over time.

Accelerated Aging Tests

Accelerated aging tests are commonly used to study the degradation of FRP bars under simulated environmental conditions. These tests involve exposing FRP bar specimens to various aggressive environments, such as alkaline solutions, chloride-rich solutions, and elevated temperatures, for extended periods [5, 10, 32, 44–47].

The results from these accelerated tests are then used to develop predictive models and estimate the long-term performance of FRP bars in concrete structures. Parameters such as tensile strength, interlaminar shear strength, bond strength, and stiffness retention are typically measured to assess the extent of degradation [10, 40, 46–49].

Durability Prediction Models

Various predictive models were developed to assess the FRP bars long-term performance in concrete structures. The developed models frequently rely on the Arrhenius relationship, which links the chemical reactions rate to temperature, and the time-shift factor (TSF) approach, which considers the impact of temperature on the degradation rate [26, 28, 40, 48, 50]. Arrhenius model is usually used to predict the interlaminar shear strength, retained tensile strength, and bond strength of FRP bars based on the activation energy and the exposure temperature [36, 40, 51]. The TSF approach, on the other hand, utilizes two sets of experimental data at different temperatures to determine the TSF, which is then used to estimate the FRP bars long-term performance in various environments [50, 52].

However, these models have several limitations. They often rely on simplified assumptions and typically focus on single environmental factors, which may not accurately reflect the complex, non-linear interactions observed in real-world conditions. Additionally, the accuracy of these models is constrained by the availability and quality of experimental data, as extrapolating from short-term tests to long-term performance can introduce uncertainties. Furthermore, variations in the composition and manufacturing processes of FRP bars can lead to differences in durability that are not adequately captured by these models, resulting in discrepancies between predicted and actual performance.

To address these limitations, future research should focus on developing multi-factor models that account for the combined effects of various environmental conditions. Incorporating non-linear analysis techniques and advanced statistical or machine learning methods can help capture the complex relationships between degradation factors and material performance. Comprehensive data collection through long-term field studies and accelerated testing under multiple environmental conditions will provide more robust data for model validation. Additionally, creating material-specific models that consider variations in fiber type, resin composition, and manufacturing processes will improve the accuracy of predictions for different materials and applications.

In addition to these analytical models, researchers have also explored the use of machine learning techniques (i.e., support vector regression, ensemble methods, artificial neural networks) to predict the durability of FRP bars based on a comprehensive database of experimental results [53–55]. These advanced techniques can enhance predictive capabilities by identifying complex patterns and interactions in large datasets, potentially offering more accurate and reliable models.

5.4. Advancements and Emerging Trends

The research on the durability of FRP bars in concrete structures has seen significant advancements in recent years, with the introduction of new materials, manufacturing techniques, and innovative assessment methods.

Hybrid FRP

Bars The development of hybrid FRP bars, which combine different types of fibers (e.g., carbon and glass, basalt and carbon) within a single bar, has shown promise in improving the overall durability of FRP reinforcement [4, 41, 46, 56]. The combination of fibers with complementary properties can enhance the resistance to environmental degradation and provide a more robust solution for concrete structures.

Nano-Modifications and Coatings

The incorporation of nanomaterials, such as carbon nanotubes and nanoparticles, into the resin matrix of FRP bars has been explored as a means of enhancing their durability [3, 57]. These nano-modifications can improve the resistance to hydrolysis, alkaline attack, and chloride-induced corrosion, leading to extended service life for FRP-reinforced concrete structures.

Additionally, the use of specialized coatings and surface treatments on FRP bars, such as weak-acid cation exchangers and self-sensing glass-metal coatings, has been investigated as a way to protect the fiber-matrix interface and improve the overall durability of the reinforcement [17, 22, 43].

Sustainable Concrete Mix Designs

The development of sustainable concrete mix designs, incorporating SCMs like fly ash, slag, and silica fume, has shown promise in mitigating the FRP bars degradation in concrete [12, 15, 22, 23, 58]. These SCMs can refine the pore structure of concrete, reduce the alkalinity of the pore solution, and enhance the overall durability of FRP-reinforced concrete.

Nondestructive Evaluation and Monitoring

Researchers have explored the use of nondestructive evaluation (NDE) techniques, such as ultrasonic testing and electrical impedance measurements, to assess the condition and degradation of FRP bars embedded in concrete structures [49, 59, 60]. These methods provide a means of monitoring the FRP reinforcement long-term performance without the need for destructive testing.

Additionally, the integration of fiber optic sensors and other advanced monitoring systems into FRP-reinforced concrete structures has enabled the real-time tracking of the performance and FRP bars degradation, facilitating the development of predictive maintenance and early warning systems for infrastructure management [61, 62].

6. Challenges and Future Directions

Despite the considerable efforts, several obstacles and challenges persist in the widespread adoption and application of FRP bars in concrete construction. One of the primary concerns is the limited understanding of long-term performance under complex environmental exposures, including combinations of mechanical load, chemical attack, and thermal variations. Moreover, the variability in manufacturing processes and material properties across different producers of FRP bars necessitates the development of standardized testing methods and durability assessment criteria. Future research should focus on:

- Developing FRP bars with improved resistance to environmental degradation, including alkalinity, chlorides, and temperatures, through innovative material formulations and nano-engineering approaches.
- Leveraging big data analytics and machine learning to refine predictive models for FRP bar durability, enabling more accurate life cycle assessment and maintenance planning.
- Integrating FRP bars in holistic sustainable construction practices, including the use of eco-friendly concrete mixes and the exploration of FRP recycling and reuse strategies to minimize environmental impact.
- Documenting and analyzing the performance of FRP-reinforced structures in real-world settings to gather empirical data that can validate laboratory findings and predictive models.

7. Conclusions

The durability of fiber-reinforced polymer (FRP) bars as reinforcement in concrete structures has been the subject of extensive research in recent decades, driven by the need for corrosion-resistant and high-strength alternatives to traditional steel reinforcement. This comprehensive literature review, underpinned by a rigorous bibliometric analysis, has synthesized the current state of knowledge, progress, innovations, and ongoing challenges in this field. The key findings and conclusions are as follows:

- The geographical distribution of research efforts, as revealed by the bibliometric analysis, highlights the need for increased global collaboration and knowledge sharing, particularly in regions with limited research output. Encouragement of international cooperation and capacity-building initiatives can accelerate the adoption of FRP reinforcement solutions and contribute to the development of more sustainable and resilient infrastructure worldwide.
- The type of polymer resin used in the manufacturing of FRP bars significantly impacts their durability. Epoxy-based FRP bars have generally demonstrated superior durability compared to polyester-based and vinyl ester-based formulations, owing to their exceptional chemical resistance, thermal stability, and strong adhesion to the reinforcing fibers.
- The manufacturing process of FRP bars, such as pultrusion, filament winding, and braiding, can influence their durability by affecting factors like fiber volume fraction, resin curing quality, and the integrity of the fiber-matrix interface. Optimizing these processes along with the implementation of specialized surface treatments and coatings can contribute to enhancing the durability of FRP bars in concrete environments.
- Accelerated aging tests involving the exposure of FRP bar specimens to simulated aggressive environments such as alkaline solutions, chloride-rich solutions, and elevated temperatures have proven invaluable in assessing the degradation behavior and developing long-term performance predictive models. Crucial parameters, including tensile strength, interlaminar shear strength, bond strength, and stiffness retention, are typically monitored to quantify the extent of degradation.
- Predictive models based on the Arrhenius relationship and the time-shift factor (TSF) approach have emerged as powerful tools for estimating the residual mechanical properties and service life of FRP bars in concrete structures. These models, which consider the effects of time and temperature on degradation rates, enable engineers to make informed decisions regarding the design and maintenance of FRP-reinforced concrete elements.
- Significant advancements in the field include the development of hybrid FRP bars, which combine different types of fibers within a single bar, leveraging their complementary properties to enhance overall durability. Additionally, the incorporation of nanomaterials and specialized coatings into the resin matrix has shown promise in mitigating environmental degradation and extending the service life of FRP reinforcement.
- The development of sustainable concrete mix designs, utilizing supplementary cementitious materials (SCMs) such as silica fume, slag, and fly ash, has demonstrated the potential to mitigate the degradation of FRP bars by refining the pore structure, reducing alkalinity, and enhancing the overall durability of the composite system.
- The development of machine learning techniques has shown promise in predicting the durability of FRP bars based on comprehensive databases of experimental results. These data-driven approaches can complement traditional analytical models and potentially offer more accurate and robust predictions, especially when dealing with complex, non-linear degradation phenomena.
- Nondestructive evaluation (NDE) techniques, such as ultrasonic testing and electrical impedance measurements, as well as the integration of fiber optic sensors and advanced monitoring systems, have enabled the in-situ assessment and real-time tracking of the performance and degradation of FRP bars embedded in concrete structures, facilitating predictive maintenance and early warning systems for infrastructure management.
- As the demand for durable and corrosion-resistant reinforcement solutions continues to grow, there is a pressing need for the construction industry to embrace the widespread adoption of FRP bars in concrete structures. Overcoming barriers to implementation, such as concerns over long-term performance, lack of familiarity with design guidelines, and potential cost implications, will require concerted efforts from researchers, practitioners, and policymakers to promote awareness, education, and the development of cost-effective solutions.

7.1. Recommendations for Future Work

In light of the extensive review of the FRP bars durability in concrete structures, the following recommendations are proposed to direct future research and practice in this field:

- Continued exploration into new composite materials, particularly those that demonstrate superior resistance to environmental stressors, should be prioritized. This includes the development of FRP bars using advanced polymers, hybrid fiber compositions, and nano-engineered additives to enhance performance.
- Despite substantial efforts dedicated to studying the durability of FRP bars in concrete environments, there is a need for standardized testing protocols and guidelines to ensure consistent and reliable evaluation of these materials across different laboratories and research groups. Harmonizing test methods and reporting practices will facilitate data sharing, cross-validation of results, and the development of more robust predictive models.
- Conduct long-term field studies on existing structures reinforced with FRP bars to gather real-world durability data of FRP reinforced structures. This performance data is crucial for validating and refining laboratory research and predictive models.
- Investigate the life cycle of FRP-reinforced structures, from production to end-of-life, to understand their environmental footprint. Research should explore not only the recyclability and reusability of FRP materials but also their behavior and stability over the lifespan of a structure.
- Work towards the integration of findings into design guidelines and building codes to facilitate the broader adoption of FRP bars in construction. Collaboration with standardization bodies to update design codes will ensure the effective and safe use of these materials in various construction contexts.
- Employ machine learning and big data analytics to develop more accurate and comprehensive predictive models for the durability of FRP bars. These models should account for the complex interactions of variables that influence degradation over time.
- Encourage the use of FRP bars as part of a sustainable construction strategy. This entails promoting practices that not only reduce the environmental impact of construction materials but also enhance the resilience and longevity of infrastructure.
- Foster educational initiatives to disseminate knowledge about FRP materials among engineers, architects, and construction professionals. Workshops, seminars, and inclusion in university curricula will promote understanding and encourage innovation in the use of FRP bars in concrete.
- Analyze the cost-effectiveness of using FRP bars in various construction scenarios to better understand their economic impact. Studies should consider not only the initial costs but also the potential savings over the life cycle of a structure due to reduced maintenance and longer service life.
- Form international research groups to tackle the global challenges associated with the use of FRP in construction. Such collaborations can harness diverse expertise, facilitate knowledge exchange, and accelerate innovation in this critical area of civil engineering.

8. Declarations

8.1. Author Contributions

Conceptualization, N.N. and M.T.J.; methodology, N.N. and M.T.J.; software, N.N. and M.T.J.; validation, N.N., M.T.J., M.M., S.A., and S.B.; formal analysis, N.N. and M.T.J.; investigation, N.N., M.T.J., M.M., S.A., and S.B.; resources, M.T.J., M.M., S.A., and S.B.; data curation, N.N.; writing—original draft preparation, N.N. and M.T.J.; writing—review and editing, N.N., M.T.J., M.M., S.A., and S.B.; visualization, N.N. and M.T.J.; supervision, M.T.J., M.M., and S.A.; project administration, M.T.J.; funding acquisition, M.T.J. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

Data sharing is not applicable to this article.

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8.4. Conflicts of Interest

The authors declare no conflict of interest.

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Appendix I: Table A1. Detailed review on studies related to durability of FRP bars

Reference	Overview	Objectives and scope	FRP Type Used	Methods Used	Results	Limitations or Future Research Directions
Abdullha et al. [63]	- Study on mechanical properties of cotton bars reinforced with fibers. - Aimed to create low-cost bars with steel-like performance and corrosion resistance. - Investigated bars made with cotton fibers treated with epoxy and fibers. - Examined the effect of alkaline solutions, acids, moisture, heat, and bonding.	- Study aimed to create low-cost bars with steel-like performance. - Scope included mechanical properties, corrosion resistance, and chemical effects.	- GFRP, CFRP, BFRP, AFRP.	- Immersed fibers in polymer. - Coated fibers with polymer through tension and relaxation.	- Cotton/Carbon bars had a tensile strength of 688 MPa. - Cotton/Glass bars had a tensile strength of 477 MPa. - Cotton bars had a tensile strength of 284 MPa. - FRP bars showed linear elastic behavior with brittle failure. - GFRP bars had high absorption leading to cavities and acid degradation.	- Lack of comparison with traditional steel reinforcement bars. - Future studies could explore the impact of different environmental conditions. - Investigate the long-term durability and performance of the FRP bars. - Further research on enhancing the bonding strength with concrete.
Ali et al. [64]	- Experimental investigation on glass fiber-reinforced polymer bars with different resins. - Evaluation of durability, microstructure, and long-term performance of GFRP bars. - Tensile strength affected by immersion time, temperature, and resin type. - Prediction of long-term behavior based on environmental factors and resin systems.	- Investigated tensile-strength retention of glass fiber-reinforced polymer bars with different resins. - Analyzed durability performance based on resin type, immersion time, and temperature. - Explored microstructure changes in glass fiber-reinforced polymer bars under different conditions.	- GFRP (glass/polyester), GFRP (glass/vinylester), GFRP (glass/epoxy).	- Experimental investigation, statistical analysis, and theoretical predictions conducted. - Microstructure analysis with SEM, EDS, and FTIR. - Arrhenius relationship for long-term behavior prediction.	- Tensile strength reduction in GFRP bars varied based on resin type. - Vinyl-ester and epoxy bars showed less degradation compared to polyester bars. - Modulus of elasticity retention was up to 99% after conditioning. - Polyester bars had higher moisture uptake and debonding than others. - Chemical degradation was observed in polyester resin but not in others.	- Future research needed to compare resin systems for optimal performance. - Limited direct resin system comparison for civil engineering applications.
Ali et al. [65]	- Investigates the effect of bar size on BFRP bars' characteristics. - Analyzes physical, mechanical, and durability properties of sand-coated BFRP bars.	- Investigated the effect of bar size on physical, mechanical, and durability characteristics. - Studied BFRP bars' physical and mechanical properties with different diameters. - Explored the impact of bar diameter on the durability of BFRP bars. - Research focused on short- and long-term characteristics of newly developed BFRP bars.	- BFRP bars.	- Mechanical testing according to ASTM, ACI, and CSA standards. - Conditioning in alkaline solution simulating concrete environment at 60°C.	- Bar size affected physical, mechanical, and durability properties of BFRP bars. - Oversized BFRP bars, varying from 2 to 39. - Water absorption within limits except for some BFRP bars. - Larger diameter bars had lower mechanical properties than smaller ones.	- Limited research on durability and applications of BFRP bars. - BFRP properties essential for material specifications and design guidelines. - Important to determine BFRP properties according to test standards.
Almusallam et al. [45]	- Investigated durability of glass fiber-reinforced polymer bars under various conditions. - Tested bars in accelerated aging methods and field environments. - Results showed varying effects on tensile strength based on conditions.	- Investigate degradation in tensile properties of glass fiber-reinforced polymer bars. - Assess performance under various environmental conditions, including accelerated aging methods. - Compare performance in laboratory vs. field conditions for GFRP bars. - Study microstructural changes using scanning electron microscope.	- GFRP bars.	- Investigated tensile properties degradation of glass fiber-reinforced polymer bars. - Conducted accelerated aging tests under various environmental conditions. - Used scanning electron microscope to study degradation mechanisms.	- Tap water and alkaline solution at 50 C had the most harm. - Field conditions showed almost no degradation in tensile properties. - Seawater at room temperature caused a 13.7% decrease in tensile strength. - Increasing tap water temperature to 50 C increased degradation rate. - SEM micrographs showed significant matrix deterioration in harsh environments.	- Variability in composite material properties affects durability study outcomes. - Conflicting results from different testing procedures hinder general conclusions.
Altalmas et al. [66]	- Investigated durability of basalt and glass FRP bars under aging conditions. - Basalt bars had excellent adhesion and bond strengths to concrete. - Conditioning reduced bond strength of basalt bars by 14-25%. - BPE model calibrated to consider bar conditioning.	- Investigated durability of basalt and glass FRP bars under aging conditions. - Studied bond strengths, adhesion, and conditioning effects on basalt bars. - Aimed to calibrate BPE model considering bar conditioning.	- BFRP and GFRP bars.	- Investigated durability of basalt and glass FRP bars under conditions. - Calibrated BPE model to consider bar conditioning.	- Basalt bars had excellent adhesion and bond strengths to concrete. - Bond strength reduced by 14-25% after conditioning basalt bars. - Slip decreased in BFRP bars after conditioning, altering stiffness. - GFRP bars showed inconsistent slip behavior after conditioning.	- Future research should include other commercially available bars for comparison. - The study's experimental work is limited to the bars used.
Arczewska et al. [44]	- Study on durability of glass fiber reinforced polymer bars in concrete. - Long-term strength predictions based on accelerated testing in harsh environments. - Investigates degradation of tensile, shear, and flexure properties of GFRP bars.	- Study durability of glass fiber reinforced polymer bars in concrete. - Model long-term durability based on short-term testing results. - Conduct accelerated testing in alkaline environment and elevated temperatures.	- GFRP bars.	- Modelling long-term durability based on short term testing results. - Accelerated testing in alkaline environment and elevated temperatures. - Mechanical testing of glass fiber reinforced bars: tensile, shear, bending.	- Quicker degradation in smaller diameter GFRP bars due to damage ratio difference. - Shear test is a good indicator of tensile strength degradation. - Bent bars deteriorate faster than straight bars. - Smaller diameter bars degrade faster than larger diameter bars. - Bars under flexural strength degrade faster than those under direct tensile strength.	- Lack of universally accepted prediction model for GFRP materials.

Bakis et al. [67]	- Investigated bond durability of E-glass fiber-reinforced polymer bars in concrete beams. - Proposed local bond-slip model incorporating concrete cover splitting for analysis. - Interfacial fracture energy remained stable except in freeze/thaw conditions. - Effective bond length varied with local slip at complete bond failure.	- Investigate bond durability of glass fiber-reinforced polymer bars in concrete beams. - Analyze bond behavior under sustained flexure and various environmental conditions.	- GFRP bars.	- Experimental and analytical investigation of bond durability in concrete beams. - Marquardt-Levenberg nonlinear curve fitting algorithm used for parameter determination.	- Bar force at free-end slip varied little after conditioning. - Interfacial fracture energy remained stable except in freeze/thaw environment. - Effective bond length varied with local slip at bond failure. - Maximum bar force in anchorage zone had insignificant variation over time.	- Limited investigation on bond properties in realistic loading situations. - No consistent trend in bar force at free-end slip onset. - Uncertainties in bond-slip results due to local confinement effects. - Need for direct force measurement on the loaded end of the bar. - Tracking longitudinal splitting to correlate with debonding extent.
Banibayat and Patnaik [68]	- Basalt FRP bars' creep rupture properties tested under sustained loads. - Study recommends time-dependent creep rupture stress limits for effective design. - Ultimate creep rupture strength coefficients determined for different service life durations.	- Determine creep rupture properties of basalt FRP bars. - Establish suitable loading arrangement and test method for study.	- BFRP bars.	- No specific methods used in the paper were mentioned.	- Determined creep rupture strength coefficients for basalt FRP bars. - BFRP bars have slightly smaller creep coefficients than AFRP bars. - Creep coefficient curves for basalt FRP bars under sustained loads.	- Limited data for BFRP bars, more research needed. - Need refinement of the one million hours creep coefficient estimation.
Bazli et al. [69]	- Investigated bond strength of GFRP bars in various concrete types. - Light-weight concrete showed significant bond strength reductions. - Maximum development lengths achieved for acid conditioned specimens.	- Investigate bond strength of GFRP bars in aggressive environments. - Assess bond durability of GFRP bars with different types of concrete.	- GFRP bars.	- Bayesian linear regression method for bond strength between GFRP bars.	- Investigated bond strength of GFRP bars in various concrete types. - Light-weight concrete showed significant bond strength reductions. - Maximum development lengths achieved for acid conditioned specimens.	- Limited standard procedures for FRP reinforced concrete members.
Benmokrane et al. [31]	- Investigated partially cured GFRP bars in steam-cured precast concrete elements. - Evaluated physical, mechanical properties, durability performance, and microstructure of GFRP bars. - Results influenced the development of CSA S807 standard for FRP bars.	- Investigate impact of partial curing on GFRP bars in concrete elements. - Assess physical, mechanical, and durability properties of partially cured GFRP bars. - Evaluate the effect of steam treatment on GFRP bars' properties.	- GFRP bars.	- Differential scanning calorimetry tests. - Scanning electron microscopy observations. - Concrete mix design simulation with steam treatment.	- Steam treatment increased cure ratio and interlaminar shear strength. - Partially cured GFRP bars retained interlaminar shear strength after conditioning. - Curing process insignificantly reduced cross-sectional area due to cure shrinkage. - Steam treatment acted as a post-polymerization promoter for GFRP bars.	- Limited information on long-term durability effects. - Need for further investigation on measuring cross-sectional area irregularities. - Future studies could explore the impact of temperature on water absorption.
Benmokrane et al. [70]	- Durability of GFRP reinforcing bars in alkaline environments assessed. - Stress corrosion mechanisms identified in GFRP bars under sustained loads. - Threshold stress levels determine stress corrosion mechanisms in GFRP bars.	- Investigate stress corrosion mechanisms of GFRP bars in moist concrete. - Determine safe operating stress levels for GFRP reinforcing bars in concrete.	- GFRP bars.	- Creep frame loading and compressed spring loading for testing GFRP bars. - New loading systems developed to overcome disadvantages of existing systems.	- Alkaline ions and moisture penetrate resin, affecting fibers and interphases. - Stress corrosion mechanisms in GFRP bars embedded in concrete identified. - Stress rupture tests on GFRP bars in moist concrete ongoing. - Resin type affects durability and stress corrosion resistance of GFRP bars.	- Limited information on long-term durability of GFRP bars. - Future studies could explore stress corrosion mechanisms in different environments.
Benmokrane et al. [11]	- Study compared durability of basalt and glass FRP bars with vinylester/epoxy. - Glass/vinylester bars showed best properties and lowest degradation in alkaline solution. - Basalt/vinylester bars had significant degradation after conditioning in alkaline solution.	- Investigated physical, mechanical, and durability characteristics of basalt/glass FRP bars. - Conducted comparative durability study under alkaline exposure simulating concrete environment.	- BFRP (basalt/vinylester), GFRP (glass/vinylester), BFRP (basalt/epoxy).	- Physical and mechanical properties assessment. - Comparative durability study under alkaline exposure.	- Glass/vinylester FRP bars had best physical and mechanical properties. - Basalt/vinylester FRP bars showed significant degradation after conditioning. - Basalt/epoxy FRP bars ranked second in physical and mechanical properties. - Basalt FRP bars need improvement for performance in concrete environments.	- Future research: Improve bond between resin and basalt fibers. - Investigate basalt FRP bars to match glass FRP bars' performance.
Benmokrane et al. [9]	- Evaluation of new headed GFRP bars for concrete reinforcement. - Study on physical, mechanical properties, pullout behavior, and durability. - Headed GFRP bars showed good mechanical interlocking and durability properties.	- Evaluate physical and mechanical properties of headed GFRP reinforcing bars. - Assess pullout behavior in concrete and long-term durability of bars.	- GFRP bars.	- Evaluation of physical and mechanical properties of headed GFRP bars. - Determination of pullout behavior in concrete for headed GFRP bars. - Characterization of long-term durability of the headed GFRP bars.	- Headed GFRP bars achieved up to 63% of guaranteed tensile strength. - No material changes in head and bars after exposure to conditions. - Suitable mechanical and durability properties for concrete reinforcement.	- Future research: Investigate long-term behavior of headed GFRP bars. - Explore effects of different exposure conditions on pullout behavior.
Benmokrane et al. [71]	- Investigated effects of bar diameter on physical, mechanical properties of GFRP bars. - Bar size had minimal impact on properties, except for water absorption. - Larger bars showed more degradation in alkaline solution than smaller ones. - Current standards not linking strength retention limit to bar size are acceptable.	- Investigated effects of bar diameter on physical, mechanical properties of GFRP bars. - Explored durability of GFRP reinforcing bars conditioned in alkaline solution.	- GFRP bars.	- Investigated effects of bar diameter on physical, mechanical, and durability properties. - Conducted microstructural analyses and physicochemical property measurements on GFRP bars.	- Bar size had minimal effect on physical and mechanical properties. - Larger bars had more significant strength reduction after conditioning. - Degradation was observed at the surface of all conditioned specimens. - Flexural strength retention increased with larger bar diameter.	- Limited research on GFRP bar durability for different sizes. - Future studies needed to explore the impact of bar types. - Investigate how bar diameter affects the design of concrete structures.

Benmokrane et al. [8]	- GFRP bars' durability with vinyl-ester, polyester, and epoxy resins assessed. - Vinyl-ester and epoxy bars showed superior properties after alkaline exposure. - Polyester bars exhibited significant degradation in physical and mechanical properties.	- Evaluate physical and mechanical properties of GFRP bars with different resins. - Assess long-term performance of GFRP bars under alkaline exposure conditions. - Compare degradation rates of GFRP bars made with vinyl-ester, polyester, and epoxy resins.	- GFRP bars with polyester, vinylester, epoxy resins. Glass is the most commonly used fiber type in manufacturing FRP bars.	- Evaluation of GFRP bars with vinyl-ester, polyester, and epoxy resins. - Alkaline exposure testing according to ASTM D7705. - Microstructural analysis using SEM before and after conditioning.	- Epoxy and vinyl-ester GFRP bars had superior physical properties. - Polyester GFRP bars showed significant degradation in physical properties. - Vinyl-ester and epoxy bars had the lowest degradation rate. - Polyester bars exhibited lower transverse-shear and flexural strength.	- Limited research on the effect of resin type on GFRP bars. - Need for further studies on GFRP bar durability and properties.
Benmokrane et al. [72]	- Study on glass fiber-reinforced polymer bars for ground control in Singapore. - Durability assessment under harsh environmental exposure conditions. - Microstructural analysis conducted to investigate deterioration due to environmental conditioning. - Predicted high long-term durability of glass fiber-reinforced polymer rock bolts.	- Assess durability of GFRP rock bolts in harsh environmental conditions. - Predict long-term performance of solid and tubular GFRP bars. - Investigate microstructural changes in GFRP bolts due to environmental exposure. - Test feasibility of using GFRP bolts in Jurong Rock Caverns.	- GFRP solid and tubular bars.	- Immersion in saline solution at 20, 40, and 50°C. - Arrhenius plots for long-term tensile strength predictions. - Tensile testing of solid and hollow GFRP bars. - Use of GFRP bars for ground control in Jurong rock caverns. - Prediction of tensile strength retention over 100 years.	- Predicted tensile strength for 50 years: 96.8% for solid, 97.3% for hollow GFRP bars. - Tensile-strength retention after 100 years would be over 82%.	- Limited studies on GFRP rock bolts in saline solutions. - Future research on GFRP bars' behavior in aggressive environments.
Benmokrane et al. [4]	- Study evaluated durability of 24 FRP bars in alkaline environment. - Manufacturing parameters significantly affect mechanical characteristics and alkaline resistance of FRP bars. - Procedure for achieving specific mechanical properties and durability with FRP bars.	- Evaluate durability of 24 FRP bars in alkaline concrete environment. - Assess mechanical properties and alkaline resistance of FRP bars. - Determine impact of manufacturing parameters on FRP bar characteristics.	- Glass, basalt, and carbon FRP bars. E-glass, ECR-glass, basalt, and carbon fibers were evaluated.	- Tensile tests with SatecBaldwin Model BTE machine as per ASTM D7205. - Transverse-shear and interlaminar-shear tests on MTS 810 machine.	- Different FRP bars showed varied strength properties and durability. - Manufacturing parameters significantly affected mechanical characteristics and alkaline resistance. - Vinyl ester resin and silane-sized fiber produced durable glass-FRP bars. - Epoxy resin yielded durable basalt- and carbon-FRP bars.	- Improve resin and fiber-sizing chemistries for better alkaline resistance. - Consider fiber-resin combinations for strength-retention criteria development. - Optimize manufacturing parameters for specific mechanical properties and durability.
Benmokrane et al. [37]	- Thermoplastic GFRP bars compared to thermosetting counterparts with stable properties. - No defects in microstructural analysis of thermoplastic GFRP bars. - Creep strain negligible after 10,000 hours under loading.	- Study focused on physical, mechanical, and durability properties of thermoplastic GFRP bars. - Comparison of thermoplastic-based GFRP bars with thermosetting counterparts. - Investigated properties include tensile strength, creep strain, and microstructural analysis.	- Thermoplastic-based GFRP bars.	- Investigation of thermoplastic-based GFRP bars in concrete structures. - Creep experimental results used to estimate creep coefficient and material constant.	- Thermoplastic GFRP bars showed stable tensile properties at 40°C. - Creep strain of thermoplastic GFRP bars was negligible after 10,000 hours. - New thermoplastic-based GFRP bars exhibited good mechanical behavior and durability. - Tensile strength and modulus retentions were 87% and 100%, respectively.	- Future research: Develop bendable FRP bars for construction industry. - Limitation: Thermoset-based FRP bars cannot be bent after solidification.
Cao et al. [12]	- AAMs replace OPC in SWSSC to enhance FRP bond performance. - SWSSAAC with AAMs shows improved bond strength and rigidity. - CFRP bars exhibit higher bond strength in SWSSAAC due to properties.	- Study bond performance of FRP bars in seawater sea-sand concrete. - Investigate bond behavior with SWSSAAC using different alkaline dosages.	- BFRP, GFRP, CFRP bars.	- Developed seawater sea-sand alkali-activated concrete using AAMs instead of OPC. - Investigated bond behavior of FRP bars with SWSSAAC at different alkaline dosages. - Conducted pull-out tests on FRP bars using ASTM D7913D7913M-14 specification.	- AAMs increase splitting tensile strength, enhancing FRP bond performance. - CFRP bars show higher bond strength and rigidity than BFRP, GFRP. - SWSSAAC integration with FRP bars achieves significant bond stiffness improvements.	- Future research: Investigate the long-term durability of FRP-reinforced SWSSC structures. - Limitation: Lack of detailed discussion on the environmental impact assessment.
Chen et al. [1]	- Paper evaluates FRP bars' durability in various simulated exposure conditions. - Accelerated aging tests conducted on FRP reinforcing bars for concrete structures. - Study includes tensile strength, interlaminar shear strength, and bond strength evaluations. - GFRP bars showed significant strength loss in accelerated exposure conditions. - CFRP bars displayed excellent durability performance in the study.	- Evaluate durability performance of FRP bars under various exposure conditions. - Assess tensile strength, interlaminar shear strength, and bond strength. - Investigate effects of accelerated exposure on FRP bars and concrete.	- Glass, aramid, carbon fibers in FRP bars. E-glass fibers and vinyl ester resin were primarily selected.	- Accelerated aging tests with FRP bars in various simulated environments. - Tensile strength and interlaminar shear strength tests conducted pre- and post-exposure. - Pullout tests to assess bond strength between FRP bars and concrete. - Use of elevated temperatures, wetting/drying, and freezing/thawing cycles for acceleration.	- GFRP bars showed significant strength loss in accelerated exposure conditions. - CFRP bars displayed excellent durability performance in the study. - Alkali resistant fibers can enhance the durability of GFRP bars. - Elevated temperatures accelerated degradation of both bare FRP and FRP-concrete specimens.	- Limited information on FRP bars in combined WD or FT cycles. - Few studies on bond strength of FRP bars in HPC. - Need for more representative evaluations of FRP reinforced concrete structures.
Chen et al. [73]	- Study on time-dependent corrosion resistance of geopolymer concrete in seawater. - Investigated mechanical properties, durability, and corrosion resistance of geopolymer materials. - Explored tensile strength of BFRP bars in different solutions. - Established models for strength degradation of BFRP bars in seawater.	- Study time-dependent corrosion resistance of GPC and BFRP bars in seawater. - Evaluate mechanical properties and durability of GPC and BFRP materials. - Investigate migration ability and pore structure in corrosive ions attack. - Analyze tensile strength of BFRP bars in different solutions. - Examine dual interface transition zones characteristics of BFRP reinforced GPC.	- BFRP bars.	- Experimental investigation on time-dependent mechanical properties and durability. - Analysis of volume expansion and strength loss rates in seawater. - Evaluation of corrosion resistance through ion migration and pore structure. - Comparative study of BFRP tensile strength in different solutions. - Investigation of dual interface transition zones characteristics under seawater.	- GPC volume expansion rate decreased by 77.6% after 360 days. - GP mortar showed excellent resistance to ion migration. - BFRP bars' tensile strength degradation model under seawater corrosion was established. - Average porosity of ITZ between geopolymer and BFRP bars increased insignificantly.	- Investigate long-term performance of BFRP GPC in real marine environments. - Explore the impact of time-dependent ion transport on BFRP bars.

D'Antino and Pisani [74]	- GFRP bars tested under sustained stress in different environments. - Limited influence of sustained stress on bar residual tensile strength. - Calibration of reduction factors for long-term behavior of GFRP bars.	- Investigate the influence of sustained stress on glass FRP reinforcing bars. - Analyze the effect of exposure to different environments on GFRP bars.	- GFRP bars.	- Analyzed tensile tests on GFRP bars exposed to various conditions. - Investigated the effect of sustained stress on GFRP bar tensile strength. - Compared results of bars exposed to different environments with and without stress.	- Sustained stress had limited influence on GFRP bar residual tensile strength. - Alkaline environment proved to be most aggressive for GFRP bars. - Results analyzed the effect of sustained stress on GFRP bar tensile strength.	- The study did not address the effect of sustained stress on durability. - Future research could explore the impact of sustained stress on GFRP bars.
D'Antino et al. [75]	- GFRP bars replace steel bars in concrete for durability. - Experimental tests on GFRP bars in alkaline environments. - Thermoset and thermoplastic resin bars compared for durability.	- Verify durability of GFRP bars in alkaline environments through experiments. - Compare tensile and interlaminar shear tests of GFRP bars.	- Thermosetting and thermoplastic resins for GFRP bars. E-glass fibers in GFRP bars.	- Experimental tests on GFRP bars with E-glass fibers. - Tensile and interlaminar shear tests conducted according to specific standards.	- Results include tensile and interlaminar shear tests of GFRP bars. - Experimental tests show the effect of alkaline conditioning on GFRP bars.	- Limited research on GFRP bars with thermoplastic resin.
Debaiky et al. [32]	- Evaluates GFRP reinforcing bars' residual tensile properties in severe environments. - Investigates stability of tensile strength, ultimate elongation, and elasticity modulus. - No significant change in elastic modulus observed under different loading conditions.	- Evaluate residual tensile properties of GFRP reinforcing bars in severe environments. - Focus on durability data for E-glass vinylester FRP reinforcing bars.	- GFRP, CFRP.	- Evaluating residual tensile properties of GFRP bars in severe environments. - Comparing residual strains of different bar sizes tested. - Measuring hydroxyl and carbon-hydrogen content in samples.	- Residual tensile properties of GFRP bars tested under severe environments. - Comparison of residual strains and strengths for different bar sizes. - Satisfactory residual strain values observed after exposure to high temperature.	- Lack of long-term durability data hinders wider FRP acceptance. - Need for more research on durability of GFRP bars under loading.
Dong et al. [38]	- Investigated FRP bar degradation influence on bond performance with concrete. - Tested different FRP bars under direct pull-out conditions. - Concluded bond durability order as CE>BE> GV>BV based on test results.	- Investigated FRP bar degradation influence on bond performance with concrete. - Tested basalt and carbon fiber-reinforced bars under various conditions. - Analyzed bond strength retention and durability of different FRP bars.	- BFRP (basalt/vinylester), BFRP (basalt/epoxy), CFRP (carbon/epoxy), GFRP (E-glass/vinylester).	- Investigated bond performance of FRP bars pre-exposed to alkaline solution. - Tested bars under direct pull-out condition with different resin and fiber types. - Analyzed bond strength retention and durability of FRP bars.	- CE bars had the largest bond strength, followed by GV bars. - BE bars with epoxy matrix showed greater bond strength retention. - BV bars had decreasing bond strength, while CE and BE increased.	- Limited study on long-term bond behavior of FRP bars. - Future research needed on bond durability of different FRP bars.
Elgabbas et al. [2]	- Physical and mechanical characterization of new basalt FRP bars. - Durability testing in harsh alkaline conditions simulating concrete environment. - Comparison of BFRP bars against FRP standards.	- Characterize new basalt FRP bars for concrete structures. - Assess durability of BFRP bars in harsh alkaline conditions. - Compare BFRP characterization and durability against FRP standards.	- BFRP bars (Types A, B, and C).	- Physical and mechanical testing of reference and alkali-conditioned specimens. - Conditioning BFRP bars in an alkaline solution to assess durability. - Investigated three types of BFRP bars for mechanical behavior. - SEM analysis to detect changes in basalt fiber microstructure.	- BFRP bars met ACI and CSA requirements for physical properties. - Long-term testing showed degradation in mechanical properties of alkali-conditioned specimens. - Basalt fibers and resins were not affected by conditioning. - BFRP bars exhibited poor alkali resistance due to resin-fiber interface issues.	- Future research: Investigate the impact of different environmental conditions. - Limitation: Lack of detailed discussion on the mechanical properties.
Elhamaymy et al. [2]	- Investigated GFRP reinforcement in concrete piles submerged in marine environments. - Validated design provisions for predicting axial capacity of submerged GFRP-RC piles. - Assessed durability and structural response of GFRP-reinforced concrete piles. - Conducted microstructural analyses on GFRP reinforcement to assess degradation.	- Investigated GFRP reinforcement in submerged concrete piles in marine environments. - Validated design provisions for predicting axial capacity of GFRP-reinforced piles.	- GFRP bars.	- Investigated GFRP reinforcement in concrete piles submerged in marine environments. - Conducted durability and structural response assessment of GFRP-reinforced concrete piles.	- Axial capacities of submerged GFRP-RC piles increased up to 22%. - GFRP reinforcement well-bonded to concrete, no microstructural deterioration. - Increasing GFRP reinforcement ratio and using GFRP spirals improved performance.	- Limited experimental work on GFRP-RC members in marine environments.
Esmaeili et al. [48]	- Experimental study on GFRP bars' long-term performance under varied conditions. - Weibull statistical analysis used to determine creep-rupture strengths. - Impact of sustained load more significant than environmental conditioning effects. - Smaller diameter bars more prone to creep rupture.	- Assess long-term performance of GFRP bars under different environmental conditions. - Determine safe creep-rupture strength value for GFRP bars.	- GFRP bars of various sizes and materials.	- Weibull statistical analysis to determine creep-rupture strengths. - Extrapolation of creep-rupture strength for GFRP bars at 114 years.	- Sustained load impacted strength more than environmental exposure. - Smaller GFRP bars were more prone to creep rupture. - Conditioning affected larger diameter bars more than smaller ones. - Current design codes' creep-rupture reduction factors are conservative for GFRP bars.	- Additional research needed to mimic creep rupture behavior in natural environments. - Investigate creep rupture behavior and long-term performance of larger GFRP bars. - Future studies can calibrate and implement other safety models.
Fan and Zhang [76]	- IPCC reinforced with basalt FRP bars compared with OPCC columns. - IPCC load capacity 30% lower than OPCC, larger ultimate displacements. - Basalt rebar in IPCC exhibited larger deformation than steel rebar. - Sine-shaped model predicts lateral deformation in IPCC columns.	- Investigate mechanical behavior of inorganic polymer concrete columns under eccentric compression. - Compare inorganic polymer concrete with steel-reinforced ordinary Portland cement concrete. - Study the effect of eccentricity on failure mode and displacement response.	- BFRP bars.	- Experimental investigation of inorganic polymer concrete columns under eccentric compression. - Comparison with steel-reinforced ordinary Portland cement concrete columns. - Analytical model for predicting lateral deformation in inorganic polymer concrete columns.	- IPCC load-carrying capacity 30% lower than OPCC. - IPCC ultimate displacements 65% and 15% larger than OPCC. - IPCC had similar overall behavior as OPCC up to final failure. - Ultimate longitudinal strains on IPCC larger than OPCC due to IPC strength. - Sine-shaped model can predict lateral deformation in IPCC columns.	- Future research: Explore enhancing load-carrying capacity and ultimate displacements. - Limitation: IPCC had 30% lower load-carrying capacity than OPCC.

Fasil and Al-Zahrani [77]	- Study on GFRP bars under harsh conditions using neural networks. - Bars exposed to different environments, temperatures, and time regimes. - Decline in shear strength over time, SEM analysis, and strength prediction.	- Predict transverse shear capacity of GFRP bars under harsh conditions. - Develop models using artificial neural networks for strength prediction. - Compare models developed with multiple linear regression and ANN techniques.	- GFRP bars.	- Multiple linear regression and artificial neural network techniques were utilized. - MATLAB functions 'fitlm' and neural network toolbox were employed.	- GFRP bars showed decline in shear strength with exposure time. - Bar A, B1, and B2 performed well, while Bar C performed worst. - ANN models had higher accuracy in predicting GFRP shear strength.	- Limited studies on the effects of conditioning on GFRP bars. - Lack of research on the impact of exposure to different conditions.
Feng et al. [3]	- Study enhances BFRP bars' corrosion resistance using CNTs modified resin. - CNTs modified resin significantly improves alkaline resistance of BFRP bars. - BFRP bars treated with CNTs show improved interlaminar shear strength retention. - CNTs prevent hydroxyl ions penetration, enhancing anti-crack behavior of resin.	- Investigate alkaline resistance of BFRP bars with CNT-modified resin. - Evaluate durability using water uptake, shear tests, SEM, and FTIR. - Improve corrosion resistance of BFRP bars in marine concrete structures.	- BFRP bars.	- Coating CNTs modified resin on BFRP bars for corrosion resistance. - SEM, X-ray micro-CT, FTIR, and TGA for analysis. - Moisture uptake and weight gain ratio measurements.	- CNTs modified resin enhances alkaline resistance of BFRP bars significantly. - Weight gain of BFRP bars decreases after treatment with CNT-modified resin. - Modified BFRP bars show improved mechanical properties and lower porosity.	- Future research: Explore long-term durability and real-world marine applications. - Limitation: Study focused on simulated conditions, real-world validation needed.
Feng et al. [34]	- Focus on BFRP bars in SWSSC degradation in lab and marine. - Lowering alkalinity enhances BFRP bars durability in marine environments. - Investigated ILSS and deterioration mechanisms of BFRP bars in SWSSC. - Natural marine environment causes less degradation to BFRP bars. - Low-alkalinity SWSSC minimizes hydrolysis of epoxy resin in BFRP bars.	- Investigate degradation of BFRP bars in SWSSC in lab and marine environments. - Study ILSS, deterioration mechanisms, and durability enhancement of BFRP bars. - Analyze the impact of temperature and humidity on BFRP bars. - Focus on using low-alkalinity SWSSC to improve FRP bars' durability.	- BFRP bars.	- ILSS test, 1H NMR, FTIR, TGA, SEM for BFRP bar investigation.	- BFRP bars in low-alkalinity SWSSC show higher ILSS retention. - Lowering alkalinity enhances durability and service life of BFRP bars. - Natural marine environment causes less degradation to BFRP bars. - High temperature and alkalinity accelerate degradation of BFRP bars.	- Future research: Explore modification or surface treatment for resin matrix. - Limitation: Conservative predictions by existing models.
Fergani et al. [25]	- Investigated GFRP bars in severe environments and under sustained stress. - Tested physical, mechanical, and chemical properties using various techniques. - Elevated temperatures accelerated degradation mechanisms in GFRP bars.	- Investigate physical and mechanical properties of GFRP bars in severe environments. - Study GFRP bars exposed to moist concrete, alkaline solution, and tap water. - Characterize mechanical properties through direct tension, flexural, and shear tests. - Determine physical and chemical properties using various techniques.	- GFRP bars.	- Direct tension, flexural, and inter-laminar shear tests. - Moisture absorption measurements, SEM, FTIR, and EDX analyses.	- Elevated temperatures accelerate degradation mechanisms in GFRP bars. - Moisture diffusion affects long-term mechanical properties of GFRP bars. - Higher conditioning temperatures lead to resin matrix deterioration. - Increased temperature favors moisture ingress and premature inter-laminar de-bonding.	- Future research: Develop a durability model for GFRP bars. - Limitation: Durability model is still under development, not discussed.
Fu et al. [78]	- Study on durability of carbon/basalt hybrid bars in alkaline solution. - Carbon fiber coating enhances properties of BFRP bars. - Investigated tensile properties, shear strength, water absorption of C/BFRP.	- Investigated properties of carbon/basalt hybrid bars in different alkaline solutions. - Studied tensile properties, interlaminar shear strength, water absorption, and diffusion behavior. - Examined the effect of carbon fiber coating on the durability of BFRP. - Analyzed the impact of alkalinity on the service life of BFRP bars.	- Carbon/BFRP bars. BFRP bars were also examined.	- Laboratory acceleration methods to examine C/BFRP properties. - Preparation of alkaline solutions with pH 10 or 13.	- Carbon fiber coating improves mechanical properties and durability of BFRP. - Tensile strength retention increased by 12 when pH decreased to 10. - BFRP bars with carbon fiber coating show better alkaline corrosion resistance.	- Future research: Explore impact of different carbon fiber volume fractions. - Limitation: No discussion on the economic feasibility of C/BFRP bars.
Genikomsou et al. [79]	- Shear testing of GFRP bars for material specifications and quality control. - Development of a device for shear testing based on ASTM and CSA standards. - Investigates shear behavior of GFRP bars from different suppliers and diameters. - Shear tests can indicate resin properties and fiber content.	- Shear testing of GFRP bars for material specifications and structural design. - Investigate shear behavior of GFRP bars with different diameters. - Shear tests as an indicator of resin and fiber content properties. - Measure shear stiffness to determine FRP bars properties.	- GFRP bars.	- Shear testing device development based on ASTM and CSA standards. - Investigation of shear capacity of GFRP bars as composite material. - Accelerated aging procedures and long-term strength prediction models development.	- Shear testing device developed for GFRP bars of various diameters. - Shear strength versus shear strain results for GFRP bars from two companies. - Shear stiffness measures for GFRP bars with different failure modes. - Shear stress reduction in aged GFRP bars after exposure to solution.	- Future research needed for better understanding shear behavior of GFRP bars. - Correlation with direct tensile testing required for shear testing. - Shear stiffness can provide information about the quality of bars. - Bar finishing plays a role in shear stiffness of bars.
Gooranorimi et al. [13]	- Investigated microstructural patterns of GFRP bars and their impact on durability. - SEM imaging on four GFRP bars with unique microstructural patterns.	- Investigate microstructural patterns on GFRP durability in concrete reinforcement. - Provide documentation of GFRP microstructure for durability assessment. - Scope limited to small sample size, single bar diameter, and four manufacturers.	- GFRP bars.	- Scanning electron microscopy (SEM) imaging at different magnification levels. - Horizontal shear test performed on GFRP bars.	- SEM imaging showed unique microstructural patterns in commercially available GFRP bars. - Accelerated conditioning in alkaline solution affected GFRP durability. - Horizontal shear tests indicated the impact of microstructural patterns on durability.	- Future research: Investigate the impact of different conditioning environments. - Explore the long-term durability of GFRP bars under various conditions. - Study the microstructural changes in GFRP bars during field use.

Guo et al. [41]	- Study on basalt-carbon hybrid FRP bars in seawater concrete. - Hybrid CFs enhance durability and mechanical properties of BFRP bars. - Investigation on microstructural evolution and failure model of HFRP bars.	- Evaluate using carbon fibers to enhance durability of basalt FRP bars. - Investigate microstructural evolution of hybrid FRP bars in seawater concrete. - Assess the tensile and interlayer interface properties of hybrid FRP bars.	- Basalt-carbon hybrid FRP bars.	- Tensile and interlayer interface properties testing after exposure to seawater. - Digital microscopy, scanning electron microscopy, X-ray CT, and matrix digestion analysis. - X-ray CT for pore structure analysis inside concrete. - Threshold segmentation algorithm for obtaining pores inside concrete.	- Hybrid CFs enhanced ILSS and TS retention in SWSC-embedded BFRP bars. - HFRP bars with central CF arrangement showed higher durability in SWSC. - TS retention of HFRP-SWSC bars was 83.72 after 360 days. - Deterioration of HFRP bars in SWSC characterized using various analyses.	- Future research: Investigate HFRP bars with different CFs hybrid contents in marine environments. - Limitation: Stress concentration can lead to critical failure in HFRP bars.
Hassan et al. [35]	- Investigated bond durability of BFRP bars in concrete in harsh environments. - Tested BFRP bars in alkaline solution at 40 C, 50 C, 60 C. - Found bond strength increased initially with temperature, then deteriorated. - Predicted long-term bond-strength retention of BFRP bars after 50 years.	- Investigate bond durability of BFRP bars in concrete in harsh environments. - Assess long-term bond-strength-retention predictions of BFRP bars.	- BFRP bars.	- Testing deformed BFRP bars in concrete with direct tensile loading. - Investigating bond strength in alkaline solution at elevated temperatures. - Using optical and scanning electronic microscopy to study bar degradation.	- Initial bond strength increases with temperature, then deterioration during immersion. - Long-term bond-strength-retention predictions after 50 years range from 71% to 92%.	- Future research: Investigate different concrete strengths, accelerated moist conditions, longer exposure.
He et al. [80]	- Study on durability of GFRP bars in concrete beams with cracks.	- Study durability of GFRP bars in concrete beams with cracks. - Analyze degradation mechanisms using SEM, FTIR, and DSC.	- GFRP bars. GFRP bars composed of 72% glass fiber, 28% vinyl ester resin.	- Accelerated tests in alkaline solution and tap water. - Tensile tests to evaluate residual tensile properties of GFRP bars. - SEM, FTIR, and DSC employed to observe and analyze deterioration.	- GFRP bars' tensile strength decreased in various environments. - Crack in concrete increased environmental effect on GFRP bar durability. - Sustained flexural loading accelerated GFRP bar degradation rate.	- Future research: Explore effects of sustained loading on GFRP bar durability. - Limitation: Study did not address the impact of crack width.
Hokura and Miyazato [81]	- Study evaluates FRTP rods in concrete reinforcements for applicability. - FRTP rods' tensile strength, elastic modulus, and pull-out test variations assessed. - Bending strength of concrete beams with embedded FRTP rods evaluated.	- Evaluate FRTP applicability in concrete reinforcement with carbon or glass fiber. - Assess tensile strength, elastic modulus, and pull-out test variations. - Examine bending strength of concrete beams with embedded FRTP rods.	- CFRP bars. GFRTP fibers.	- Evaluation of FRTP rods in concrete reinforcements. - Testing tensile strength and elastic modulus before and after exposure. - Immersion in water and alkaline solution for durability assessment.	- FRTP rods had consistent tensile strength and elastic modulus. - Pull-out test results between CFRTP and concrete were normal. - Small variation in tensile strength-strain of test materials. - Relationship between tensile strength before and after water immersion.	- Future research: Explore the impact of temperature fluctuations on FRTP. - Limitation: Limited focus on FRTP applicability in concrete structures.
Hussain et al. [82]	- Concrete damage by aggressive media studied with Basalt Fiber Reinforced Polymer bars. - BFRP bars bond strength tested in alkaline solution and sea water. - Bond strength retention of BFRP bars evaluated using Fib bulletin model.	- Investigate bond strength reduction between concrete and BFRP bars. - Evaluate bond performance of BFRP bars in aggressive environments. - Study bond durability with varying parameters like bar diameter and length. - Procure BFRP bars with specific diameters and embedment lengths.	- BFRP bars.	- Pull-out testing to investigate bond strength between concrete and BFRP bars. - Utilization of the Fib bulletin model for future bond strength prediction.	- BFRP bars showed 86% and 82% bond strength retention. - Future bond strength retention for BFRP bars was evaluated. - BFRP bars were tested in aggressive media like seawater and alkaline.	- Limited study on BFRP bar bond strength in different aggressive environments. - Need for research on BFRP bars with higher diameters for accessibility.
Iqbal et al. [54]	- Prediction of GFRP bar strength in harsh alkaline environments using metaheuristic models.	- Predict residual tensile strength of GFRP bars in harsh alkaline environments. - Develop accurate models using metaheuristic algorithms like PSO, GA, SVM. - Analyze influential parameters like GFRP bar size, fiber volume fraction.	- GFRP bars.	- Fuzzy metaheuristic ensembles developed using 715 experimental database samples. - Particle swarm optimization, genetic algorithm, and support vector machine utilized. - ANFIS-SVM and ANFIS-PSO models deployed for predicting TSR accurately. - K-fold cross-validation used to assess model reliability. - Statistical tests conducted to analyze the efficiency of metaheuristic algorithms.	- ANFIS-SVM model accurately predicts TSR of conditioned GFRP bars. - ANFIS-PSO model provides reasonable results for GFRP bars in alkaline concrete. - GFRP bar size, fiber volume fraction, and pH are influential parameters.	- Limited exploration of other AI optimization algorithms for model enhancement. - Future studies could focus on the impact of additional environmental factors.
Ji et al. [58]	- Focus on FRP bars and SCMs for sustainable construction materials. - FRP bars are more durable than traditional steel rebar. - SCMs reduce carbon emissions in concrete. - Study compares sustainability, durability, and mechanical properties of FRP and SCMs.	- Compare sustainability, durability, and mechanical performance of FRP bars and SCMs. - Evaluate carbon emissions and resistance against alkali, chloride, and freeze-thaw cycles. - Analyze the effects of various SCMs on concrete quantitatively.	- CFRP, BFRP, GFRP.	- Comparison of FRP bars and SCM blended concrete sustainability and durability. - Quantitative analysis of various SCMs effects on concrete. - Evaluation of FRP bars durability against alkali, chloride, and freeze-thaw cycles. - Analysis of concrete durability against alkali, chloride, sulfate attack, and carbonation. - Mitigation of alkaline corrosion of FRP bars by carbonating concrete.	- FRP bars have higher tensile strength and lower density than steel. - BFRP offers better sustainability compared to other materials. - SCMs refine concrete pores, improving resistance against various factors.	- Future research: Investigate long-term deflection control in FRP-reinforced concrete. - Limitation: Lack of detailed analysis on the economic aspects of materials.

Jia et al. [33]	- Study on GFRP bars in concrete exposed to various environments. - Impact of water, saline solutions, and humidity on GFRP bars. - Concrete cover depth and water-to-cement ratio influence durability.	- Investigate GFRP bar durability in concrete under various environmental conditions. - Assess the impact of water content, humidity, and cover depth. - Study the tensile strength retention of GFRP bars in different environments.	- E-glass fibers and vinyl ester resin.	- Tensile strength testing of GFRP bars in various environmental conditions. - Electrical impedance method to evaluate water content in concrete cover. - Classification of GFRP specimens into groups based on environmental exposure.	- GFRP bars lost strength in tap water and high humidity. - Concrete cover depth influenced GFRP bar durability in various environments. - Reduction in water-to-cement ratio negatively impacted GFRP reinforcing bars.	- Lack of information on durability assessment in various environments.
Jiang et la. [83]	- Study on BFRP bars coated with SSGM for shear performance. - Investigated effects of SSGM coatings on BFRP bars in seawater.	- Investigate shear performance of BFRP bars coated with SSGM in seawater. - Study effects of SSGM coatings and sustained loading on BFRP degradation. - Assess protection provided by SSGM compared to cement-based concrete. - Examine impact of alkaline content of activator in SSGM on degradation.	- BFRP bars. BFRP bars had a nominal diameter of 8 mm.	- Fourier transform infrared spectroscopy, scanning electron microscopy, energy dispersive x-ray spectroscopy. - Pultrusion process, x-ray fluorescence spectroscopy, accelerated aging tests.	- SSGM-coated BFRP bars showed better protection than cement-based concrete. - BFRP bars with 6 alkaline contents had slightly higher shear strength degradation. - FTIR analysis showed no significant chemical structure alterations after seawater immersion. - Interlaminar shear strength of SSGM-coated BFRP bars had lower retention.	- Long-term shear behavior of BFRP bars coated with SSGM not studied. - Future research can explore the impact of different immersion temperatures.
Jin et al. [84]	- GFRP bars degrade under mechanical load and alkaline solution effects. - Tensile strength degradation model proposed for GFRP bars. - Combined effects of stress levels and alkaline solution impact degradation. - Resin-fiber interface corrosion leads to mechanical properties decline.	- Investigate tensile properties and degradation of GFRP bars under stress. - Study degradation mechanisms at micro-, meso-, and macro-scales. - Develop a strength-degradation model to predict tensile strength under conditions.	- GFRP bars.	- Scanning electron microscopy and three-dimensional X-ray microscopy for analysis. - Proposed a strength-degradation model fitting well with experimental data.	- Tensile strength degrades faster at higher stress levels. - Elastic modulus and Poisson's ratio initially increase, then decrease. - Ultimate elongation significantly reduces under combined effects of load and solution.	- Durability under sustained stress not considered in the study.
Kaloop et al. [53]	- Soft computing models estimate GFRP rebar strength in alkaline concrete. - DNN and ANFIS-GA models outperform MPMR in predicting rebar strength. - Environmental factors like temperature and pH affect GFRP rebar strength.	- Develop soft computing techniques for GFRP rebar tensile strength estimation. - Assess sensitivity of production parameters and environmental factors in TSR estimation. - Compare MPMR, DNN, and ANFIS-GA models for accuracy and performance. - Analyze the impact of temperature, pH, bar diameter, and fiber volume.	- GFRP bars.	- Minimax probability machine regression (MPMR). - Deep neural network (DNN). - Integrated adaptive neuro-fuzzy inference system with genetic algorithm (ANFIS-GA).	- DNN and ANFIS-GA outperformed MPMR in predicting tensile strength retention. - RMSE and R2 values for ANFIS-GA, DNN, and MPMR were compared. - Temperature and pH sensitivity significantly affect GFRP bars' tensile strength retention. - Diameter and fiber volume fraction are crucial in GFRP rebar degradation.	- Future research: Explore impact of different environmental factors on GFRP bars. - Limitation: Consider additional variables for more accurate tensile strength estimation.
Karim et al. [85]	- Study on turning alkaline-treated banana fibre-reinforced polymer composite. - Emphasizes machining constraints' influence on surface roughness and cutting force. - Taguchi orthogonal array L25 used for experiments and optimization. - Analysis shows depth of cut and feed rate as key factors. - Optimal parameters determined for surface roughness and cutting force.	- Investigate surface roughness and cutting force in turning T-BaFRP composite. - Optimize machining constraints using Taguchi orthogonal array L25. - Explore benefits of hybridizing banana and glass fibers for composites. - Conduct validation studies for T-BaFRP composite materials on a larger scale.	- BaFRP composite.	- Taguchi orthogonal array L25 for experimental design and optimization. - Quadratic regression equations for surface roughness and cutting force.	- Achieved surface roughness of 2.594 µm and cutting force of 14.258 N. - Optimal parameters: depth of cut 0.362 mm, speed 55 m/min. - Cutting force optimization: 0.8 mm depth, 154 m/min speed. - Experimental values error: 0.517% for surface roughness, 1.181% for cutting force.	- Investigate impact of alternative cooling techniques like MQL or flood cooling. - Study machining behavior of T-BaFRP composites using different cutting inserts. - Explore properties of composite material with various fiber treatment techniques. - Incorporate additional factors like tool shape and nozzle angle.
Li et al. [20]	- BFRP bars in coral concrete degrade faster than in ordinary concrete. - Temperature influences the degradation rate of BFRP bars. - Life prediction of BFRP bars in coral concrete under marine environment.	- Investigate mechanical properties of BFRP bars in coral concrete. - Study degradation rate of BFRP bars under high temperature and humidity.	- BFRP bars.	- Accelerated erosion method in a laboratory environment for investigation. - Durability and tensile tests of BFRP bars in seawater concrete.	- BFRP bars in coral concrete degrade faster than in ordinary concrete. - Temperature significantly affects the degradation rate of BFRP bars. - Lifetime prediction of BFRP bars in coral concrete under marine environment.	- Future research: Quantify damage value for more accurate prediction models. - Limited studies on BFRP bars in harsh environments, warranting more research.
Li et al. [86]	- Examined impact performance of BFRP bars in saline-alkaline environment. - Investigated effects of exposure duration and temperature on BFRP bars. - Studied deterioration mechanism using ESEM and FTIR.	- Examine impact performance of BFRP bars in saline-alkaline environment. - Measure load-bearing, deformation, and energy absorption capacities of deteriorated BFRP bars. - Study deterioration mechanism using ESEM and FTIR. - Investigate impact performance after exposure to elevated temperatures.	- BFRP bars.	- ESEM and FTIR used to study deterioration mechanism. - Exposure solution prepared to simulate saline-alkaline environment.	- BFRP bars show decreased fracture threshold and bending stiffness with temperature. - Surface deterioration increases with exposure temperature and duration. - Moisture absorption impacts dynamic mechanical performance of BFRP bars.	- Limited research on FRP bars in saline-alkaline environments. - Need for more accurate degradation models for BFRP composites. - Further studies on dynamic performance and residual tensile strength needed.

Li et al. [87]	- Investigated GFRP bars' durability in seawater environments using various tests. - Analyzed microstructure changes, hydrolysis degree, and glass transition temperature differences. - Established a durability prediction model for GFRP bars in the Yellow Sea.	- Investigated GFRP bars' durability in seawater environments. - Analyzed degradation mechanisms using ILSS, microstructure, and aging data. - Established a durability prediction model for GFRP bars in China.	- GFRP bars.	- Investigated GFRP bars in seawater, saline-alkali solution, and concrete. - Conducted short-beam shear tests to study aging effects on GFRP bars. - Analyzed microstructure changes using SEM, DSC, and FTIR. - Established a durability prediction model for GFRP bars in the Yellow Sea.	- GFRP bars degraded significantly in different environments after 183-day aging. - Strength degradation rate was fastest in SA environment, followed by SWC. - Temperature increases accelerated hydrolysis reaction rate of GFRP bars. - Microstructures showed fiber and resin separation after aging in SA and SWC.	- Model limitations: neglects material degradation mechanism, assumes infinite strength. - Future research: explore impact of Y values on model accuracy.
Liu et al. [88]	- Study compares bond strength degradation of BFRP, ECR, and OSBs. - Corrosive environments and freeze-thaw cycles impact bond strength differently. - BFRP-bar-CC and ECR-CC specimens show unique failure modes.	- Compare bond strength degradation of BFRP, ECR, and OSBs in CC. - Analyze bond performance in corrosive environments coupled with freeze-thaw cycles.	- BFRP bars.	- Comparative analysis of BFRP bars, ECR, and OSBs in CC. - Three corrosive environments: acid, salt, alkaline salt, with FT cycles. - Immersion of specimens in alkaline salt, salt, and acid solutions.	- BFRP-bar-CC and OSB-CC specimens failed to pull out. - ECR-CC specimens showed splitting failure when corrosive and FT cycles combined. - OSB-CC specimens changed failure type from pullout to splitting with FT cycles. - Bond strength decayed most rapidly in acid environment for all bars.	- Limited study on bonding properties in harsh environments. - Few studies on reinforcement with ceramsite concrete in corrosive conditions.
Lu et al. [89]	- Investigated shear performance of cement mortar-coated BFRP bars in corrosive environments.	- Investigate shear performance of cement mortar-coated BFRP bars in corrosive environments. - Study durability of BFRP bars in different immersion mediums and temperatures.	- BFRP bars.	- Transverse shear tests conducted according to ASTM D7617 standards. - Dynamic mechanical thermal analysis performed using a TA instrument.	- Alkaline immersion deteriorates BFRP interface properties and shear strength. - Thicker cement mortar coating leads to more apparent shear strength degradation. - ASR caused by silica in basalt fiber affects BFRP bars.	- Future research: Investigate the impact of temperature on FRP durability. - Explore the long-term shear behavior of BFRP and GFRP bars.
Lu et al. [20]	- Durability of BFRP bars in seawater with cement mortar cover.	- Investigate degradation of BFRP bars in simulated seawater environment. - Study the impact of AAR on mechanical properties of BFRP.	- BFRP bars.	- Experimental investigation with SEM, FTIR, and XRD analysis. - Immersion in alkaline solution and distilled water for comparison.	- Alkalinity degrades BFRP, thicker mortar worsens degradation, AAR affects mechanical properties. - A white gel at BFRP-cement interface indicates alkali-aggregate reaction. - BFRP bars are more durable than GFRP due to higher fiber volume fraction.	- Future research: Investigate the impact of different immersion temperatures. - Limitation: Lack of study on the effect of chloride ions.
Lu et al. [19]	- Investigated FRP bars' tensile performance after exposure to different solutions. - Found no significant changes in Tg values after exposure to solutions. - Moisture absorption varied with exposure period and type of solution.	- Investigate tensile performance degradation of FRP bars in different solutions. - Compare effects of water, seawater, and alkaline solutions on FRP bars.	- BFRP, CFRP, GFRP.	- Immersion tests in tap water, artificial seawater, and alkaline solutions. - DSC analysis to determine Tg values of FRP bars.	- GFRP bars showed more surface appearance changes after exposure. - BFRP bars experienced significant damage in harsh environments. - CFRP bars had noticeable strength loss in seawater solution. - Moisture absorption was higher in GFRP bars after exposure.	- Discrepancies in BFRP material and exposure conditions require further research. - Investigate tensile performance of FRP bars in normal civil engineering environments.
Lu et al. [90]	- Study on durability of BFRP bars in marine environments. - Alkalinity key factor causing BFRP degradation. - AAR of SiO_2 in basalt fiber found at BFRP-concrete interface.	- Study durability of BFRP bars in marine environments. - Investigate degradation mechanisms of BFRP bars in different immersion media.	- BFRP bars.	- Transverse shear test performed according to ASTM D7617. - Flexure behavior tested based on ASTM D 4476-14. - Immersion in ocean water and simulated seawater at different temperatures. - Alkaline activity test conducted following ASTM C1260.	- Uncovered BFRP in 60°C simulated seawater showed the most degradation. - Alkalinity is a key factor causing BFRP degradation. - Degradation mechanism includes resin degradation and interfacial debonding. - Seawater's alkalinity decomposes Si-O-Si bone in basalt fiber. - BFRP bars in actual concrete degrade differently than in simulated solutions.	- Limited investigation on the impact of fiber type on durability. - Future studies could explore the effect of different resin matrices. - Further research needed on the long-term durability of BFRP bars.
Lu et al. [18]	- Investigates bond durability of BFRP bars in concrete with fly ash. - Examines degradation in aggressive environments through pull-out tests. - Fly ash enhances bond strength in BFRP-ordinary and BFRP-fly ash concrete.	- Investigate bond durability of BFRP bars in concrete with fly ash. - Analyze bond strength in alkaline solution and simulated seawater. - Determine mechanical properties of BFRP bars under different immersion conditions.	- BFRP bars.	- Pull-out tests to investigate bond durability of BFRP bars. - Immersion in alkaline solution and seawater at different temperatures. - Determination of mechanical properties of BFRP bars under various conditions. - Use of fly ash in concrete to improve interfacial bond strength.	- BFRP bars' bond strength decreases with immersion time. - Addition of fly ash in concrete improves interfacial bond strength. - Prediction of long-term bond strength based on fib Bulletin 40. - Experimental study on bond durability in chloride and alkaline environments.	- Limited studies on long-term performance of BFRP bar-concrete interfaces. - Need for new prediction model for long-term bonding properties. - Explore methods to improve interfacial performance in aggressive environments.

Lu et al. [28]	- Investigated durability of BFRP bars in seawater sea sand concrete. - Alkaline solution damages BFRP bars more than tap-water or seawater. - SWSSC thickness affects tensile strength retention of BFRP bars. - Arrhenius relationship used to predict long-term tensile properties of BFRP bars. - Bare BFRP bars degrade faster in seawater than tap-water.	- Investigate durability of BFRP bars in seawater sea sand concrete. - Study tensile properties of SWSSC-wrapped BFRP bars in marine environments.	- BFRP bars.	- Laboratory accelerated corrosion tests in simulated seawater environments. - Prediction of tensile strength retention based on Arrhenius relationship. - Preparation of alkaline solution and seawater according to ACI standards.	- SWSSC-wrapped BFRP bars had accelerated degradation in tap-water or alkaline solution. - BFRP bars in seawater had better tensile strength retention than bare bars. - Tensile strength decreased with time and temperature in all immersion environments. - Tensile strength more affected by immersion environment than tensile modulus. - Long-term tensile strength retention of SWSSC-wrapped BFRP bars can be predicted.	- Lack of research on BFRP bars in real concrete environments. - Accuracy concerns in long-term performance predictions due to simulation differences.
Lu et al. [24]	- Investigated durability of GFRP bars in seawater with prestressing effects. - SSC coating accelerated tensile strength degradation, but shear properties degraded slowly.	- Investigated durability of SSC-coated GFRP bars under prestressing and seawater. - Effects of immersion temperature, time, and prestress levels were examined.	- GFRP bars.	- Investigated durability of SSC-coated GFRP bars under prestressing and seawater. - Used tensile properties, shear strength, and prestress loss for analysis. - Employed FBG sensors and strain gauges for data acquisition.	- SSC wrapping negatively impacted GFRP bars' long-term performance. - Prestressing accelerated tensile strength degradation in GFRP bars immersed in seawater. - Shear properties degraded slower than tensile properties in prestressed GFRP bars.	- Limited studies on the variation of pH around GFRP in concrete. - Unclear performance degradation mechanism of FRP in concrete with prestressing. - Future research on the coupling effect of prestress and SSC-coated immersion.
Lu et al. [91]	- Long-term tensile performance of GFRP bars in aggressive environments.	- Investigate long-term tensile performance of GFRP bars in aggressive environments. - Study degradation mechanisms of GFRP bars in concrete. - Analyze tensile properties of GFRP bars under various exposure conditions.	- GFRP bars.	- Tensile testing on GFRP bars in aggressive environments. - Immersion in alkaline and saline solutions. - Long-term tensile strength retention prediction based on experimental data.	- GFRP bars showed degradation in tensile strength under aggressive conditions. - Tensile strength retention ranged from 62.8% to 75.1% after 100 years. - Failure modes of GFRP bars were consistent regardless of exposure conditions. - Degradation mechanism attributed to reduction of bonding between fiber and matrix. - Tensile strength retention was around 93% after one year in concrete.	- Limited studies on GFRP bars in concrete under marine environments. - Lack of research on GFRP bars' performance under sustained loads.
Manalo et al. [92]	- Study compared GFRP bars in concrete vs. simulated environments. - Evaluated physical, mechanical, and microstructural properties of GFRP bars. - Investigated durability in high moisture, saline, and alkaline environments. - Developed master curves and time-shift factors for GFRP bars.	- Evaluate durability of GFRP bars in concrete and simulated environments. - Investigate interlaminar shear strength in high-moisture, saltwater, and alkali conditions.	- GFRP bars. Grade III GFRP bars with a nominal diameter of 9.53 mm.	- Comparative evaluation of GFRP bars in concrete and simulated environments. - Development of master curves and time-shift factors for durability assessment. - Evaluation of interlaminar shear strength in different solutions for durability. - Calculation of time-shift factors for different conditioning cases and temperatures.	- GFRP bars' interlaminar shear strength decreased with higher exposure temperature. - Concrete-embedded GFRP bars had higher ILSS than bare GFRP bars. - Alkaline solution was more aggressive to GFRP bars than tap water. - Direct immersion degraded GFRP bars' ILSS more than concrete-embedded bars.	- Future research: Investigate the impact of different concrete environments on GFRP bars. - Limitation: Lack of study on the effect of bar size on durability.
Moon et al. [93]	- Investigated GFRP bars exposed to high temperature in alkali concrete. - Studied shear strength and stiffness degradation in GFRP bars. - Longer alkali immersion led to rapid degradation in shear properties.	- Investigated shear strength and stiffness of thermally damaged GFRP bars. - Evaluated the effect of alkali concrete environment on GFRP reinforcing bars.	- E-glass fiber and vinyl ester resin matrix.	- Investigated inter-laminar shear strength and stiffness of GFRP bars. - Conducted an accelerated aging test in an alkaline concrete environment. - Compared performance changes in inter-laminar shear strength and stiffness capacities.	- GFRP bars damaged by heat show more shear strength degradation. - Longer immersion in alkali leads to rapid shear stiffness degradation. - Exposure to high temperatures accelerates alkali penetration, causing performance degradation.	- No specific limitations or future research directions mentioned in the paper.
Mufti et al. [94]	- GFRP durability in concrete field structures analyzed for alkali attack. - GFRP found stable in concrete, leading to CHBDC permitting its use.	- Study durability of GFRP in concrete structures exposed to environment. - Analyze GFRP reinforcement and concrete using various microanalysis methods. - Investigate effect of cover depth on concrete cracking over GFRP bars. - Determine glass transition temperatures of GFRP specimens from in-service structures. - Measure hydroxyl content in GFRP specimens to assess polymer hydrolysis.	- GFRP bars for primary reinforcement.	- Optical microscopy, SEM, EDX analysis, DSC, FTIR spectroscopy.	- GFRP in concrete structures showed no damage after 5-8 years. - GFRP is durable in concrete, allowing primary reinforcement and prestressing. - No cracks observed over GFRP bars in concrete structures. - Minimal change in hydroxyl content of in-service GFRP specimens.	- Future research: Investigate long-term durability of GFRP in various environments. - Explore effects of different stress levels on GFRP in concrete. - Study the impact of GFRP exposure on the glass transition temperature.
Nassar et al. [95]	- Study on GFRP bars' strength loss in highly alkaline concrete. - Alkali attack decreases tensile strength, influenced by fiber volume fraction. - Accelerated aging affects GFRP bars' alkali resistance and bond strength.	- Investigate the impact of high alkalinity on GFRP bars' tensile strength. - Assess factors like fiber volume, diameter, and protective coating on alkali resistance.	- GFRP bars.	- Accelerated aging techniques evaluated GFRP characteristics in alkaline environments. - Wet-dry cycles, continuous immersion, and tension tests were conducted. - Bond tests assessed the interface between GFRP bars and concrete.	- Alkali attack decreased GFRP tensile strength, increasing with age. - Fiber volume fraction influenced alkali resistance; lower fractions preserved strength. - Larger diameter GFRP bars offer better protection against alkali attack. - Epoxy coating generally improved alkali resistance of GFRP bars. - Accelerated aging did not change bond strength but altered failure mechanism.	- Future research: Investigate the impact of different protective coatings. - Explore the effectiveness of vinylester resin in improving alkali resistance. - Study the bond strength of GFRP bars under various environmental conditions.

Nkurunziza et al. [96]	- Research evaluates GFRP bars' creep behavior in different environments under load.	- Evaluate creep behavior of GFRP bars under sustained load in environments. - Measure change in tensile properties like strength, modulus, and elongation.	- E-glass fibers in vinylester resin for GFRP bars.	- Creep behavior evaluation of GFRP bars in different environments. - Testing GFRP bars under sustained load levels and surrounding mediums. - Monitoring axial strain in the central conditioned part of the bars. - Testing GFRP bars in axial tension for residual tensile strength.	- GFRP bars showed high residual tensile strength under extreme conditions. - No significant change in elastic modulus observed under different stress levels. - Creep strain in GFRP bars was less than 5% after 10,000 hours. - Research focused on creep behavior, modulus change, and tensile strength.	- Limited discussion on the effect of sustained loading on creep behavior. - Future research could explore the impact of stress levels on durability.
Pan and Yan [56]	- Study on GFRP and HFRP bars durability in alkaline solution. - CFRP layer enhances GFRP bars durability in alkaline environment.	- Evaluate durability of GFRP and HFRP bars aged in alkaline solution. - Assess water absorption behaviors and interlaminar shear strength degradation. - Predict long-term interlaminar shear strength using Arrhenius theory.	- GFRP bars. HFRP bars.	- Water absorption characterization, interlaminar shear strength degradation investigation. - Arrhenius theory for predicting long-term interlaminar shear strength. - Calculation of time-shift factor for shear strength retention at different temperatures. - Prediction of long-term performance of GFRP and HFRP bars.	- HFRP bars had higher interlaminar shear strengths than GFRP bars. - Deterioration in HFRP bars occurred at the CFRP/CFRP interface. - CFRP layer improved GFRP bars' durability in an alkaline environment.	- Limited publications on durability of carbon-glass HFRP bars in solutions. - Need to clarify adverse effects of water and hydroxyl ions. - Explore effects of fiber hybridization on FRP durability.
Refai [97]	- Durability study on basalt fiber-reinforced polymer bar-anchor system. - BFRP bars tested under static and fatigue loading conditions. - Conditioning in saline and alkaline solutions affected tensile capacity. - Fatigue life primarily influenced by applied stress range.	- Study focused on durability and fatigue of basalt fiber-reinforced polymer bars. - Investigated effects of saline and alkaline solutions on bar-anchor systems. - Examined static and fatigue tests on unconditioned and conditioned bars. - Recommendations for stress ranges and fatigue limits of BFRP bar-anchor systems.	- BFRP, GFRP, CFRP.	- Durability study on basalt fiber-reinforced polymer bars under static and fatigue loading. - Conditioning bars in saline and alkaline solutions before testing. - Testing unconditioned basalt, glass, and carbon specimens as controls. - Conducting fatigue tests to determine the fatigue life of the system. - Immersing BFRP bars in alkaline solution to assess premature fracture.	- BFRP bars endured ultimate tensile loading without slippage or failure. - Conditioning in saline and alkaline solutions decreased tensile capacity. - Fatigue life primarily affected by applied stress range. - Alkaline solution increased premature fracture tendency in anchor zone. - Fatigue limit of BFRP bar-anchor system determined to be 4%.	- Future studies should validate results with realistic environmental conditions. - Consider other types of environmental exposure and gripping mechanisms for research.
Rifai et al. [36]	- BFRP bars tested in alkaline solution and moist concrete environments. - Evaluation of tensile strength and microstructural characteristics of BFRP bars. - Master curves developed for service life prediction of conditioned BFRP bars.	- Evaluate BFRP bar durability in alkaline solution and moist concrete. - Develop master curves for service life prediction of BFRP bars.	- BFRP bars.	- Fourier transform infrared analysis to assess degradation due to hydrolysis. - Regression analysis to determine best-fit relationship for data at temperature.	- BFRP bars in alkaline solution had comparable tensile strength to moist concrete. - BFRP bars at 60°C in alkaline solution had lower strength. - Moisture uptake was higher in alkaline solution conditioned BFRP bars. - Conditioning temperature affected tensile strength retention in different media.	- Basalt FRP bars may need further study in practical settings. - Overcoming limitations of FRP bars in alkaline environments is crucial. - Master curves for service life prediction of BFRP bars need validation.
Robert and Benmokrane [98]	- Study on GFRP bars in salt solution and concrete durability. - High tensile strength retention in aged GFRP bars. - No chemical degradation detected in polymer after aging. - Prediction of long-term tensile strength performed.	- Study durability of GFRP bars in saline solution and concrete. - Predict long-term tensile strength of GFRP bars.	- Resins: polyester, vinylester, epoxy. Vinylester matrix has fewer ester units compared to polyester.	- Arrhenius relation for degradation rate prediction based on tensile strength. - Mechanical, durability, and microstructural characterizations of GFRP bars in harsh environments. - Immersion of concrete-wrapped bars in salt solution at elevated temperatures.	- GFRP bars showed high tensile strength retention after aging. - No chemical degradation of the polymer was detected after aging. - Long-term durability of GFRP bars in salt solution was high.	- Limited data on combined effect of moist concrete and saline solution. - Future research needed on GFRP bars durability in harsh environments.
Robert et al. [99]	- Study on GFRP bars in concrete environment using various tests. - Durability of GFRP bars in concrete differs from simulated solutions. - Aging effects on GFRP bars in tap water and concrete observed.	- Study durability of GFRP bars in concrete environments. - Assess aging effects using various analytical techniques. - Compare durability in tap water versus simulated pore-water solution. - Predict long-term properties based on Arrhenius theory.	- Sand-coated GFRP bars by Pultrall Inc.	- Tensile strength measurement, Fourier transform infrared spectroscopy, scanning electron microscopy. - Differential scanning calorimetry, accelerated aging in tap water and alkaline solution. - Characterization of aging effect on GFRP reinforcing bars.	- Aging in tap water less pronounced than in simulated pore solution. - No significant microstructural changes observed after 240 days immersion. - Polymer matrix not affected by moisture absorption and high temperatures. - Long-term predictions show tensile strength retention decreases by 20-25%. - Durability of mortar-wrapped bars less affected by tap water aging.	- Future research: Investigate effects of temperature on GFRP bars in concrete. - Limitation: Accelerated aging studies may not correspond to actual service life. - Future research: Explore the influence of FRP material components on durability.

Rolland et al. [5]	- Investigates GFRP rebars' durability and bond with concrete in aging. - Conducted accelerated aging tests on GFRP rebars in alkaline solution. - Residual tensile properties determined for rebars subjected to direct immersion. - Short-beam tests showed no significant evolution of interlaminar shear strength. - Bond tests revealed initial increase followed by decreasing trend in bond strength.	- Investigate durability of GFRP rebars in alkaline environments. - Assess bond properties of concrete/GFRP over aging. - Monitor physical, mechanical properties of GFRP rebars during aging.	- GFRP rebars.	- Accelerated aging tests on GFRP rebars in alkaline solution. - Residual tensile properties determination for predictive Arrhenius model. - Short-beam tests on rebars under direct/indirect immersion conditions. - Bond tests on pull-out specimens after immersion in alkaline solution. - Complementary characterizations by SEM, DSC, and FTIR spectroscopy.	- Significant reduction in tensile strength after direct immersion in alkaline solution. - Indirect aging showed less degradation compared to direct immersion. - No notable variation in mass/diameter of GFRP rebars during aging. - Interlaminar shear strength remained stable after aging, indicating good chemical resistance.	- Future research: Validate hypotheses with extended aging periods. - Comparative studies needed between real aging and accelerated aging methods.
Sayyar et al. [43]	- Glass fiber composites coated for enhanced alkali resistance in concrete. - Coating improved durability without affecting mechanical performance of composite bars.	- Enhance alkali resistance of glass fiber composites for concrete reinforcement. - Improve durability in alkaline environments without compromising mechanical performance. - Conduct flexure, shear, and compression tests on modified glass fiber bars.	- GFRP composites.	- Weak-acid cation exchangers as coating for glass fiber reinforcements. - Use of hardened block glass fiber composite bars with ion exchanger.	- Weak-acid ion exchanger coating enhanced glass fiber composite bar durability. - Coating did not affect mechanical performance of composite bars. - Strong-acid ion exchanger particles did not bond well with bars. - Glass fiber bars with weak-acid coating showed improved durability in concrete.	- Limited information on long-term durability in alkaline environments. - Need for further research on glass fiber composite reinforcement systems.
Sen et al. [100]	- Study evaluated E-glass/vinylester reinforcement durability in simulated pore solution. - Results showed limited durability, unsuitability of glass fiber-reinforced polymer bars.	- Evaluate durability of E-glass/vinylester reinforcement in high pH environment. - Assess residual tensile strength of specimens exposed to simulated pore solution. - Confirm unsuitability of first-generation glass fiber-reinforced polymer bars for reinforcement.	- GFRP (E-glass/vinylester) reinforcement bars. GFRP bars for construction.	- Experimental study with E-glass/vinylester reinforcement exposed to simulated pore solution. - Testing specimens to failure after exposure periods of 1, 3, 6, and 9 months. - Investigating specimens at stress levels of 0, 10, and 25.	- E-glass/vinylester bars had limited durability, especially at stress levels. - Specimens stressed to 25% failed within 25 days of exposure. - Prediction of remaining life ranged from 0.5 to 4.6 years.	- Future research: Explore alternative materials for concrete structural reinforcement. - Limitation: First-generation glass fiber-reinforced polymer bars unsuitable for concrete reinforcement.
Shakiba et al. [101]	- Study on bond durability of GFRP and steel bars in concrete. - Concrete type affects bond strength under harsh environments. - Experimental study with sand-coated GFRP and steel bars.	- Investigate bond durability of GFRP and steel bars in concrete. - Assess bond strength under harsh conditions like seawater and alkaline solution. - Study the impact of concrete type on bond strength.	- GFRP bars for concrete beam reinforcement.	- Flexural pullout tests conducted on 54 beam specimens. - Comparison of sand-coated GFRP bars and steel bars. - Symbols used for calculations and experimental conditions detailed.	- Bond strength of GFRP bars decreased less after seawater exposure. - Steel bars showed negligible bond loss in alkaline solution. - Different concrete types affect bond strength with GFRP and steel bars. - Load-slip curves showed different failure modes for GFRP and steel bars.	- Lack of consideration for bar surface configuration in bond strength models. - Need for further research on the effect of concrete type. - Limited studies on the durability behavior of GFRP bars.
Silva and Estevao [102]	- Study on GFRP rods in alkaline solution, impact on degradation. - Immersion effects, pore reduction, SEM images, energy absorption loss discussed. - Protective covers, mortar cylinders, accelerated effects, and damage analysis included.	- Investigate degradation of glass fiber-reinforced polymer rods in alkaline solution. - Study the influence of protective covers on the degradation of rods.	- GFRP rods.	- Diffusion and porosimetry studies to interpret results. - Spectroscopy (FTIR), DSC, SEM techniques for degradation analysis.	- Embedment delayed damage initiation but did not shield rods from degradation. - Loss of energy absorption capacity in low-velocity impact tests. - Immersion in solution at 60°C caused marked degradation of rods.	- Future research: Explore long-term effects of GFRP rods in aggressive environments. - Limitation: Study focused on short-term effects of GFRP rods.
Singhvi and MirMiran [61]	- FRP-RC beams experience stiffness degradation due to bond deterioration. - Fiber optic sensors are used for in-service monitoring of FRP-RC structures. - Environmental conditioning affects FRP-RC beams' strength, stiffness, and post-cracking stiffness. - Moisture absorption in FRP bars is 2%-3% after accelerated environmental conditioning.	- -Evaluate FRP-RC beams under environmental conditions and sustained loads. - Assess fiber optic sensors for long-term monitoring in harsh environments.	- GFRP bars.	- Creep and durability tests on FRP-RC beams using fiber optic sensors. - Findlay's creep model used for FRP strain calculations.	- Creep rate increases with environmental conditioning, affecting FRP-RC beams. - Moisture absorption is 2%-3%, with no significant effect on strength. - Stiffness degradation due to bond deterioration between FRP bars and concrete. - Fiber optic sensors less sensitive to temperature compared to foil gages.	- Limited data on long-term behavior of FRP-RC structures. - Need for in-service monitoring of FRP-RC structures. - Investigate sensitivity and ruggedness of fiber optic sensors in harsh environments.
Su et al. [62]	- Investigated durability of FRP profiles in concrete under varying conditions. - Analyzed strength degradation and morphology of FRP profiles using SEM.	- Study focused on FRP profile tensile strength degradation in concrete. - Analyzed degradation mechanism using SEM in concrete environment. - Proposed long-term prediction method for tensile strength retention.	- BFRP (unidirectional), BFRP (multidirectional), Basalt-carbon hybrid FRP profiles.	- Analysis with scanning electron microscopy to study degradation mechanism. - Prediction of tensile strength retention based on the Arrhenius equation.	- Alkaline environment decreased FRP profiles' tensile strength, accelerated degradation with temperature. - MD FRP profiles showed more significant strength degradation than UD profiles. - Concrete environment had no effect on the elastic modulus of FRP. - SEM used to analyze morphology and degradation mechanism of FRP profiles.	- Limited focus on FRP profiles with multidirectional or hybrid fibers. - Lack of clarity on the long-term properties of FRP profiles. - Need for further research on durability of FRP profiles.

Sumida and Mutsuyoshi [103]	- Investigated heat-resistant resins for FRP bars, enhancing heat resistance. - Tested FRP bars with different fibers and matrix resins for durability.	- Investigated heat-resistant resins for FRP bars to enhance durability. - Evaluated heat resistance through tensile tests and alkaline resistance tests. - Conducted pull-out and flexural tests on concrete members with FRP bars.	- Resol type phenolic resin (PH), M type cross-linked polyester-amide resin (CP), Epoxy resin (EP) for FRP bars.	- Investigated new heat-resistant resins for FRP bars. - Conducted tensile tests, alkaline resistance tests, pull-out tests, and flexural tests. - Tested FRP bars with different fibers and matrix resins. - Evaluated heat resistance through tensile tests during and after heating. - Tested breaking load of FRP bars after exposure to fire.	- PH or CP matrix resin had higher heat resistance than EP. - Carbon fiber and PH matrix resin bars had heat resistance like steel. - Retention of breaking load was almost 100% for carbon fiber. - Elastic modulus of FRP bars decreased at high temperatures.	- Future research: Explore other fiber types for FRP bar development. - Investigate the impact of different matrix resins on FRP bars. - Study the bond strength of FRP bars at various temperatures. - Assess the durability of FRP bars in different environmental conditions.
Sun et al. [6]	- GFRP bars studied for degradation in alkaline environments using experiments. - Alkaline ions disrupt hydrogen bonding network, leading to degradation. - Study reveals resin-fibre strength decline due to hydroxide concentration. - Interaction between alkaline ions and epoxy network investigated.	- Study mechanical property evolution and degradation mechanism of GFRP bars. - Investigate the impact of alkaline environments on GFRP bars.	- FRP bars made of E-glass fibers and epoxy resin. GFRP bars made of E-glass fiber and epoxy resin.	- Experimental and molecular dynamics simulations to study GFRP bar degradation. - Characterization of intermolecular forces using interaction energy.	- GFRP bars' strength declined with increasing pH in alkaline solutions. - Alkaline ions disrupted hydrogen bonding network, leading to resin degradation. - Interaction between alkaline ions and epoxy network was investigated.	- Future research: Investigate the impact of different alkaline ion concentrations. - Explore methods to enhance the corrosion resistance of GFRP bars.
Sun et al. [7]	- Predicting GFRP bars degradation in concrete for long-term applications. - FTIR spectroscopy reveals resin degradation and functional group ratio changes. - Relationship between functional group ratio change and TS retention established.	- Predict degradation properties of GFRP bars in concrete for long-term applications. - Analyze tensile strength retention and microstructure evolution of GFRP bars.	- GFRP bars.	- FTIR spectroscopy for TS retention and microstructure evolution analysis. - Accelerated tests exposing glass fibres to alkaline solutions at different temperatures.	- TS retention above 70% due to resin degradation. - Chemical degradation observed by FTIR and SEM. - TS retention below 70% caused by resin/fibre debonding. - Linear relationship between functional group ratio change and TS retention.	- Future research: Enhance FTIR-TS relationship comprehensiveness and rigor. - Limitation: Need for more work on FTIR-TS retention relationship.
Tabsh et al. [104]	- Investigated effects of harsh conditions on glass FRP concrete flexural behavior. - Exposed GFRP bars to various environments before testing concrete beams. - Proposed a mathematical equation for GFRP over-reinforced concrete beams.	- Investigate the effect of long-term storage conditions on concrete beams. - Study the flexural behavior of concrete beams with GFRP reinforcement.	- Glass fibers: E-glass, S-glass, C-glass, AR-glass.	- Experimental investigation on concrete beams with E-Glass FRP bars. - Raw data analysis to determine the influence of GFRP rebar exposure.	- GFRP bar exposure to harsh conditions affected mechanical properties negatively. - Outdoor storage reduced cracking and ultimate moment capacities slightly. - Alkaline solution and sunlight exposure decreased stiffness and ductility. - Proposed mathematical equation for predicting ultimate flexural strength.	- Limited study on the effects of harsh environmental exposure on GFRP bars. - Future research could explore the impact of different chemical solutions. - Investigate the long-term behavior of GFRP bars in various environmental conditions.
Taha et al. [42]	- Investigated bond durability of basalt FRP bars in saline environment. - Analyzed influence of basalt fiber reinforced concrete on bond performance. - BMF addition improved bond strength of HWBFRP bars in concrete. - CMR model showed better reliability in describing bond-slip behavior.	- Investigate bond durability of basalt FRP bars in saline environment. - Analyze influence of basalt fiber reinforced concrete on bond durability.	- Helically wrapped BFRP bars. BFRP bars compared to GFRP bars.	- Analyzed bond durability of basalt FRP bars in saline environment. - Conducted SEM analysis to investigate degradation of HWBFRP bars. - Calibrated BPE and CMR models for bond-slip behavior prediction.	- Addition of BMF improved bond performance of HWBFRP bars. - CMR model showed better reliability than BPE model in bond-slip behavior.	- Limited to effects of investigated parameters; caution needed for generalization. - Future studies could explore different fibers, FRP bars, or conditions.
Tu et al. [49]	- Predicts GFRP rebar durability by monitoring elastic modulus degradation. - Establishes relationship between tensile strength and elastic modulus of GFRP rebars. - Uses Arrhenius equation to simulate elastic modulus degradation model.	- Predict durability of GFRP rebars by monitoring elastic modulus degradation. - Establish relationship between tensile strength and elastic modulus of GFRP.	- GFRP bars predominantly used.	- Real-time monitoring of strain for GFRP rebars to study degradation. - Accelerated aging tests in an alkaline environment for GFRP rebars. - Relationship between degradation rate of elastic modulus and tensile strength	- Relationship between tensile strength and elastic modulus of GFRP rebars proposed. - Feasibility of using Arrhenius equation to simulate elastic modulus degradation model. - Durability of GFRP rebars can be predicted by monitoring elastic modulus.	- Limited data on long-term durability of GFRP bars in service. - Need for effective methods to monitor tensile strength degradation. - Lack of technology to monitor GFRP bars' tensile strength in service.
Wang et al. [15]	- CSAC concrete durability tested with GFRP and CFRP bars. - GFRP degrades more than CFRP in CSAC pore solution. - Tensile strength reduction: GFRP 56.9%, CFRP 15.1%. - CFRP meets alkaline resistance standard, GFRP does not.	- Compare durability of GFRP and CFRP bars in CSAC pore solution. - Assess degradation mechanisms and strength retention of FRP bars. - Investigate impact of sea salt on GFRP and CFRP bars.	- GFRP and CFRP bars.	- Mechanical tests: tensile, horizontal, transverse shear tests. - Microstructural analyses: SEM, EDS, FTIR spectroscopy.	- GFRP bars degraded more than CFRP bars in CSAC pore solution. - CFRP bars met alkaline resistance standard, GFRP bars did not. - GFRP suffered damage to fiber, epoxy, and interface; CFRP did not. - Maximum tensile strength reduction: GFRP 56.9%, CFRP 15.1%.	- Future research: Investigate the impact of different temperatures on FRP bars. - Explore the long-term durability of FRP bars in various concrete environments.

Wang et al. [105]	- Experimental study on bond between GFRP bars and concrete.	- Study bond performance between GFRP bars and concrete. - Factors include surface treatment, bond length, immersion solution, and time.	- GFRP bars.	- Calculation models comparison, bond strength analysis, and immersion solution effects. - Bond-slip curves, bond strength comparisons, and immersion solution influence analysis.	- GFRP-concrete bond strength decreased with saline and alkaline solution exposure. - Comparison of test and calculated values for GFRP-concrete pullout.	- Limited research on bond properties in corrosive environments. - Future studies could explore long-term degradation performance in extreme conditions.
Wang et al. [21]	- Investigated durability of GFRP bar-reinforced SWSSC beams in chloride environments. - SWSSC showed good performance with GFRP bars, enhancing durability. - Proposed a re-correction model to estimate residual flexural strength.	- Investigate coupling effects of sustained loading and chloride exposure on GFRP beams. - Assess durability of GFRP bar-reinforced SWSSC beams in chloride environments.	- GFRP bars.	- Investigation of GFRP bar-reinforced SWSSC beams under chloride environment. - SEM for GFRP bar degradation mechanism. - Alkalinity measurement of SWSSC for concrete strength analysis.	- SWSSC exhibited good durability with GFRP bars in chloride environments. - Concrete strength increased, positively influencing flexural stiffness of conditioned beams. - Failure of conditioned beams controlled by concrete due to over-reinforcement.	- - Limited investigation on GFRP bar-reinforced beams under sustained loading. - Future studies could explore longer exposure times for conditioned beams. - Need for research on the durability of large-diameter GFRP bars.
Wiciak et al. [60]	- Evaluates GFRP bar damage using ultrasonic waves and shear strength. - New methodology based on wave velocity and amplitude for damage evaluation. - Ultrasonic parameters estimate shear strength reduction with less than 7% error.	- Evaluate damage in GFRP bars using ultrasonic guided waves. - Study progressive damage due to highly alkaline environment. - Correlate NDT results with shear strength reduction from destructive tests.	- GFRP bars.	- Accelerated aging with alkaline immersion test. - Ultrasonic tests based on wave velocity and amplitude approaches. - Reference intrusive test (shear test) for verification.	- Ultrasonic parameters capture deterioration in GFRP bars. - Ultrasonic measurements estimate shear strength reduction with less than 7% error.	- Future research: Include GFRP bars embedded in concrete in accelerated aging tests. - Limitation: Lack of studies on ultrasonic features' frequency content.
Wiciak et al. [59]	- GFRP bars' life estimation challenge addressed by numerical wave propagation model. - Model assists ultrasonic non-destructive testing for GFRP bars' degradation evaluation. - Low strain measurements can estimate progressive damage effect on GFRP bars.	- Develop a numerical model for ultrasonic wave propagation in GFRP bars. - Assist in non-destructive testing for evaluating progressive damage of GFRP bars. - Study wave dispersion and amplitude to estimate progressive damage effects.	- GFRP.	- Development and calibration of numerical model in Abaqus. - Simulation of deterioration of GFRP bars. - Comparison of experimental tests with numerical simulations. - Correction of ultrasonic and numerical tests based on shear test.	- Numerical model captures deterioration rates in shear strength tests. - Ultrasonic evaluation trends align with shear test observations. - Small strain measurements can estimate progressive damage on large strain properties. - Corrected ultrasonic and numerical tests show improved correlation with shear test. - Study presents a tool for NDT evaluation of GFRP bars.	- Future research: Improve ultrasonic tests by addressing coupling and transducer selection. - Limitation: No comparison of shear test and ultrasonic evaluation at different levels.
Wone t al. [57]	- Nano-GFRP rebar durability in water and alkaline solutions evaluated. - Nanomaterials added to vinyl ester resin for enhanced performance. - Tensile strength tests conducted after exposure to water and alkaline solutions. - Moisture diffusion coefficient compared with general GFRP rebar.	- Evaluate nano-GFRP rebar performance in water and alkaline solutions. - Compare tensile strength and moisture diffusion coefficient with general GFRP rebar. - Assess durability and chemical stability of inorganic nanomaterials in rebar. - Determine the impact of exposure on tensile residual strength of rebar.	- Nano-GFRP composite bars. E-glass fiber and vinyl ester resin for Nano-GFRP.	- Nano-GFRP rebar fabrication using pultrusion method with nanomaterials. - Tensile strength tests after exposure to water and alkaline solutions. - Determination of moisture diffusion coefficient for comparison with general GFRP rebar.	- Nano-GFRP rebar had higher tensile residual strength after exposure to alkaline solution. - Moisture diffusion coefficients of nano-GFRP rebar were comparable to general GFRP. - Dispersion of nanoparticles affects composite material properties in nano-GFRP rebar.	- Consider uniform dispersion of nanoparticles for consistent composite properties. - Investigate the impact of nanomaterial properties on composite durability. - Explore enhancing flexural toughness of FRP rebar for broader applications.
Wu et al. [51]	- Evaluates BFRP bar durability under harsh environments using SEM analysis. - Predicts long-term performance based on exposure to different corrosive solutions. - Investigates effects of stress levels on BFRP bar degradation processes. - Shows accelerated degradation under high stress levels in alkaline solution. - Compares tensile strength reductions in various corrosive solutions.	- Evaluate BFRP bars' residual tensile properties in harsh environments. - Analyze microstructural degradation of BFRP bars in alkaline environment. - Assess the impact of sustained stress levels on BFRP bars. - Predict long-term performance of BFRP bars under different environmental conditions.	- BFRP bars.	- Prediction based on Arrhenius theory for BFRP bars in harsh environments. - Microstructural analysis using scanning electronic microscopy for degradation mechanism. - Evaluation of residual tensile properties of BFRP bars in different solutions.	- BFRP bars exposed to alkaline solution showed significant degradation effects. - Stress levels below 20% of ultimate strength had minor degradation effects. - Predicted exposure time for 50% strength reduction in alkaline solution. - SEM images revealed fiber-matrix-interface debonding as the degradation mechanism.	- Limited studies on BFRP bars compared to GFRP bars. - Lack of experimental studies on the coupling effect of stress.
Wu et al. [16]	- Investigates BFRP bars' degradation in alkaline environments and resistance mechanisms. - Compares BFRP and GFRP bars' tensile strength degradation trends. - BFRP bars maintain over 60% strength after 9 weeks in alkaline solution.	- Investigates BFRP bars' degradation in an alkaline environment. - Analyzes tensile strength, elastic modulus, shear strength, and moisture absorption rate. - Compares BFRP bars' degradation with GFRP bars under similar conditions.	- BFRP bars. SFCB bars.	- Tension test, short-beam test, and moisture absorption weighting. - Accelerated corrosion test for mechanical property degradation analysis.	- BFRP bars maintain over 60% strength after 9 weeks in alkaline solution. - BFRP bars show good resistance to alkaline corrosion compared to GFRP. - Moisture absorption of BFRP bars follows Fick's law degradation mechanism.	- Limited discussion on the impact of environmental factors. - Future studies could explore the long-term durability of BFRP bars.
Wu et al. [106]	- Investigates GFRP bars' durability in alkaline concrete environment for 8 years. - Analyzes tensile strength degradation law and micro deterioration mechanism. - Establishes a tensile strength prediction model for GFRP bars. - Proposes an improved long-term tensile strength prediction model.	- Investigate long-term durability of GFRP bars in alkaline concrete. - Analyze micro deterioration mechanism and establish tensile strength prediction model. - Evaluate 8-year residual tensile strength of GFRP bars according to codes.	- Alkali-free glass fiber (E-glass) and vinyl ester.	- Tensile strength test, SEM scanning, FTIR analysis, and DSC test.	- Tensile strength decreases with exposure time under different conditions. - Pre-cracks are the main reason for GFRP bar strength decrease. - Elastic modulus is not significantly affected by exposure time. - Hydrolysis at the micro-level accelerates GFRP bar corrosion.	- Future research: Explore GFRP bars in FRP-RC beam structures. - Further tests needed on GFRP bars in concrete with precracks. - Investigate influencing factors like temperature, alkalinity, and sustained load.

Xie et al. [107]	- Investigated BFRP bars in seawater-sea sand concrete for shear performance. - Alkalinity affects BFRP degradation, with SSC leading to lower shear strength.	- Investigate long-term shear performance of BFRP bars in different solution environments. - Compare durability of BFRP bars wrapped with SSC and conventional concrete.	- BFRP bars.	- Shear tests on BFRP bars in different solution environments. - FTIR spectroscopy and XRD for chemical composition changes detection.	- Alkalinity controls BFRP performance degradation; SSC wrapping thickness affects degradation. - SSC leads to higher pH, accelerates alkali-silica reaction, degrades BFRP. - Horizontal shear strength degrades faster than transverse shear strength. - SSC wrapping thickness affects FTIR results, correlates with shear strength degradation.	- Future research: Investigate measures to reduce alkalinity in SSC. - Limitation: Effect of SSC wrapping on BFRP shear performance not studied.
Xin et al. [108]	- CRS concrete beams with BFRP bars tested in marine environment. - Study analyzes failure modes, capacities, deflections, and crack development. - BFRP-CRS beams show increased stiffness and reduced crack width after aging. - Formula for shear capacity in CRS concrete beams modified.	- Investigate durability of CRS concrete beams with BFRP bars in seawater. - Analyze failure modes, capacities, deflections, and crack development of beams. - Modify formula for calculating shear capacity in CRS concrete beams.	- BFRP bars.	- Flexural tests on CRS concrete beams aged in wet-dry saline solution. - Monitoring deflection and strain using LVDTs and strain gauges.	- Ultimate load of beams shows no degradation after aging. - BFRP-CRS concrete beams transition from flexure to shear after aging. - Aged BFRP-CRS beams have over 70% increase in initial stiffness. - Crack width decreases significantly in BFRP-CRS beams after aging.	- Future research: Investigate long-term effects of BFRP bars in CRS concrete. - Explore the impact of different aging durations on BFRP-CRS beams. - Study the bond behavior of BFRP bars with CRS concrete.
Yan and Lin [50]	- Study on bond durability of GFRP bars to FRC in saline solutions. - Steel FRC samples showed better bond durability than PVA FRC. - Developed models to predict long-term bond degradation under different conditions.	- Assess bond durability of GFRP bars to FRC in saline solutions. - Predict long-term bond degradation under different environmental conditions.	- GFRP bars for durability assessment.	- Analytical models mBPE and CMR for GFRP bond to FRC. - Prediction methods using Arrhenius law and time shift factor (TSF). - TSF method for bond strength retention under different temperatures.	- Steel FRC samples had better bond durability than PVA FRC. - Predicted bond strength retention over 75 years in different environments.	- Limited exploration of Arrhenius-based methods for GFRP to FRC elements. - Future research needed to verify the applicability of predictive models.
Yan et al. [52]	- GFRP bars as corrosion-free concrete reinforcement with bond strength analysis.	- Review bond mechanism and strength of GFRP bars in concrete. - Analyze factors affecting bond behavior and bond strength. - Investigate bond degradation under environmental conditions like freezing-thawing cycles.	- GFRP bars commonly used.	- Review of bond mechanism and bond strength of GFRP bars. - Analysis of factors affecting bond behavior and bond strength/slip relationship. - Presentation of bond degradation under environmental conditions like freezing-thawing cycles.	- Analyzed bond strength factors and environmental influences on GFRP bars. - Compared bond stress-slip models and their reliability in predicting behavior. - Relationship between bond strength and concrete compressive strength explored.	- Lack of universal analytical models for GFRP bar bond-slip behavior. - Need for further studies on combined environmental effects. - Investigation required on the influence of bar surface profile.
Yang et al. [109]	- Investigated fracture performance of GFRP bars in concrete beams with cracks. - Analyzed changes in microscopic structures using SEM, FTIR, and DSC. - Conducted durability tests to determine permissible crack values for GFRP-RC beams.	- Investigate fracture performance of GFRP bars in concrete beams with cracks. - Analyze changes in microscopic structures using SEM, FTIR, and DSC.	- GFRP bars.	- Scanning electron microscopy, Fourier transform infrared spectroscopy, differential scanning calorimetry. - Interfacial fracture energy analysis under various environmental conditions.	- Cracks worsen environment impact on GFRP-RC beams but don't alter degradation mechanisms. - Interfacial fracture energy decreases in GFRP-RC beams conditioned in alkaline environment. - Glass fiber reaction with alkali degrades mechanical properties of GFRP bars. - GFRP bars with precrack show more residual matrix after failure.	- Future research: Investigate the impact of cracks on GFRP-RC structures. - Limitation: No significant changes observed in hydroxyl peak.
Yi et al. [110]	- Lowering alkalinity in SWSSC mitigates shear strength loss of BFRP bars. - Interlaminar shear strength is more sensitive to alkali attack. - pH reduction from 13.2 to 10.1 eliminates alkalinity-induced degradation. - Developing low-alkalinity SWSSC extends service life of BFRP bars.	- Investigate alkalinity impact on basalt fiber-reinforced polymer bars in concrete. - Focus on shear performance degradation and durability of BFRP bars.	- BFRP bars.	- Thermogravimetric analysis to study weight loss at different pH levels. - Chemical reactions involving residual iron compound in basalt fiber.	- Lowering alkalinity mitigates shear strength loss of BFRP bars. - Interlaminar shear strength is more sensitive to alkali attack. - pH reduction to 10.1 eliminates alkalinity-induced degradation. - Developing low-alkalinity SWSSC extends service life of BFRP bars.	- Limited study on BFRP bars in real SWSSCs. - No mention of specific limitations or future research directions found.
Yi et al. [111]	- Investigates BFRP bar durability in low-alkalinity seawater sea sand concrete. - Reduction in pH enhances tensile strength retention of BFRP bars. - Microstructural analysis shows mitigation of degradation in low-alkalinity environment. - NMR used to examine pore size distribution in conditioned SWSSMs.	- Investigate durability enhancement of BFRP bars in seawater sea sand concrete. - Examine tensile properties of BFRP bars in varying alkalinity environments. - Mitigate BFRP bar deterioration using low-alkalinity SWSSC.	- BFRP bars.	- Arrhenius model for long-term tensile strength prediction. - Scanning electron microscopy, X-ray microcomputed tomography, and NMR. - Vacuum-saturation and NMR relaxometry tests for SWSSMs.	- Reduction in alkalinity enhances BFRP bar tensile strength retention. - Simulated SWSSC pore solution is more aggressive to BFRP bars. - Resin hydrolysis and fiber corrosion are reduced in low-alkalinity SWSSMs. - Silica fume reduces SWSSM alkalinity and increases compactness.	- Future research: Evaluate long-term performance of BFRP bars in SWSSC. - Limitation: Lack of detailed discussion on specific microstructural changes.

Yi et al. [23]	- Investigated reducing SWSSC alkalinity to enhance BFRP bar durability. - Used OPC, SF, and FA to design low-alkalinity ternary mixtures. - Evaluated BFRP bars in low-alkalinity SWSSC through accelerated aging tests. - Findings support durability design of BFRP-SWSSC structures in marine environments.	- Investigated reducing SWSSC alkalinity for BFRP bar compatibility. - Evaluated durability of BFRP bars in low-alkalinity SWSSC columns.	- BFRP bars.	- Simplex centroid design method for low-alkalinity ternary mixtures. - Isothermal calorimeter, SEM, XRD, and thermogravimetric analysis for characterization. - Accelerated aging tests in a simulated marine environment at 55°C. - Isothermal calorimeter for testing heat output during hydration of cement pastes. - SEM-EDS examination for phase analysis of low-alkalinity SWSSC after seawater immersion. - Autogenous shrinkage monitoring through the corrugated tubes method.	- Low-alkalinity SWSSC enhances BFRP bar durability in marine environments. - SF and FA inhibit AFm phases and Friedel's salt formation. - Tensile strength retention of BFRP bars in low-alkalinity SWSSC improves. - Durability design for BFRP-SWSSC structures in marine environments is feasible.	- Future research: Test other low-alkalinity cementitious materials for durability enhancement. - Durability design not included in current building codes for FRP structures.
Yu et al. [46]	- Investigates durability of carbon-glass hybrid FRP bars in water, alkaline solution. - Carbon fiber coat improves HFRP bars' interlaminar shear strength in alkaline solution.	- Investigate durability of carbon-glass hybrid FRP bars in water and alkaline solution. - Compare water absorption behavior and interlaminar shear strength of GFRP and HFRP bars. - Analyze diffusivity coefficient and saturation water absorption of HFRP bars.	- Carbon-glass hybrid FRP bars.	- Characterized water absorption behavior and interlaminar shear strength in different solutions. - Defined boundary conditions for hybrid FRP and discussed diffusion of water. - Plotted water concentration with respect to length at various exposure temperatures.	- Carbon fiber coat improves HFRP bars in alkaline solution. - HFRP bars have higher diffusivity coefficient and water absorption. - Interlaminar shear strength of HFRP bars retained in alkaline solution.	- Investigate effects of varied alkalinity on durability of HFRP bars. - Study the application of bare HFRP bars in water.
Yu et al. [47]	- -Study on GFRP bar strength in basic environments and aging effects. - Proposed predictive equation for GFRP bar long-term interlaminar shear strength. - Research supported by various foundations.	- Study durability of glass fiber-reinforced polymer bars in different solutions. - Predict long-term interlaminar shear strength of GFRP bars accurately. - Compare predicted and field interlaminar shear strength of GFRP bars.	- GFRP bars.	- Studied GFRP bars in alkaline solutions at different temperatures. - Proposed equations for predicting long-term interlaminar shear strength.	- GFRP bars in pH 13.0 solution had highest water absorption. - Interlaminar shear strength reduced significantly in pH 13.0 solution. - Predictive equation proposed for GFRP bar long-term interlaminar shear strength. - Water absorption in normal concrete pore solution was higher than distilled water. - Interlaminar shear strength retention of 0.7 recommended by ACI 440.1R-15.	- Future research: Explore effects of different environmental factors on GFRP bars. - Limitation: Study focused on GFRP bars in specific environmental conditions.
Zeng et al. [14]	- Study on durability of GFRP bars in alkaline solution with loads. - Investigated effects of aging times, stress levels, and resin matrices. - GFRP bars exposed to alkaline solution and elevated temperature.	- Assess durability of GFRP bars in alkaline solution with sustained loads. - Investigate tensile properties of GFRP bars made of different resins. - Examine the influence of aging times, stress levels, and exposure conditions.	- Epoxy, vinyl ester, polyester as FRP types.	- Tensile tests on GFRP bars with different resin matrices. - Exposure to alkaline solution, elevated temperature, and constant load. - Residual tensile properties testing. - Microscopy for internal defects examination.	- Three months of alkaline solution immersion led to significant strength decreases. - Tensile strength of GFRP bars reduced after exposure to alkaline solution. - The strength decreases were attributed to high exposure temperatures.	- Explore effects of temperature on GFRP bars under constant stress. - Investigate protective remedies for GFRP bars in alkaline environments
Zhang and Deng [27]	- Investigated GFRP bars' compressive performance under sustained stress. - Proposed a degradation model for GFRP bars under compressive stress.	- Investigated GFRP bars' axial compressive performance under sustained stress. - Proposed a degradation model for GFRP bars under sustained compressive stress.	- GFRP bars.	- Investigated GFRP bars under sustained compressive stress in marine and concrete environments. - Proposed a degradation model for GFRP bars under sustained compressive stress.	- GFRP bars' compressive strength retention decreased with higher stress levels. - High temperature postcured resin matrix, benefiting compressive performance of GFRP bars. - Exposure to alkaline solution led to lower compressive strength retention. - Failure modes included longitudinal splitting of resin matrix and fiber fracture. - Proposed degradation model for GFRP bars under sustained compressive stress.	- Limited research on compressive performance of FRP bars in marine environments. - Need for prediction models considering sustained compressive stress and temperature.
Zhang et al. [55]	- Predicting tensile strength of glass fiber bars in alkaline environments. - Developed machine learning models for accurate TSR prediction.	- Develop accurate TSR prediction model using machine learning. - Assess sensitivity of input variables for TSR prediction. - Explore optimal training set/test set division ratio. - Expand machine learning application in civil engineering.	- GFRP bars.	- Generalized additive model (GAM) based on generalized linear model. - Machine learning models: GAM, BPNN, ELM, SVR, RF, XGBoost, LSTM.	- XGBoost had the highest generalization performance among the models. - pH and temp were identified as the most significant variables. - 8:2 was found to be the optimal training set/test set division ratio. - Nonlinear prediction of TSR using ML models is feasible.	- Limitations: Incomplete data on influencing factors, indoor test data used. - Future Research: Explore real engineering samples, optimize model parameter selection.

Zhang et al. [112]	- Waste HFRP bars recycled into fiber clusters for concrete reinforcement. - Mechanical recycling enhances concrete properties, energy absorption, and toughness. - Study used FT-IR, SEM, and AE techniques to analyze enhancement mechanisms. - Fiber clusters improve concrete strength, toughness, and deformation under load.	- Investigate recycling waste FRP bars into fiber clusters for concrete. - Study the mechanical properties of concrete with recycled fiber clusters.	- HFRP bars recycled into fiber clusters.	- Mechanical recycling of waste HFRP bars into fiber clusters for concrete. - Compression test, splitting tensile test, and four-point bending test conducted. - FT-IR, SEM, and AE techniques used to analyze enhancement mechanisms.	- Recycled fiber clusters improved concrete's mechanical properties, enhancing energy absorption. - Alkaline environment caused slight damage to the fiber clusters. - Increase in fiber clusters led to more AE event localization points.	- Lack of study on failure process of recycled fiber reinforced concrete.
Zhao et al. [26]	- Investigated durability of BFRP bars in seawater with prestressing effects. - Prestress level at 20% of ultimate tensile strength, seawater at different temperatures. - Prestress losses monitored, tensile tests conducted up to 240 days.	- Investigate durability of BFRP bars in seawater with prestressing effects. - Assess prestress losses and tensile strengths of BFRP bars over time.	- BFRP bars.	- Experimental investigation on durability of BFRP bars in seawater. - X-ray fluorescence spectroscopy for chemical compositions of FA and GGBS. - FTIR and TGA analysis of BFRP bars after 240 days.	- Prestress losses of BFRP bars were less than 40% after 240 days. - Elevated temperatures led to severe degradation of BFRP bars. - Tensile strength retention decreased with increasing immersion temperature.	- Real-time pH monitoring around BFRP bars needs further research. - pH measurement accuracy at room temperature requires improvement.
Zheng et al. [39]	- Study on GFRP bar-concrete bond behavior in aggressive environments. - Investigated bond strength, degradation, and failure modes under different exposures. - Saline solution caused the highest bond strength loss after 270 days.	- Study bond behavior of GFRP bars in aggressive environments. - Evaluate bond strength, degradation, and failure modes in different conditions. - Investigate the influence of resin type and exposure duration on bonding. - Compare bond strength losses in tap water, alkaline, and saline solutions.	- GFRP bars.	- Experimental investigations with 60 pullout specimens under harsh solution environments. - Analysis of bond stress, tensile load, and embedment length. - Comparison of bond strength between GFRP bars and concrete.	- Saline solution caused 51.5% bond strength loss at 270 days. - Vinylester resin showed better durability in aggressive environments than epoxy resin. - Bond strength decreased gradually with exposure period for treated specimens.	- Lack of evaluation of diverse aggressive environments on bond performance.
Zhou et al. [113]	- The study evaluates the durability of GFRP and steel bars in concrete under various environmental conditions. - It focuses on comparing bond strength as a critical performance measure for long-term durability. - GFRP bars are explored as an alternative to steel, primarily to address corrosion issues in aggressive environments.	- The objective is to assess the bond strength retention of GFRP and steel bars in concrete after exposure to different environments. - The study aims to simulate real-life environmental conditions, including moisture, acidity, and alkalinity. - It examines the long-term viability of GFRP as a replacement for steel reinforcement in concrete.	- GFRP	- The bond strength was measured through pullout tests on 90 concrete specimens. - Specimens were exposed to five environmental conditions, including tap water, alkaline, salt, and acidic solutions. - The pullout test configuration simulated real-life structural applications of embedded reinforcing bars in concrete.	- Bond strength generally improved or remained stable in tap water, alkaline, and salt environments. - A reduction in bond strength was observed in the acidic environment, with GFRP showing up to a 20.4% loss. - GFRP and steel bars showed similar performance under alkaline conditions, with slight bond strength increases over time.	- Limited experimental data on bond effects due to different environmental conditions. - Need for establishing standard accelerated methods to assess bond behavior. - Study required on special conditions affecting polymer behavior in concrete.
Zhou et al. [29]	- Investigated durability of GFRP bars in UHP-ECCs under sustained loads. - GFRP bars with UHP-ECC covers showed less degradation. - Degradation of GFRP bars attributed to matrix hydrolysis.	- Investigated durability of GFRP bars in UHP-ECCs under sustained loads. - Explored degradation of GFRP bars with different matrix resins. - Studied the impact of alkaline solutions on GFRP bars' tensile properties. - Analyzed SEM and CT results to understand GFRP bars' degradation.	- GFRP bars (epoxy-based, vinyl ester-based, polyester-based).	- Accelerated aging tests at 40 degrees Celsius. - Immersion in alkaline solutions at elevated temperatures with sustained loads. - Evaluation of tensile properties after exposure.	- Polyester-based GFRP bars degraded more than vinyl ester and epoxy bars. - GFRP bars with UHP-ECC covers showed less degradation. - Matrix hydrolysis led to stress transfer reduction in GFRP bars.	- Future research: Explore the impact of sustained loads on GFRP bars. - Investigate alternative matrix resins for GFRP bars in UHP-ECCs.