International Journal of Trend in Scientific Research and Development (IJTSRD)
Volume 10 Issue 4, Jul-Aug 2026 Available Online: www.ijtsrd.com e-ISSN: 2456 – 6470

Durability Assessment of Corrosion-Resistant Reinforcement Materials in Marine Structures

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ABSTRACT

Marine reinforced concrete structures are continuously exposed to aggressive environmental conditions such as chloride ingress, seawater immersion, wetting–drying cycles, and high humidity, which accelerate the deterioration of conventional steel reinforcement through corrosion. This study investigates the durability performance of Glass Fiber Reinforced Polymer (GFRP)-reinforced M40 concrete as a corrosion-resistant alternative for sustainable marine infrastructure. An experimental program was conducted using GFRP-reinforced concrete specimens subjected to accelerated marine exposure in a 3.5% sodium chloride (NaCl) solution with cyclic wetting and drying for 0, 3, 6, 9, and 12 months. The results revealed that after 12 months of exposure, compressive strength retained 93.7%, bond strength retained 89.2%, split tensile strength retained 92.6%, and flexural strength retained 92.8% of their original values. RCPT values increased slightly from 620 to 782 Coulombs but remained within the "Very Low" chloride permeability category. Water absorption increased from 2.34% to 2.93%, while carbonation depth remained limited at 2.4 mm. SEM observations showed only minor pore development, EDS confirmed the absence of iron corrosion products, and XRD demonstrated mineralogical changes without compromising structural integrity.

How to cite this paper: Sunil Kumar | Er. Rajbala "Durability Assessment of Corrosion-Resistant Reinforcement Materials in Marine Structures" Published in International Journal of Trend in Scientific Research and Development (ijtsrd), ISSN: 2456-6470, Volume-10 | Issue-4, August 2026, pp.980-990, URL: www.ijtsrd.com/papers/ijtsrd141953.pdf

IJTSRD141953

KEYWORDS: *Glass Fiber Reinforced Polymer (GFRP), Marine Structures, Corrosion Resistance, Reinforced Concrete.*

1. INTRODUCTION

The marine structures like offshore platforms, coastal bridges, ports, harbors, jetties, seawalls, breakwaters, and marine terminals are constantly subjected to harsh environmental conditions which have a profound effect on the long-term structural performance of the structures [1]. The deterioration of reinforced concrete structures is promoted by the combined effect of chloride ions, seawater immersion, wetting-drying cycles, tidal movements, high humidity, sulfate attack, and thermal changes [2]. Corrosion of the conventional steel reinforcement is among the most commonly observed processes that cause structural deterioration and is one of the main causes of cracking, concrete spalling, loss of bond between reinforcement and concrete, loss of load bearing capacity and higher maintenance costs [3]. Offshore renewable energy, coastal urbanisation and increased maritime transportation activities have increased the investment in coastal structures worldwide, thereby making the need for long-lasting and corrosion resistant construction materials more significant [4].

Traditional reinforced concrete structures use mostly carbon steel reinforcement due to its high tensile strength, ductility and cost-effectiveness. In marine applications however, chloride ions easily migrate into concrete by diffusing through the pores, by capillary absorption and by migrating through microcracks, which reach the embedded steel reinforcement [5]. Electrochemical corrosion takes place when the chloride concentration is higher than what is needed to break down the passive oxide layer on the steel [6]. The products of corrosion will occupy a much greater volume than the volume of the original steel, causing expansive stresses that will begin to cause cracks and delamination of the concrete cover. This degradation process reduces the safety of the structure and significantly increases repair, rehabilitation and life cycle costs, but also significantly decreases the service life [7]. This makes corrosion damage a significant problem for infrastructure owners and engineers around the world.

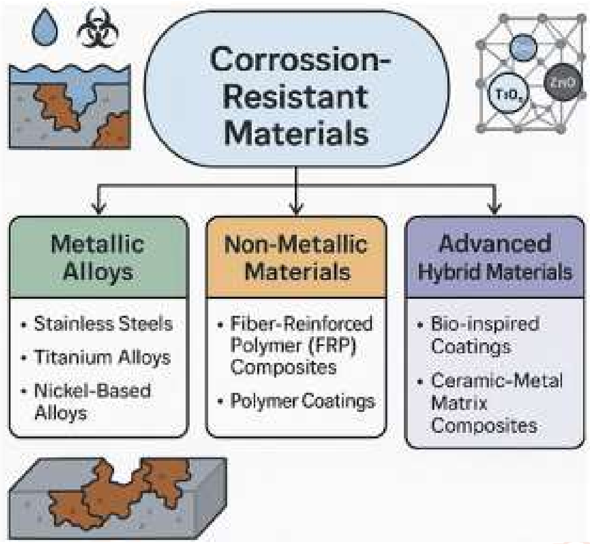


Figure 1: Classification of Corrosion-Resistant Materials for Marine Structures [8]

In order to address these drawbacks, much attention has been given to the production and use of corrosion resistant reinforcement materials that offer better durability under corrosive marine exposure [9-11]. The use of FRP reinforcement such as Glass Fiber Reinforced Polymer (GFRP) has become an alternative to the traditional steel reinforcement [12]. These materials offer good resistance to chloride induced corrosion, high tensile strength, low density, are electro-magnetic neutral and have reduced maintenance [13]. Likewise, stainless steel reinforcement and epoxy coated steel bars have been proven to be corrosion resistant than the traditional carbon steel and are suitable for critical marine structures where it is required to have a long service life [14].

Hence, this study aims at the Durability Assessment of Corrosion-Resistant Reinforcement Materials in Marine Structures by systematically studying new reinforcement materials under simulated marine conditions. Here are the research objectives of the study follows as:

- To develop and prepare GFRP-reinforced M40 concrete specimens using a durable concrete mix suitable for aggressive marine environments.
- To evaluate the effect of accelerated marine exposure (3.5% NaCl solution with wetting–drying cycles) on the mechanical properties of GFRP-reinforced concrete through compressive, bond, split tensile, and flexural strength tests.
- To investigate the durability performance of GFRP-reinforced concrete by measuring chloride permeability, chloride diffusion coefficient, surface resistivity, water absorption, sorptivity, water penetration depth, and carbonation depth after different exposure durations.
- To characterize the microstructural changes in GFRP-reinforced concrete under marine exposure using Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS), and X-ray Diffraction (XRD).

2. Related Work

The durability of FRP (fiber-reinforced polymer) reinforcement has been studied by a few researchers for marine use. Kappenthuler et al. (2021) [15] evaluated sixteen FRP composites, using a variety of polymer resins and glass, carbon, basalt, and natural fibers, and found that carbon- and basalt-based composites had the highest durability and sustainability, while natural fiber composites had similar environmental benefits with lower mechanical strength. Emparanza et al., 2022 [16] tested six rebar types from GFRP under accelerated seawater exposure for 365 days at 23–60 °C and found that the most significant property to be affected by the exposure was tensile strength. Predictions based on the Arrhenius model showed that even GFRP bars that met ASTM D7957 would lose about 85% of their tensile strength after long-term exposure. Wang et al. (2024) [17] also found that alkaline environment led to enhanced degradation compared to seawater caused by resin hydrolysis, fiber–matrix debonding and crack generation while seawater alone showed minimal effects on degradation. Likewise, Hosseini et al. [18] studied the compressive ability of GFRP bars in seawater and alkaline solution for up to 3000 h at 20–60 °C. Seawater and alkaline solutions showed a retention of 0.81-0.87 and 0.73-0.86, respectively, of the compressive strength after 100 years, and the severity of alkaline environments was confirmed.

Another area of research has been on the durability of concrete materials used in marine infrastructure. Feng et al. (2025) [19] used a modified chloride diffusion model and reliability analysis to analyze marine concrete structures, which determined the tidal and splash zones as the most corrosive areas. When one combined these two techniques with the corrosion-resistant steel, corrosion initiation was pushed to over 120 years and the required 100-year service life was met. Sobhan et al. (2022) [20] studied the properties of PFC by incorporating polyolefin fiber with fly ash geopolymer concrete and concluded that the addition of 0.1 to 0.5 percent of PFC reduced the amount of cracking due to corrosion by 24 percent and also increased the residual flexural capacity of the fly ash geopolymer concrete by 109 percent. Similarly, Zhang et al. 2024 [21] found that basalt fiber-reinforced geopolymer concrete had just 10.1% reduction in compressive strength after marine dry–wet cycles, and 5.6% reduction after immersion exposure, as opposed to 15.5% and 10.1% reductions in compressive strength, respectively, for plain geopolymer concrete. The results show that the combination of advanced FRP reinforcement, fiber-reinforced geopolymer concrete and ECP methods significantly improves the durability and service life of marine structures.

3. Methods and Materials

3.1. Material Used

➢ **Ordinary Portland Cement (OPC 53 Grade)**

OPC 53 grades are chosen as a main binder because of its high early strength, very good mechanical properties and its broad usage in the products of structural concrete. It meets the requirements of IS 12269 and the compressive strength requirements for M40 grade concrete.

➢ **Silica Fume (SF)**

Incorporation of SF as a supplementary cementitious material around 8% of the cement content to increase the durability of marine concrete. It is made of very fine amorphous SiO_2 particles which react with the calcium hydroxide generated during cement hydration, to produce further C-S-H gel. This pozzolanic reaction has a great refining effect on the pore structure, lowers permeability and minimizes chloride ion penetration.

➢ **Fine Aggregate (River Sand)**

Fine aggregate (FA) is taken as a natural river sand which meets the requirements of "Zone II as per IS 383". The sand has clean, hard and durable particles and low content of silt and organic impurities, which enable high quality and workability of the concrete. A good particle size distribution can help to achieve a high packing density, which minimizes the number of voids in the concrete matrix.

➢ **Coarse Aggregate (CA) (Crushed Granite)**

Crushed granite aggregate of nominal maximum size 20 mm is chosen because of its high strength, hardness and resistance to abrasion. Granite is low absorbing, has good durability and can be used to make marine concrete with cyclic wetting and drying. Aggregate meets IS 383 requirement and helps to achieve dimensional stability, minimization of shrinkage and cracks.

➢ **Glass Fiber Reinforced Polymer (GFRP) Bars**

GFRP bars consist of high strength glass fibres in a thermosetting polymer matrix. They have high corrosion resistance, chemical resistance and electromagnetic interference resistance, and can be used in marine structures where the steel reinforcement is prone to rapid corrosion.

Figure 2:Material Used

3.2. Concrete Mix Design and Specimen Preparation

This stage entails the design of a durable M40 grade concrete and the production of GFRP reinforced concrete specimens for assessing the long-term durability of GFRP in aggressive marine environment. The performance of GFRP reinforcement in chloride-rich environment is the main focus of this research; therefore, all reinforced specimens are made using only GFRP bars. The concrete mix is formulated to give high "compressive strength, low permeability and excellent resistance to chloride penetration", thus helping to minimize the deterioration of the concrete and to focus the study on the performance, durability and structural behaviour of the GFRP reinforcement.

Proporting of concrete for "M40 Grade Concrete" has been done as per IS 10262:2019 and IS 456:2000. The main cementitious material used is OPC 53 Grade with its high early strength and consistent performance. The addition of silica fume contributes about 8% of the cement content, with the purpose of increasing the density of the cement matrix created, which is obtained by decreasing the permeability of the matrix and the number of pores that are connected. FA is river sand of zone II and the CA is crushed granite of nominal maximum size of 20mm. The use of a polycarboxylate ether (PCE) based superplasticizer ensures that adequate workability is obtained without increasing the amount of water used, keeping the water-to-binder ratio at 0.38. Concrete mixing and curing are done with potable water that is free from harmful impurities.

All materials are accurately weighed and checked for compliance with relevant standards before mixing. Cement and silica fume are first mixed dry to achieve uniformity of dispersion. The fine and coarse aggregates are placed in a pan mixer and then the blended binder materials are added. About 70% of the water required for the mix is delivered at start and the remaining water containing the dissolved superplasticizer is pumped in as a graded addition to achieve a “homogeneous and workable concrete mix”. The mixing is continued until a uniform consistency is obtained, which will take about 5-7 minutes. Before casting, the properties of fresh concrete (slump, fresh density, and air content) are measured to verify that the concrete would meet the performance requirement.

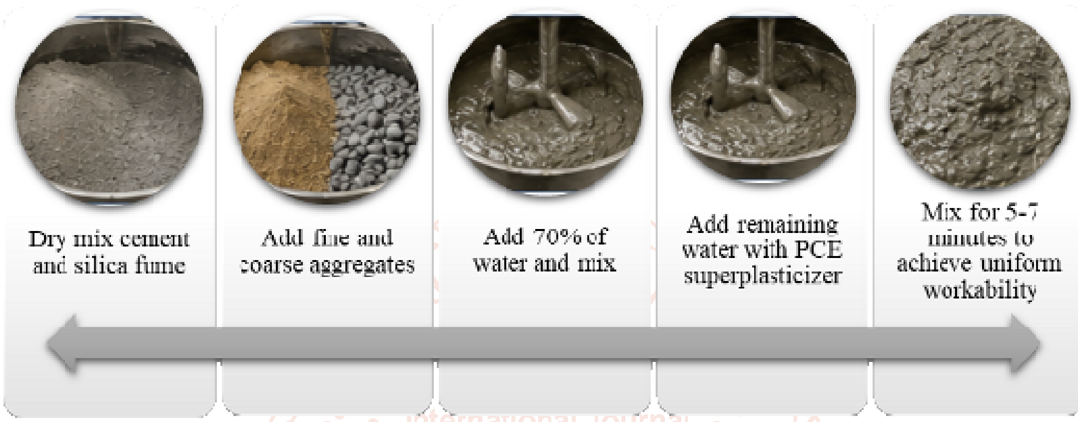


Figure 3: Mixing process

After demoulding, all the specimens are taken to the curing tank filled with potable water and cured for 28 days at 27 ± 2°C. Completeness of hydration of the cementitious matrix obtained by water curing leads to high compressive strength, lack of permeability, and durability. Once cured, the specimens are taken out of the curing tank, surface dried for 24 hours in a laboratory environment and then subjected to accelerated marine exposure and durability testing.

The various geometries of specimens are created to assess the mechanical, durability, and structural behavior of GFRP-reinforced concrete under simulated marine environments. The compressive strength is measured using cubes, the split tensile strength and modulus of elasticity is measured using a cylinder, flexural strength is measured using prisms, structural behavior and crack propagation is measured using reinforced beams, and long-term chloride exposure and durability is measured using reinforced slab panels.

1. Prepare moulds and place GFRP reinforcement (Cover:40mm)

2. Cast concrete in layers

3. Compact using vibrator for proper consolidation

4. Finish the surface and cover

5. Keep for 24 hours (Initial setting period)

6. Demould and cure in water for 28 days (27 ± 2°C)

Figure 4: Specimen preparation

The mechanical properties of the baseline specimens are then measured after curing prior to the accelerated marine exposures. The initial measurements serve as reference values for assessing changes in strength, stiffness, crack formation, bond properties, chloride penetration and overall durability during the exposure duration. The same mix proportions, curing conditions, specimen size and testing procedures allow the observed performance to be attributed to behavior of GFRP reinforcement in marine environments. This systematic experimental method allows for a detailed evaluation of the performance of GFRP-reinforced concrete, and to design long-lasting and corrosion-free structural solutions for sustainable coastal and offshore structures.

3.3. Accelerated Marine Exposure and Corrosion Monitoring

This phase tests the durability of GFRP-reinforced concrete structures in simulated marine environmental conditions for the long term. The factors of interest in the investigation are the durability of the concrete matrix, the stability of the GFRP bars, the bond interface between the concrete and GFRP, and the overall performance of the structure in chloride rich environment. Accelerated exposure techniques are used to simulate the years of natural marine exposure in a shorter testing time in the laboratory.

All specimens are cleaned, surface dried and the first mechanical strength properties, such as “compressive strength, flexural strength, and bond strength” are obtained after 28 days of water curing. The specimens are then placed in an artificial seawater solution with a salinity of 3.5% sodium chloride (NaCl), which is the average salinity of a marine environment. To emulate the tidal actions, the specimens experience repeated wetting and drying processes of 12 hours in 12 hours in the chloride solution with 12 hours drying in 40 ± 2°C. These cyclic conditions will exacerbate chloride penetration, water migration and deterioration of the concrete. Exposure duration for the exposure program is carried out for 3, 6, 9 and 12 months to assess progressive deterioration of GFRP-reinforced concrete.

Figure 5: Exposure setup

For each exposure interval, samples are taken for durability testing. Monitoring of the quality and integrity of the concrete is done using the following parameters: chloride penetration depth, water absorption, sorptivity, surface electrical resistivity and the Ultrasonic Pulse Velocity (UPV) since the GFRP bars are not subjected to electrochemical corrosion. The bond strength of the concrete to the GFRP reinforcement is determined by pull-out tests and the width of the cracks and surface deterioration is inspected by a digital crack microscope. The weight change of specimens is also measured to measure the amount of moisture uptake and material degradation. “Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS), and X-ray Diffraction (XRD)” are used to investigate the chloride penetration, presence of hydration products, fiber–matrix interaction, and potential degradation of the polymer resin. The experimental results gathered are used to establish the effect of extended marine exposure on the durability and structural behavior of GFRP-reinforced concrete and for reliable input to service-life prediction and development of durable design recommendations for sustainable marine infrastructure.

4. Result and Discussion

4.1. Mechanical Test Results of GFRP-Reinforced M40 Concrete after Accelerated Marine Exposure

The compressive strength and bond strength test results show that the GFRP-reinforced M40 concrete exhibited excellent mechanical properties for 12 months of marine accelerated exposure. The compressive strength ranged from 50.8 MPa at 0 months to 47.6 MPa at 12 months, which means that 93.7% of their strength has been maintained. Likewise, the bond strength was decreased from 15.8 MPa to 14.1 MPa, which is 89.2% of the original strength. Slight reduction is believed to be due to chloride ingress, moisture diffusion and some degradation of the interfacial transition zone between the concrete and the GFRP, rather than due to corrosion of the reinforcement. In the absence of the steel corrosion, the structural integrity was retained, indicating that the GFRP reinforcement can maintain the load carrying capacity and bond performance under long-term exposure to marine environment.

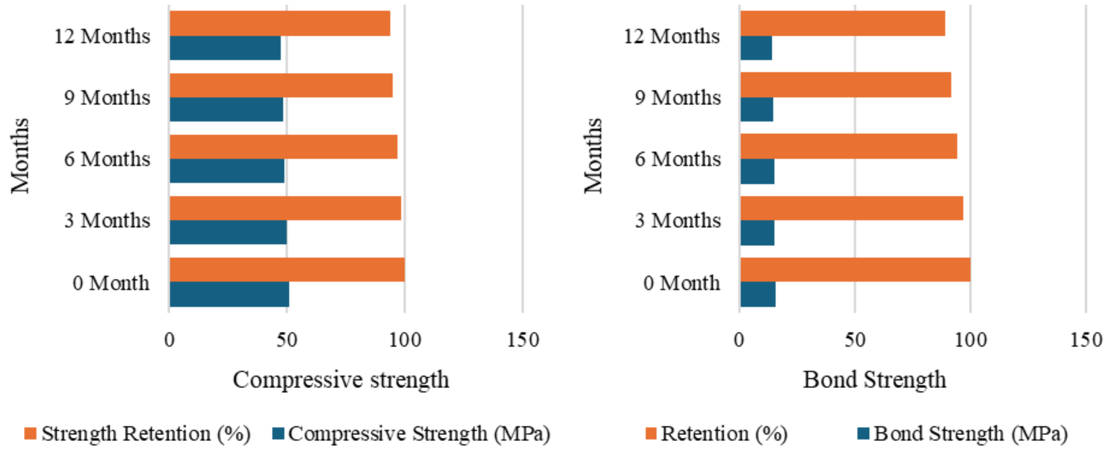


Figure 6: Graph of Compressive and bond strength

The split tensile and flexural strength results show that the concrete with GFRP reinforcement was still highly resistant to tensile and bending stresses after being exposed to continuous marine environment. The split tensile strength dropped slowly from 4.62MPa to 4.28MPa, which corresponds to 92.6% of the original value after 12 months. Similarly, the flexural strength was decreased from 6.28 MPa to 5.83 MPa, which is 92.8% of its initial value. The slight reduction is associated with gradual chloride penetration, moisture movement, and limited microstructural deterioration within the cement matrix. A lack of reinforcement corrosion, however, resulted in no significant cracking or bond failure. The results validated the structural stiffness and crack resistance of GFRP reinforcement, which is a stable option to replace the traditional steel reinforcement in long-term marine infrastructure applications.

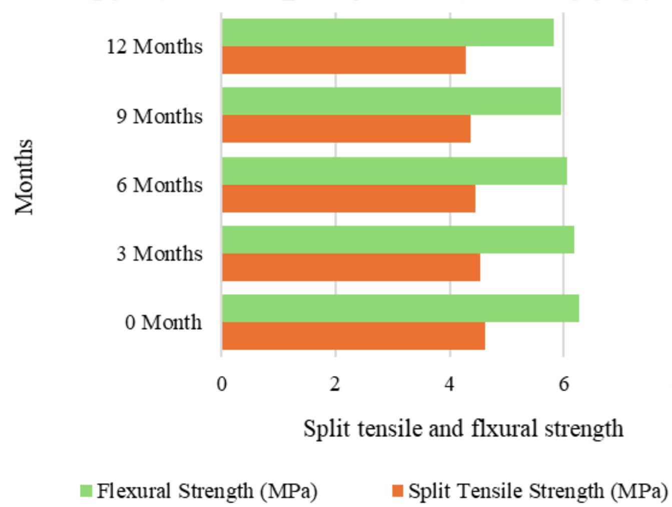


Figure 7: Graph of STS and FS

4.2. Durability Test Results of GFRP-Reinforced M40 Concrete under Accelerated Marine Exposure

The Rapid Chloride Permeability Test (RCPT) values show that the concrete has an excellent "resistance to chloride ion penetration" during the test. The charge passed has been elevated due to small moisture ingress and pore connectivity growth after 12 months from 620 Coulombs to 782 Coulombs. All specimens, however, stayed in the "Very Low" chloride permeability category as set forth by ASTM standards, even with this rise. However, the low charge values indicate that the dense concrete matrix, which includes silica fume, was sufficient to control chloride movement even in the case of cyclic marine exposure. This slow rise is due to normal ageing and should not be interpreted as a serious deterioration. The results obtained in this study have been found to be in agreement with the designed M40 concrete, which demonstrates its durability in protecting GFRP reinforcement and improves the long-term durability of marine reinforced concrete structures.

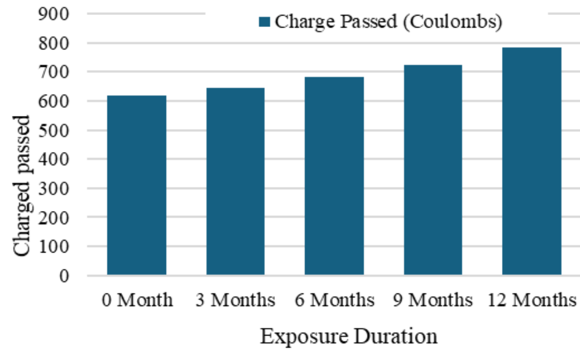


Figure 8: Graph of RCPT results

Chloride diffusion coefficient and surface resistivity results show that the durability of concrete decreased gradually during marine exposure. The diffusion coefficient was calculated to be 4.18×10^{-12} m²/s at 0 months and 5.11×10^{-12} m²/s at 12 months, showing a slight increase in the transport of chlorides through the concrete matrix. At the same time, the electrical resistivity went down from 34.8 kΩ·cm to 29.2 kΩ·cm, indicating that the moisture content and ionic conductivity in the concrete pores increased. These changes, however, did not make the resistivity drop below adequate levels, which would suggest a dense and durable concrete matrix. The overall outcomes show that the silica fume was able to effectively reduce the chloride ingress and GFRP reinforcement prevented any corrosion related issues, thus providing good durability in the presence of aggressive marine conditions.

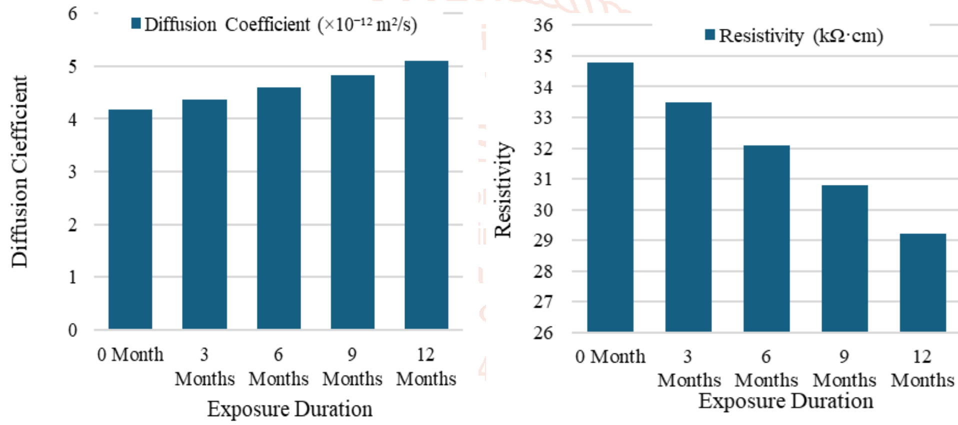


Figure 9: Graph of Chloride diffusion coefficient and Resistivity results

The water absorption and sorptivity results showed that the moisture transport increased gradually with increasing exposure time. The water absorption increased from 2.34% at 0 months to 2.93% after 12 months and the sorptivity increased from 0.078 mm/√min to 0.099 mm/√min. The increments are due to progressive chloride intrusion, small-scale pore formation and moisture migration due to repeated wetting–drying cycles. However, the values were still relatively low, due to the silica fume that refined pore structure and decreased the capillary connectivity. The high cement pastes content effectively restricted water penetration, and thus discouraged significant degradation. The results obtained agree that the GFRP-reinforced concrete has a strong resistance to moisture-induced degradation and is therefore very well suited for long-term use in marine structures.

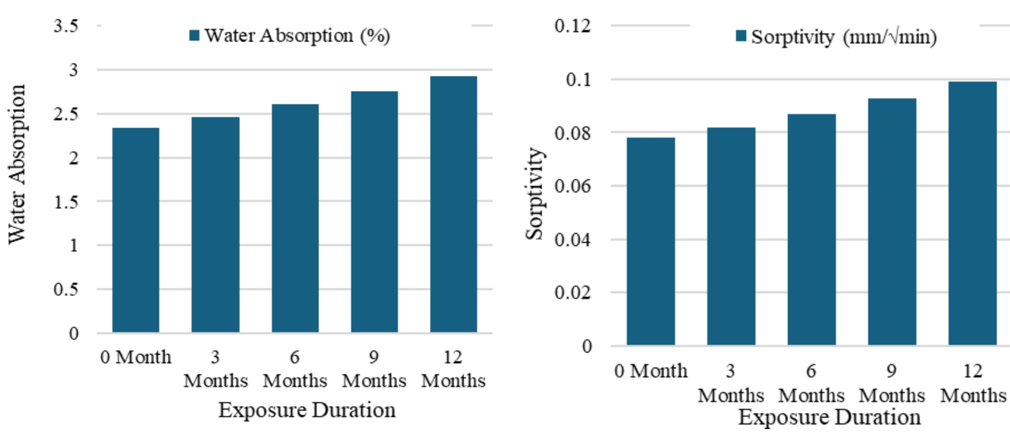
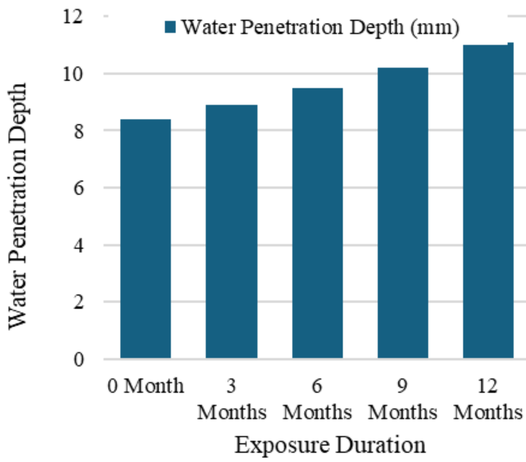


Figure 10: Graph of Water absorption and Sorptivity results

The results of water penetration depth and carbonation depth illustrate that environmental deterioration is progressive, but the overall durability of the concrete is not affected. The depth of water penetration increased from 8.4 mm at 0 months to 11.1 mm after 12 months and the depth of carbonation increased from 0.7 mm to 2.4 mm over the same period. The changes are the result of long-term wetting/drying cycles as well as exposure to marine conditions with high chloride content. However, both parameters remained relatively low because the silica-fume-modified concrete produced a dense microstructure that effectively restricted moisture and carbon dioxide ingress. The limited carbonation depth also suggests that there is concrete alkalinity around the GFRP reinforcement preserved. The overall results indicate that the system developed for marine concrete has very good durability and protection properties.



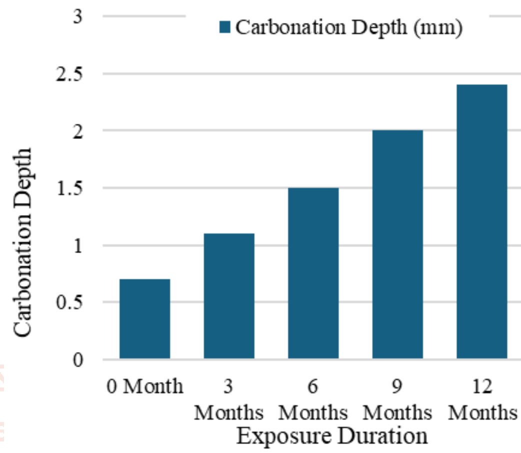


Figure 11: Graph of Water penetration depth and carbonation depth results

4.3. Microstructural Characterization Results of GFRP-Reinforced M40 Concrete

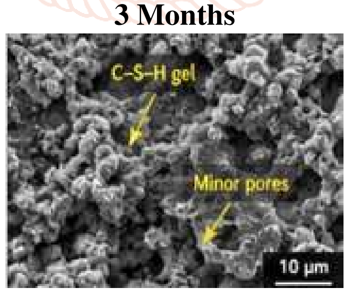
➢ **Scanning Electron Microscopy (SEM)**

The SEM images show the evolution of the microstructural changes in the GFRP reinforced concrete samples under marine conditions for 12 months. The C–S–H gel matrix is dense and compact, and the porosity of the control specimen is very low at 0 months, demonstrating good structure and hydration. The matrix is still compact after 3 months, indicating that there is limited degradation. After 6 months, slight microcracks and moisture entry causing localized pore development are observed, caused by chloride ingress and moisture entry. At 9 months, chloride deposits are seen and moderate degradation of the IZT is occurring with an increase in pore formation. After 12 months, more clearly defined microcracks and salt deposits are formed; the matrix, however, is still relatively dense, and the GFRP reinforcement is seen to be more durable and corrosion resistant than the other materials when exposed to the marine environment over a prolonged period.

0 Months (Control)

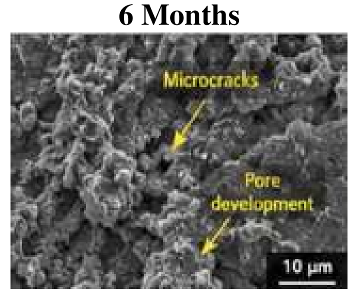
Dense C-S-H matrix, very few pores

3 Months



Compact matrix, minor pores

6 Months

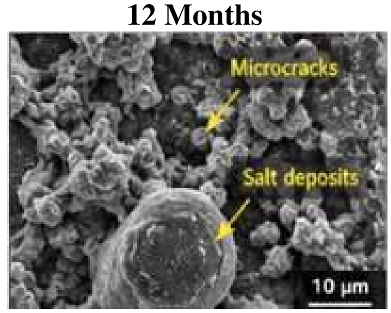


Slight microcracking, small pore

9 Months

Chloride deposits, moderate pore development

12 Months



Increased microcracks, salt deposits, still dense matrix

Figure 12: Scanning Electron Microscopy (SEM)

➢ Energy Dispersive Spectroscopy (EDS)

The elemental composition of the GFRP-reinforced M40 concrete after accelerated marine exposure was determined using EDS analysis. The oxygen (O) content was 47.3 wt.%, the calcium (Ca) content was 28.6 wt.%, the silicon (Si) content was 13.5 wt.%, the aluminium (Al) content was 3.2 wt.%, the magnesium (Mg) content was 1.9 wt.%, and the chlorine (Cl) content was 0.18 wt.%, which means that the cement matrix was dense and well-hydrated at 0 months.

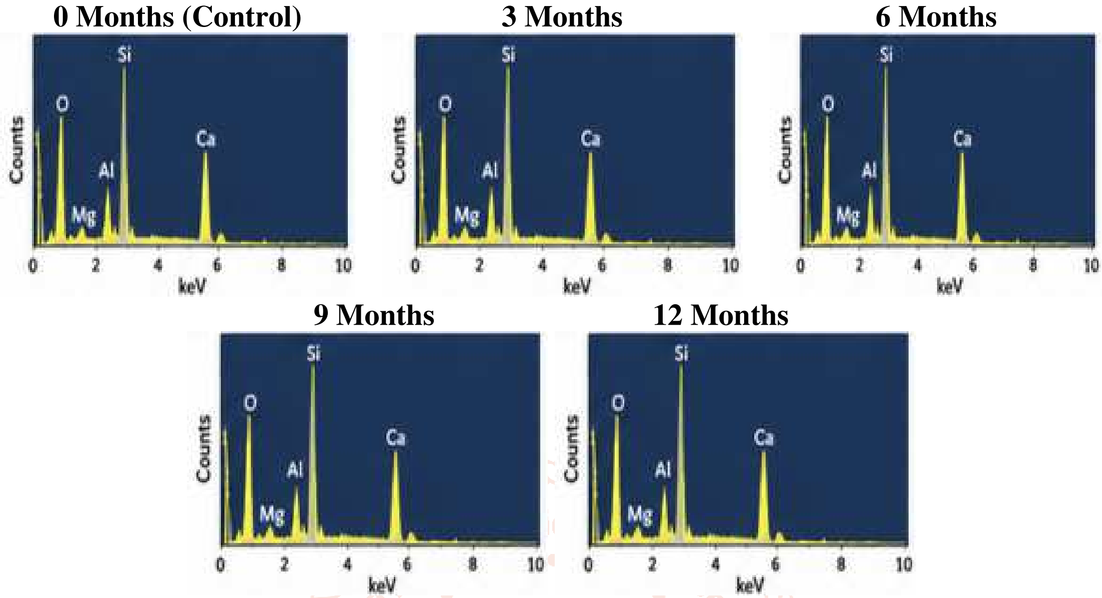
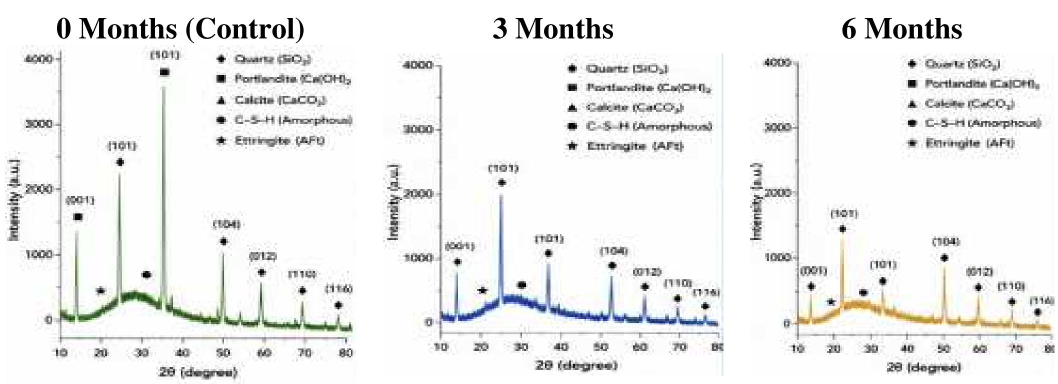


Figure 13: Energy Dispersive Spectroscopy (EDS)

The chloride content gradually rose to 0.46, 0.74, 0.96 and 1.12 wt.%, respectively, after 3, 6, 9 and 12 months due to marine conditions, and the calcium content decreased slightly from 28.6 to 27.9 wt.%, as a result of ongoing hydration and carbonation. The amount of oxygen decreased slightly from 47.3 to 45.8 wt.%, while the amount of silicon was almost constant (13.5–13.9 wt.%) indicating the stability of silica-rich hydration products. Importantly, no iron (Fe) was detected throughout the exposure period, signifying that there was no corrosion products detected and confirmed that the corrosion performance of the GFRP reinforcement in the aggressive marine environment was satisfactory.

➢ X-ray Diffraction (XRD)

The mineralogical changes of M40 GFRP reinforced concrete under accelerated marine exposure were identified using XRD analysis. The Portlandite ($Ca(OH)_2$) peak intensity at 0 months was 100a.u. whilst that of Calcite ($CaCO_3$) and the C–S–H amorphous hump was 100a.u., which represents well-hydrated concrete matrix. In 3 months, the Portlandite intensity went down to 78a.u. while Calcite's went up to 165a.u. After 6 months, Portlandite was further reduced to 52a.u., and Calcite was elevated to 245a.u. At 9 months, more substantial changes were seen with Portlandite dropping to 22a.u. and the Calcite rise to 380a.u. At the end of 12 months, the peak of the Portlandite was only 10a.u. The Calcite peak increased to 520a.u., while the other peak went down by ~90%. (approximately 5.2-fold increase).



9 Months **12 Months**

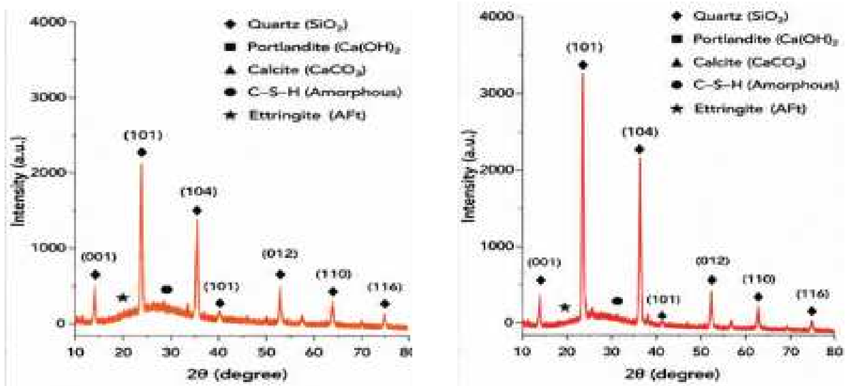


Figure 14: X-ray Diffraction (XRD)

In the exposure period, amorphous hump of C–S–H decreased from 100 to 22a.u. as the exposure time increased, showing that the aggregate had stabilized, while the peak of Quartz (SiO_2) did not change. No diffraction peak for any iron oxides or corrosion products were detected, which indicates a high corrosion resistance and long durability of GFRP-reinforced concrete for an aggressive marine environment.

5. Conclusion

The main objective of this study was to assess the durability of the GFRP-reinforced M40 concrete for marine environment conditions and its durability performance in comparison to the M40 concrete reinforced with steel, under simulated marine exposure conditions and to find out if the GFRP reinforcement is a suitable material for the long-term marine infrastructure. A comprehensive experimental methodology has been employed which includes material selection, M40 concrete mix design with the incorporation of silica fume, preparation of GFRP-reinforced specimens, 28-day water curing and accelerated exposure testing using alternating wetting and drying cycles in 3.5% NaCl solution for 3, 6, 9 and 12 months. Based on the experimental results, it was found that the GFRP-reinforced concrete exhibited good structural performance over the exposure period. The compressive strength went down by only 3.2 MPa to 47.6 MPa (93.7%) and the bond strength went down by only 1.7 MPa to 14.1 MPa (89.2%). The split tensile strength and flexural strength were reduced by less than 42 MP and 62 MP respectively, and were still over 92% of the original values. The RCPT values increased slightly from 620 Coulombs to 782 Coulombs; chloride permeability still stayed in the Very Low category. The values of the chloride diffusion coefficient rose slightly from 4.18×10^{-12} to $5.11 \times 10^{-1}2$ m^2/s.

References

[1] Dauji, Saha. "Reinforcement corrosion in coastal and marine concrete: A review." *Challenge Journal of Concrete Research Letters* 9, no. 2 (2018): 62-70.

[2] Sarode, Deepika, Upendrra Saharkar, Hemanshu Hari Ahire, Milind Manikrao Darade, Sukhadip Mhankali Chougule, Sagar Arjun Dalvi, and Anant Sidhappa Kurhade. "Corrosion-resistant materials for ocean structures: innovations, mechanisms, and applications." *Sustainable Marine Structures* (2025): 63-87.

[3] Okuma, Silas Oseme, Martins Obaseki, Dickson Okiemute Ofuyekpone, and Odili Endurance Ashibudike. "A review assessment of fiber-reinforced polymers for maritime applications." *Journal of Advanced Industrial Technology and Application* 4, no. 1 (2023): 17-28.

[4] Anna, Ananeva A., and Valentin Romanovski. "Corrosion and Degradation of Materials in Marine Environments: Implications for Coastal and Offshore Infrastructure." *Engineering Reports* 8, no. 7 (2026): e70922.

[5] Hassan, Abual, Krzysztof Woloszyk, and Przemyslaw Krata. "FRP-based reinforcement coatings of steel with application prospects in ships and offshore structures: a review." *Ships and Offshore Structures* 20, no. 5 (2025): 740-754.

[6] Moser, Robert, R. Brett Holland, Lawrence Kahn, Preet Singh, and Kimberly Kurtis. "Durability of Precast Prestressed Concrete Piles in Marine Environment: Reinforcement Corrosion and Mitigation–Part 1." (2011).

[7] Liu, Ming, Xuequn Cheng, Xiaogang Li, Jiezhen Hu, Yue Pan, and Zhu Jin. "Indoor accelerated corrosion test and marine field test of corrosion-resistant low-alloy steel rebars." *Case Studies in Construction Materials* 5 (2016): 87-99.

[8] Wijewickrama, Lahiru, Janitha Jeewantha, G. Indika P. Perera, Omar Alajarmeh, and Jayantha Epaarachchi. "Fiber-Reinforced composites used in the manufacture of marine decks: A review." *Polymers* 17, no. 17 (2025): 2345.

[9] Younis, Adel, and Usama Ebead. "Long-term cost performance of corrosion-resistant reinforcements in structural concrete." In *Proceedings of the International Conference on Civil Infrastructure and Construction (CIC)*, pp. 801-805. 2020.

[10] Bao, Huiming, Hanqing Meng, Wei You, and Feng Qin. "Study on the corrosion resistance of sisal fiber concrete in marine environment: H. Bao et al." *SN Applied Sciences* 1, no. 12 (2019): 1558.

[11] Xia, Ruilin, Chen Jia, and Yordan Garbatov. "Deterioration of marine offshore structures and subsea installations subjected to severely corrosive environment: A review." *Materials and Corrosion* 76, no. 6 (2025): 758-775.

[12] Ren, Chi, Sheng Li, Yirui Zhang, Xing Wei, Yang Wei, and Guofen Li. "Durability of seawater and sea sand concrete (SSC)-filled BFRP-steel composite tube columns in simulated marine environment." *Engineering Structures* 343 (2025): 121010.

[13] Elewa, Remilekun R., Imhade P. Okokpujie, Stella I. Monye, Aderonke O. Akinwumi, and Adewumi Toluwalase Boluwatife. "A Review on the Effect of Environmental Factors on the Long Term Stability of Corrosion-Resistant Coating." *NIPES JSTR SPECIAL ISSUE-PREPRINT PLATFORM* 7, no. 2 (2025): 4168-4174.

[14] Naveen Kumar, V., J. Daniel Ronald Joseph, M. Ashok, and M. P. Suresh Kumar. "An experimental study on assessing the corrosion performance of steel reinforcement for the durability of concrete." In *IOP Conference Series: Materials Science and Engineering*, vol. 989, no. 1, p. 012025. IOP Publishing, 2020.

[15] Emparanza, Alvaro Ruiz, Raphael Kampmann, Francisco De Caso, Carlos Morales, and Antonio Nanni. "Durability assessment of GFRP rebars in marine environments." Construction and Building Materials 329 (2022): 127028.

[16] Feng, Taotao, Hongfa Yu, and Yongshan Tan. "Strategy for enhancing the durability of marine concrete structures in northeast China." Case Studies in Construction Materials 22 (2025): e04788.

[17] Kappenthuler, Steve, and Stefan Seeger. "Assessing the long-term potential of fiber reinforced polymer composites for sustainable marine construction." Journal of Ocean Engineering and Marine Energy 7, no. 2 (2021): 129-144.

[18] Sobhan, Khaled, Francisco J. Martinez, and Dronnadula V. Reddy. "Corrosion resistance of fiber-reinforced geopolymer structural concrete in a simulated marine environment." Canadian Journal of Civil Engineering 49, no. 3 (2022): 310-317.

[19] Zhang, Y. H., W. L. Zhong, and L. F. Fan. "Long-term durability investigation of basalt fiber-reinforced geopolymer concrete in marine environment." Journal of Materials Research and Technology 31 (2024): 593-605.

[20] Wang, Yaocheng, Zihan Xiong, Xin Wang, Dingkun Liu, Yu Jin, Yingwu Zhou, Weiwen Li, and Baojian Zhan. "Deterioration mechanism and hardness degradation for GFRP bars used in marine concrete structures." Case Studies in Construction Materials 20 (2024): e02932.

[21] Hosseini, Alireza Sadat, and Pedram Sadeghian. "Long-term compressive performance of GFRP reinforcement in marine and alkaline environments." Construction and Building Materials 537 (2026): 147154.