SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V11I3P101

Volume 11 Issue 3, 1-11, March 2024

Original Article

Evaluation of Tensile Strength of Glass Fiber Reinforced Polymer Rebars under the Marine Environment - A Durability Approach

Mohamed Firdows Mohamed Zakkaria[1], Packialakshmi Shanmugam[2]

[1,2]*Department of Civil Engineering, Sathyabama Institute of Science and Technology, Tamilnadu, India.*

[1]*Corresponding Author : m.firdows@caec.ae*

Received: 03 January 2024 Revised: 02 February 2024 Accepted: 01 March 2024 Published: 31 March 2024

Abstract - *Over the past decade, there has been a significant rise in the use of Glass Fiber-Reinforced Polymer (GFRP) bars as internal reinforcement for concrete structures, primarily owing to their remarkable corrosion resistance. However, a critical concern has arisen regarding their susceptibility to degradation in terms of tensile strength and elastic modulus when exposed to harsh alkaline and saline environments. This study specifically focuses on the impact of such environments on two distinct types of GFRP rebars: sand-coated and twisted. The experiment involved subjecting these rebars to an accelerated temperature of 60 degrees Celsius for 180 days. The primary objective is to assess the extent to which GFRP rebars experience a reduction in tensile strength under the influence of moisture, alkaline solutions, and saline conditions. Preliminary findings reveal that the tensile strength of the GFRP rebars underwent a significant reduction during exposure to alkaline conditions. Specifically, the twisted GFRP rebars experienced a 25-30% reduction, while the sand-coated counterparts exhibited a 20% reduction in tensile strength. These observations highlight the vulnerability of GFRP rebars in alkaline environments. Furthermore, the study has identified a 15% reduction in tensile strength for both types of GFRP rebars under the influence of saline conditions. The implications of these reductions are currently the subject of further investigation as the research delves into understanding the effects of alkaline and saline exposure on the overall performance and durability of GFRP bars in concrete structures.*

Keywords - *Glass Fiber Reinforced Polymer rebars (GFRP), Sand-coated, Tensile strength, Elastic modulus, Twisted GFRP.*

1. Introduction

The corrosion of steel rebar stands out as a pivotal factor influencing the life cycle expectancy of reinforced concrete structures, often necessitating costly repairs or replacements. In some instances, repair costs can even surpass the original construction expenses. Conventionally, concrete structures have relied on steel rebars for reinforcement. Still, exposure to aggressive environmental conditions-characterized by combinations of moisture, temperature, and chlorides-can lead to the corrosion of these steel reinforcements.

This corrosion, in turn, results in the deterioration of concrete and compromises the overall serviceability of the structure. In response to these challenges, Fibre-Reinforced Polymer (FRP) materials, such as GFRP rebars, have gained considerable attention as an alternative to steel reinforcement in concrete structures (Benmokrane et al., 2017) [1]. Engineers view FRP as an innovative solution capable of overcoming the inherent deficiencies of steel rebars in harsh environments prone to corrosion. GFRP bars have found extensive use in various applications, including bridges, parking garages, water tanks, tunnels, and marine structures, where the corrosion of traditional steel reinforcement has historically led to substantial deterioration and the need for rehabilitation.

However, the adoption of GFRP rebars introduces new structural considerations. Notably, concerns arise regarding low structural ductility, serviceability issues, and reductions in strength when exposed to alkaline and marine environmental conditions (H. Kim et al., 2008) [2]. This is attributed to the brittle behaviour and relatively low modulus of elasticity of GFRP compared to traditional steel reinforcement. Studies have shown that GFRP bars embedded in concrete can experience significant strength loss when exposed to tap water or high ambient humidity.

Moreover, the degradation of GFRP bars wrapped in concrete and immersed in saline solutions may exhibit different characteristics (Daoguang Jia et al.,2019) [3]. Researchers have observed that the degradation rate of the strength of GFRP bars increases significantly at a 40% stress level (Jianwei Tu et al., 2020) [4]. These findings highlight the need for a comprehensive understanding of the structural performance of GFRP rebars in various environmental conditions to ensure their practical use as a corrosion-resistant alternative in reinforced concrete structures.

2. Research Significance

The degradation of reinforced concrete structures often stems from the corrosive effects on their reinforcing steel, prompting the need for innovative solutions. In this context, the utilization of composite materials, notably Fibre-Reinforced Polymers (FRPs), emerges as a promising avenue to counteract corrosion-induced deterioration. Nonetheless, it's important to note that while FRPs offer corrosion resistance, their mechanical properties, characterized by a low elastic modulus and suboptimal bond characteristics, can present challenges.

This can result in a propensity for these materials to exhibit premature splitting tendencies under certain loading conditions. The primary thrust of this study revolves around formulating an innovative non-ferrous reinforcement strategy to counteract the corrosion susceptibility inherent in Reinforced Concrete (RC) structures.

The literature survey provided focuses on addressing the issue of corrosion-induced degradation in reinforced concrete structures through the utilization of composite materials, specifically Glass Fiber Reinforced Polymers (GFRP). Firstly, it underscores the significant problem of corrosion-induced deterioration in concrete structures, primarily attributed to the corrosive effects on the reinforcing steel. This challenge necessitates innovative solutions to improve these constructions' longevity and structural durability.

The article focuses on exploring environmentally friendly materials, particularly emphasizing the use of Glass Fiber-Reinforced Polymer (GFRP) rebars. Previous research, as cited by Shrivastava et al. in 2019 [5], has indicated that the utilization of GFRP rebars not only comes with lower costs compared to traditional steel structures but also results in a significant reduction of carbon dioxide (CO_2) emissions-specifically, a 43% decrease. This environmental benefit positions GFRP as an attractive alternative, particularly in the context of sustainability.

One of the primary advantages of GFRP rebars highlighted in the article is their corrosion resistance. This quality makes them a potential solution to address the pervasive corrosion-induced degradation in concrete structures. Despite these advantages, the article acknowledges mechanical limitations associated with FRPs, including a low elastic modulus and suboptimal bond characteristics. These limitations pose challenges in the application of GFRP rebars within structural contexts.

The article delves into the impact of severe environmental conditions and sustained loads at elevated temperatures on GFRP bars. It suggests that such conditions play a significant role in triggering and accelerating critical degradation mechanisms in GFRP. Moreover, the high moisture uptake is identified as a factor leading to a substantial reduction in flexural and transverse properties, as highlighted by Fergani et al. in 2017 [6].

The durability of GFRP reinforcing bars in seawater concrete is also discussed, focusing on assessing tensile strength. As presented by Morales et al. in 2020 [7], the findings reveal that environmental conditioning, especially under aggressive conditions, leads to a 20% reduction in tensile strength.

To address these challenges and enhance structural integrity, researchers have explored modifications to GFRP rebars. The article mentions two notable approaches: adding a sand coating over the rebars and incorporating high-strength concrete with polypropylene fibres. These modifications aim to enhance the tensile strength of the concrete and, by extension, improve the overall performance of the reinforced structures.

In summary, the literature survey highlighted in the article underscores the need for innovative solutions to combat the deterioration in tensile strength and elastic modulus when GFRP rebars are exposed to severe environmental conditions. The proposed solution combines FRPs with modifications like sand coating and high-strength concrete with polypropylene fibres. This approach is positioned to enhance structural integrity and durability and address the challenges associated with corrosion in concrete structures.

3. Experimental Program

This research explores the durability aspects of Glass Fiber-Reinforced Polymer (GFRP) rebars, explicitly focusing on their exposure to moisture, saline, and alkaline solutions. The study employed 18 bare rebars, consisting of nine (9) GFRP-Twisted and nine (9) Sand-coated rebars. To reveal their performance characteristics, the objective was to thoroughly evaluate these specimens under marine/saline and alkaline conditions.

The rebars were fully immersed in solutions containing 3.5% NaCl (saltwater) to simulate marine settings. The research adhered to the guidelines established by ACI Committee 544R for alkaline conditions, with immersion durations lasting 180 days for each environment. A meticulous comparative analysis was conducted, calculating the specimens' tensile capacity and elastic modulus before and after exposure to the respective environments [8]. The author explicitly emphasizes the durability behaviour of GFRP rebars under marine environments, mainly two types of GFRP rebars: twisted and sand-coated. This focus is noteworthy as it addresses a topic that has received limited attention in existing research. The study involved the preparation of GFRP-Reinforced Concrete (RC) cylinder specimens following the specifications outlined in ACI report 440.3 sec.8.1. After the 180-day exposure period, these specimens were subjected to direct tension. The research findings indicate that GFRP bars show promise as an alternative to steel for reinforcing concrete. However, it's noted that GFRP twisted rebars exhibited a 33% reduction in tensile strength, which was higher than what the provisions predicted by ACI 440.1R-15 suggested-interestingly, adding a sand coating to the GFRP rebars effectively compensated for this reduction. When comparing the two types of GFRP rebars, the sand-coated ones exhibited less tensile capacity and elastic modulus reduction than the twisted GFRP rebars [9].

In comparing experimental results with predictions from various models, the research observed that no existing model satisfactorily predicted the percentage reduction in tensile capacities for all GFRP rebar specimens. This highlights the need for further research to develop more accurate predictive models for composite materials like GFRP. Overall, the study provides valuable insights into the performance of GFRP rebars under specific environmental conditions, emphasizing the importance of surface modifications such as sand coating to mitigate potential reductions in mechanical properties.

4. Materials

4.1. FRP Rebars

In academic or technical papers, Figure 1 typically represents a visual aid, such as a diagram, illustration, or photograph, that supplements the text and enhances the reader's understanding of the study. In this case, it sounds like Figure 1 illustrates the two distinct variants of Glass Fiber-Reinforced Polymer (GFRP) reinforcing bars used in the study: GFRP - Twisted bars and GFRP - Sand coated bars for GFRP - Twisted bars; you might expect to see a visual representation of the structure of these bars, which likely have a twisted or helical configuration.

The twisting can be a notable feature in terms of the mechanical behaviour and properties of the bars for GFRP - Sand-coated bars; the visual could display the surface modification of these bars with a layer of sand coating. The sand coating is an additional layer applied to the GFRP bars, and the figure might depict how this coating looks or its thickness compared to the GFRP - Twisted bars.

The visual representation in Figure 1 might include details such as dimensions, surface characteristics, or any other distinctive features of the two types of GFRP bars. It could be a schematic diagram or an actual image, depending on the nature of the study and the available resources. The purpose is to provide readers with a clear and concise understanding of the materials under investigation in the research, facilitating comprehension and aiding in the interpretation of the study's findings.

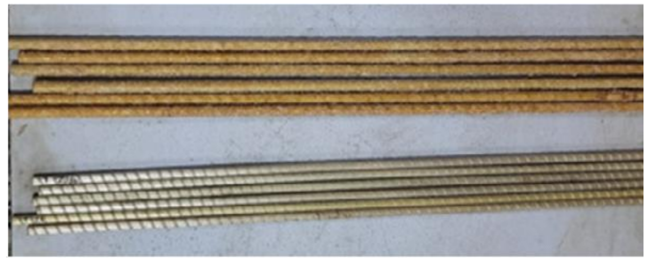


Fig. 1 GFRP rebars (twisted and sand-coated)

Table 1 displays the mechanical characteristics of Glass Fiber-Reinforced Polymer (GFRP) bars, specifically the GFRP - Twisted and GFRP - Sand Coated variations. Important characteristics comprise tensile strength, elastic modulus, yield strength, ultimate strain, and density. This table provides a thorough reference for comprehending the fundamental properties of the materials being examined in the study.

Table 1. Mechanical and physical properties of GFRP rebars

Description	Details
Type	Twisted/Sand Coated
Diameter	12mm
Elastic Modulus	43GPa
Density	1.9g/cc
Fiber Content	78%
Weight	0.21kg/m
Ultimate Tensile Strength	550 MPa
Ultimate Tensile Load	62.4KN
Ultimate Elongation	3%
Co-Efficient of Thermal Expansion - Longitudinal	$8*10^{-6}$ per degC
Co-efficient of Thermal Expansion - Transverse	$26*10^{-6}$ per degC

Table 2. Concrete mix design for c45 concrete

Description	Plain Concrete
Cement	360kg/m^3
Coarse Aggregates-20mm	718kg/m^3
Coarse Aggregates-10mm	478kg/m^3
River Sand	752kg/m^3
W/C	0.35
Super Plasticizer	1.0%
Mix Ratio	1:2.09:3.32

4.2. Concrete

Table 2 contains the details of trial mixes conducted for normal concrete with a designed cube strength of 45 megapascals (C45) after 28 days of curing. This table provides a comprehensive overview of the concrete mix design, outlining the specific proportions of ingredients used in the trial mixes to achieve the desired strength. The mix design typically includes details such as the types and quantities of cement, aggregates, water, and any additional admixtures used in the concrete formulation.

4.3. Conditioning of Samples

Table 3 details the conditioning of Glass Fiber-Reinforced Polymer (GFRP) samples for 180 days under three categories: Calcium solution, Saline Solution, and water. The table outlines the specific compounds utilized in accordance with the exposure conditions outlined by ACI440.3R. This information is essential for readers to understand the environmental conditions to which the GFRP samples were subjected during the study.

Table 3. Conditioning of GFRP rebars

Description	Details	Quantity (g/lit)
Alkaline Exposure	Calcium Hydroxide ($Ca(OH)_2$ Sodium Hydroxide (NaOH) Pottasium Hydroxide (KOH)	118.5 0.9 4.2
Saline Exposure	Sodium Chloride (NaCl)	3.5 %
Water	Distilled Water	-

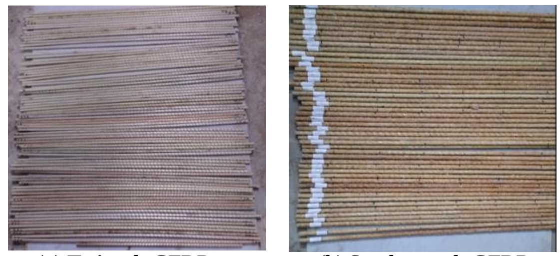
GFRP rebars of sand-coated and twisted were cut into one-meter lengths to accommodate the tensile test on the rebars by using a Universal Testing Machine as per ASTM D3916 requirements [10]. The specimens were tested for tensile capacity before and after exposure to alkaline and saline solutions. The rebar diameter was measured, weighed, and recorded before exposure to the alkaline solutions, and their weights were compared after 180 days of exposure.

Table 4. Specimen details

Description	Diameter (mm)	Avg. Length (mm)	Avg. Weight (g)	Remarks
GFRP - Twisted Rebar	12.0	1000	214.82	Bare Rebars
GFRP - Sand Coated	12.7	1000	240.58	
GFRP - Twisted Rebar	12.0	1000	3928.56	Rebars with Cylinder
GFRP - Sand Coated	12.7	1000	3954.32	

Cylinders of 100 mm diameter and 200 mm length were cast with centrally placed GFRP rebars to carry out the alkaline test as recommended by the Canadian Standard S806-02 [9]. The specimen shape and details of the specimen shape are presented in Table 4.

Figure 2 illustrates the GFRP rebar specimen details used in the study. Figure 3 illustrates the GFRP rebar specimen details used in the study.



(a) Twisted- GFRP (b) Sand coated- GFRP
Fig. 2 Rebar specimen details for direct tension test

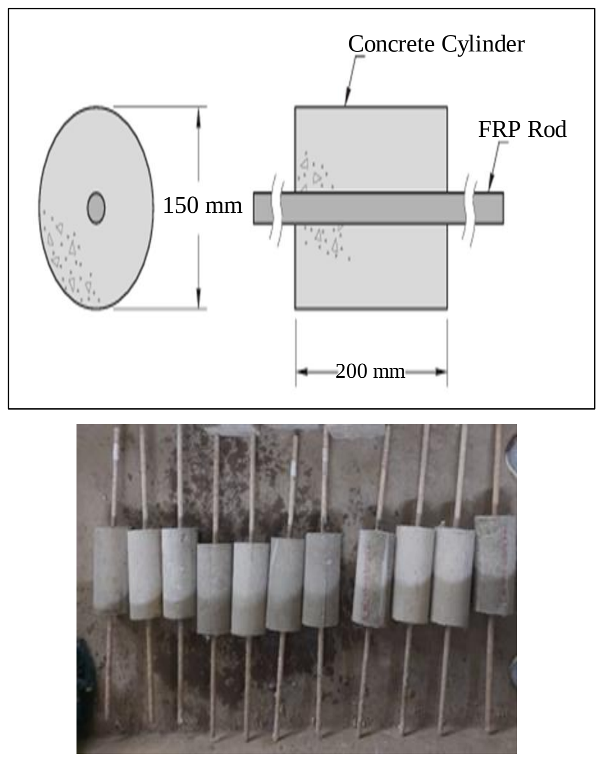
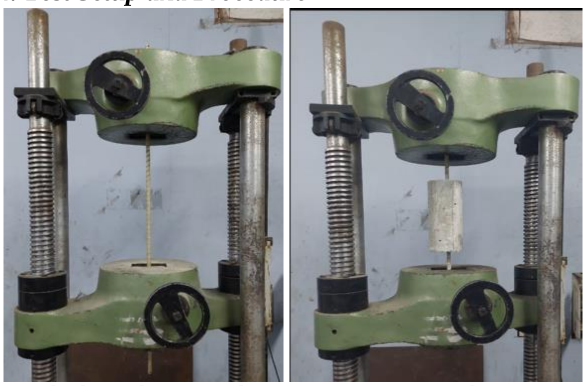


Fig. 3 Cylinder specimen details for alkaline test

Casting the specimens required a typical laboratory drum mixer to do the job. At the same time, 32 reinforced concrete cylinders and 24 control cube specimens measuring 100 x 100 x 100 mm each were cast to conduct a compression test. Every cylinder specimen had three layers of fill applied to it, and consolidation was achieved with the help of an internal vibrator. Every specimen was allowed to dry at room temperature for a full day. After 24 hours, the specimens were taken from their molds and allowed to cure in the tank at room temperature for

28 days. After 28 days, the reinforced cylinders were exposed to alkaline or saline conditions, as well as normal exposure conditions, in their respective curing tanks before being put to the test. The age of the specimens when they were tested was 180 days. All specimens were subjected to direct axial tension testing, as shown in Figure 4.

4.4. Test Setup and Procedure



Cylinder with GFRP rebar **GFRP rebar**

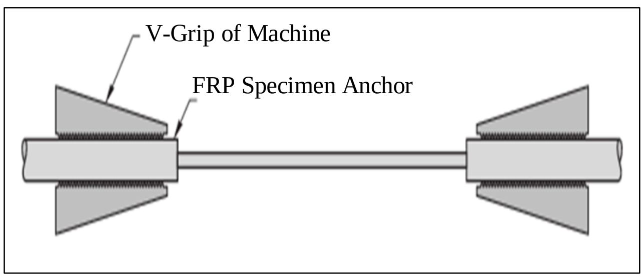


Fig. 4 Uniaxial tension test setup

The specimen preparation and testing procedures were conducted in accordance with ASTM D570 and ASTM D7205 standards. These standards provide guidelines for preparing and testing materials, ensuring consistency and accuracy in experimental processes. The Glass Fiber-Reinforced Polymer (GFRP) rebar specimens, each measuring 0.95 meters long, underwent meticulous preparation. Initially, the rebars were received. The maker sealed the products with epoxy at both ends. This sealing aimed to inhibit moisture diffusion from the cut ends, thus preserving the integrity of the specimens. Subsequently, the rebars were exposed to different environments, including seawater, alkaline solutions, and distilled water, as part of an accelerated ageing process. The exposure period lasted 180 days, simulating harsh conditions to assess the long-term performance of the GFRP rebars.

After exposure, the rebars were removed from the respective tanks, and tensile strength testing was conducted. Figure 4 visually illustrates the testing setup, where the rods were fixed at both ends and loaded at a uniform rate-the GFRP bars, cut to a length of 1000 mm Performed tension testing according to ASTM D7205. An MTS 810 testing machine with a 500 kN load cell was used for the tensile tests. The specimens were subjected to increasing stress until they reached failure.

During the test, the loading rate ranged between 250 and 500 MPa/min. This range reflects the speed at which the load was applied to the specimens. The applied load was continuously recorded using a data acquisition system monitored by a computer. The bar elongation and tensile loads were recorded throughout the testing process. These recorded parameters provide valuable data for analyzing the mechanical behaviour and performance of the GFRP rebars under different exposure conditions.

Table 5 is a reference for identifying the test specimens based on exposure conditions and rebar types. The notation system used in the table is explained, where the first letter ("T" or "SC") denotes the type of GFRP rebar (Twisted or Sand-Coated). The second letter ("A," "S" or "W") indicates the exposure conditions (Alkaline, Saline, or Distilled water). This systematic notation aids in organizing and categorizing the test specimens for subsequent analysis and interpretation of results. This detailed testing procedure comprehensively evaluates the GFRP rebars' performance under varying environmental conditions.

Table 5. Test specimens details

Specimen ID	GFRP Rebar Type	Exposure Type	Remarks
TA1, TA2,TA3	Twisted	Alkaline	Group -1
SCA1,SCA2,SCA3	Sand Coated		
TS1, TS2, TS3	Twisted	Saline	Group -2
SCS1,SCS2,SCS3	Sand Coated		
TW1, TW2, TW3	Twisted	Distilled Water	Group -3
SCW1,SCW2,SCW3	Sand Coated		

5. Test Results and Discussions

The test results presented in this study offer insights into the physio-mechanical properties of Glass Fiber-Reinforced Polymer (GFRP) samples subjected to standard accelerated alkaline conditioning, saline conditions (NaCl), and natural water exposure. The accelerated conditioning involved immersing the specimens in a solution at a constant temperature of 60 ± 3°C (140 ± 5°F) for a prolonged period of 180 days (equivalent to 4320 hours).

Following the exposure period, a visual inspection was immediately conducted upon removing the specimens from the alkaline resistance chamber. This inspection likely involved assessing the external condition of the GFRP samples, looking for any visible signs of degradation, discolouration, or other changes resulting from exposure to the different solutions.

Before conducting physical and mechanical testing, a recovery period was implemented. This recovery period was sufficiently long to allow the samples to reach moisture equilibrium with the laboratory testing conditions, and it lasted for a minimum of 72 hours. This step is crucial as it ensures that the specimens are stable, reflecting the conditions under which subsequent testing will be performed. After the recovery period, the samples were prepared and tested using the relevant standard test methods. These traditional methods would include procedures for assessing various mechanical properties, such as tensile strength, elastic modulus, or other characteristics relevant to the study's objectives.

Figure 5 visually represents GFRP specimens, including rebars and cylinders, during a tension test conducted after 180 days of exposure. The tension test involves applying a force to the specimens to assess their response to stretching or pulling, providing valuable data on their tensile strength and overall mechanical behaviour; this testing methodology is comprehensive, involving accelerated exposure to harsh conditions, recovery to a stable state, and subsequent evaluation of physio-mechanical properties through standard testing procedures. The results obtained from these tests contribute to a better understanding of how GFRP materials perform under different environmental exposures and can inform decisions related to their application in various structural contexts.

Fig. 5 Tension test on GFRP specimens after exposure to water /alkaline/saline solution

5.1. Moisture Absorption

Moisture and water can infiltrate the resin of GFRP bars incorporated into reinforced concrete parts, impacting the fibre-resin contact. Furthermore, the phenomenon of water volume expansion at low temperatures. Prior exposure of Glass Fiber Reinforced Polymer (GFRP) rebars to moisture before their placement in concrete can harm their tensile strength. This is because it leads to the breakdown of the polymer constituents, including fibres and resins.

The GFRP rebars were submerged in water until they reached a state of saturation, indicating no mass increase. The rebars were then exposed to a period of 180 days. The GFRP bars achieved a moisture content of 0.50% for Twisted GFRP rebars and 0.32% for sand coated rebars by fully immersing the specimens in water, following procedure 7.4 of the ASTM D570 standard. The only deviation was using a water temperature of 50°C. Table 6 presents the Water absorption test outcomes for GFRP-twisted and sand-coated rebars in accordance with ASTM D 570. Figure 6 Shows the change in weight due to moisture exposure for GFRP rebars.

It is inferred that Sand-Coated GFRP rebars absorbed 37% less when compared to Twisted GFRP rebars, which shows the effect of Sand-coating against the moisture absorption of GFRP rebars. Moisture absorption is a crucial issue that can considerably impact the mechanical and durability characteristics of GFRP bars. The study [12] provided compelling evidence that the deterioration rate of GFRP bars when exposed to fluid environments is directly linked to the pace at which they absorb fluids. Rebars with excessive moisture absorption were shown to have poor durability, primarily impacting tensile strength. The citation (Alvara Ruiz et al., 2022) [11].

After completing the water absorption test on GFRP rebars, the rebars were prepared and subjected to a tensile strength test according to ASTM D 7205. The test results were then compared to the original tension capacity of the rebars. Table 7 presents the mechanical characteristics of GFRP twisted and sand-coated rebars when exposed to moisture.

Table 6. Water absorption test results for GFRP rebars as per ASTM D570

Bar Type	Bar Mark	Diameter (mm)	W_0 (g)	W_1 (g)	Water Absorption %	$Rwa=wa_T/wa_{sc}$
				215.84	0.493	
	Tw1		214.78	215.96	0.514	
Twisted	Tw2	12	214.85	215.88	0.491	1.000
	Tw3		214.82	MEAN	0.499	
				COV	2.083	
				241.32	0.313	
	Scw1		240.56	241.34	0.307	
Sand Coated	Scw2	12.7	240.6	241.38	0.327	0.632
	Scw3		240.59	MEAN	0.316	
				COV	2.728	

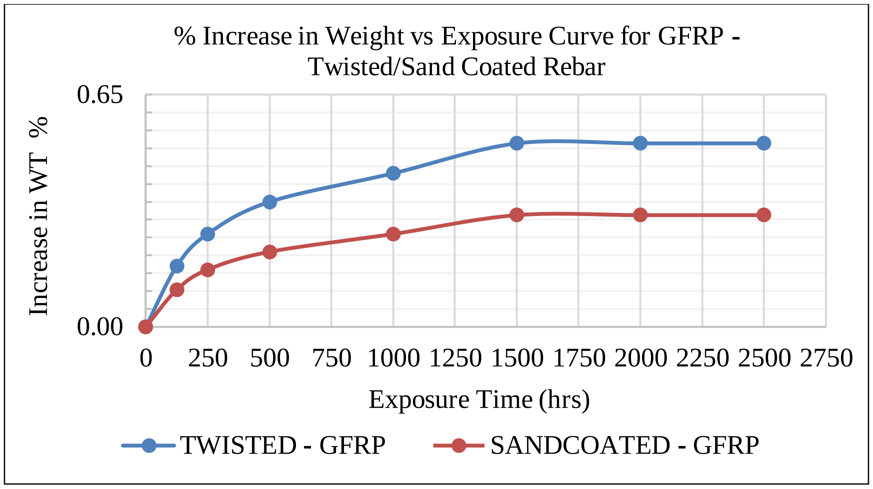


Fig. 6 Moisture absorption of GFRP specimens after exposure to water

Table 7. Tensile strength retention on GFRP rebars due to moisture exposure

Bar Type	Bar Mark	Diameter (mm)	F_{U1} KN	F_{U2} KN	RA= (F_{U1}/ F_{U2})*100	Elastic Modulus E (Gpa)	Strain %	RU=Ret_T/ Ret_{sc}
Twisted	Tw1 Tw2 Tw3	12	62.50 MEAN SD COV	54.65 53.35 53.75 53.917 0.125 0.219	87.440 85.360 86.000 86.267 0.867 1.008	47.510 43.390 37.640 42.847 4.048 9.447	1.430 1.320 1.340 1.363 0.048 3.509	0.946
Sand Coated	Scw1 Scw2 Scw3	12.7	62.50 MEAN SD COV	57.12 56.85 57.05 57.017 0.125 0.219	91.440 90.960 91.280 91.227 0.200 0.219	51.480 51.210 51.390 51.360 0.112 0.219	1.470 1.420 1.460 1.450 0.022 1.490	1.000

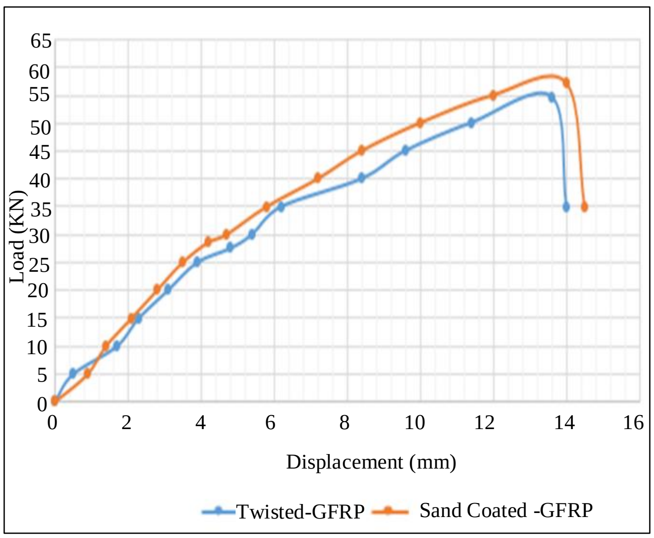


Fig. 7(a) Load vs. Displacement curve for GFRP rebar after water absorption

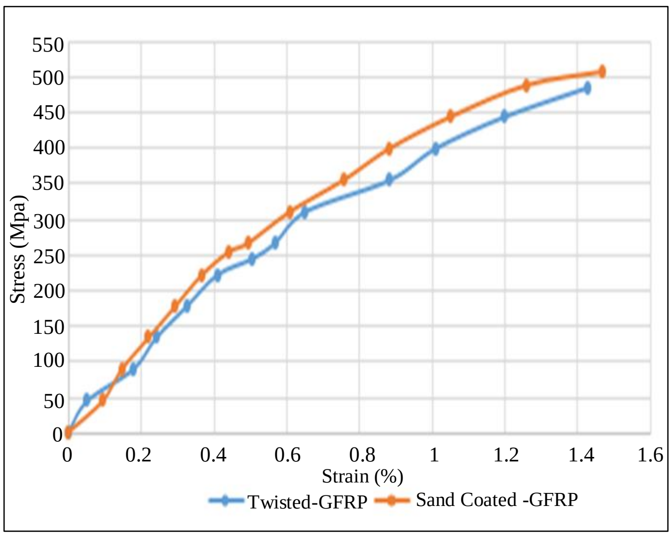


Fig. 7(b) Tensile stress vs. Strain curve for GFRP rebar after water absorption

It is to be noted that there is a tensile strength reduction in the range of 13.7% and 8.8% for GFRP - Twisted and Sand-coated rebars, respectively. Based on the Arrhenius model, at 23°C, all the GFRP rebars that met the acceptance criteria by ASTM D7957 are expected to retain 85 % of the tensile strength capacity and less than 1% mass increase due to moisture absorption. Combined ultraviolet and moisture exposure tests with and without applied stress to the bars have shown tensile strength reductions in the 0 to 40% range for GFRP bars (Sasaki et al., 1997; Uomoto, 2000) [13, 14]. Figures 7(a) and 7(b) show the load, displacement, stress, and strain curves for GFRP twisted and sand-coated rebars after the moisture exposure, respectively.

5.2. Alkaline Exposure

The test results presented herein provide samples' aged physio-mechanical properties under evaluation post-standard accelerated alkaline conditioning exposure [15]. The accelerating condition protocol consisted of the submersion of samples in an aqueous alkaline solution with a pH value of 12.6 to 13.0, as measured by ASTM E70 (Standard Test Method for pH of Aqueous Solutions with the Glass Electrode). The alkaline solution was set to a constant temperature of 60 ± 3°C (140 ± 5°F) for 180 days (4320 hrs). This solution reproduces the concrete alkalinity, while the high temperature accelerates any potential degradation mechanisms in the composite rebars.

After exposure, a visual inspection was conducted immediately after removing the specimens from the alkaline resistance chamber. Before physical and mechanical testing, a lengthy recovery period was established so that the samples reached moisture equilibrium with laboratory testing conditions (minimum 72 hours). Samples were then prepared and tested per each standard test method of reference. Table 8 shows the mechanical properties of both GFRP twisted and sand-coated rebars after alkali exposure [16]. It is to be noted that there is a tensile strength reduction in the range of 33.5 % and 21.0% for GFRP - Twisted and Sand-coated rebars, respectively.

Based on the results, it is revealed that Sand-coated rebars exhibited a 16% superior performance compared to twisted rebars in direct tension. The specific type of glass fibre used significantly influences the ability of GFRP bars to withstand alkali (Devalapura et al., 1996) [17].

Table 8. Tensile strength retention on GFRP rebars due to alkaline exposure

Bar Type	Bar Mark	Diameter mm	F_{U1} KN	F_{U2} KN	RA= (F_{U1}/ F_{U2}) *100	Elastic Modulus E GPa	Strain %	RU= Ret_T/ Ret_{sc}
Twisted	TA1 TA2 TA3	12	62.50	41.60 41.85 41.15	66.560 66.960 65.840	44.070 44.160 44.120	1.260 1.280 1.280	0.842
			MEAN SD COV	41.533 0.290 0.697	66.453 0.463 0.697	44.117 0.037 0.083	1.273 0.009 0.740	
Sand Coated	ScA1 ScA2 ScA3	12.7	62.50	51.35 51.75 51.15	79.840 78.720 78.320	48.410 47.730 47.480	1.290 1.240 1.220	1.000
			MEAN SD COV	51.42 0.249 0.485	78.960 0.643 0.815	47.873 0.393 0.821	1.250 0.029 2.355	

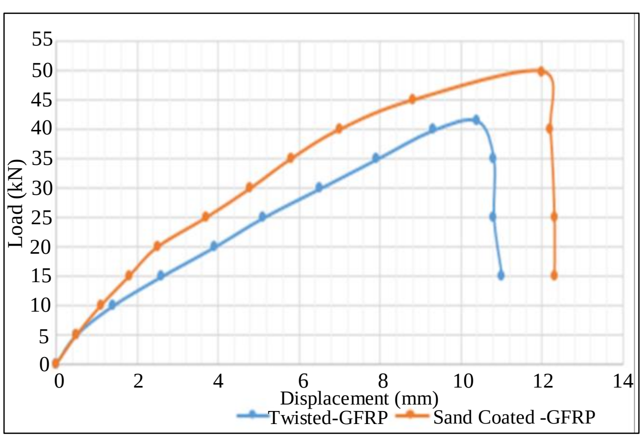


Fig. 8(a) Load vs. Displacement curve for GFRP rebar after alkaline exposure

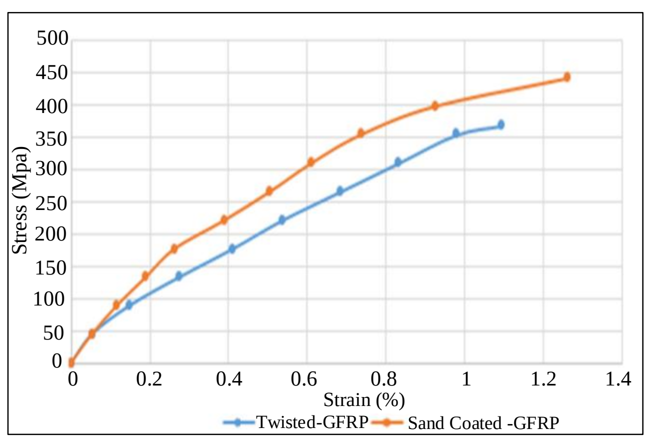


Fig. 8(b) Tensile stress vs. Strain curve for GFRP rebar after alkaline exposure

Studies have shown that the tensile strength of GFRP bars can decrease by up to 75 percent of their initial values, while the tensile stiffness of strained and unstressed GFRP bars can decrease by up to 20 percent in many instances. The reference cited is (Alvaro Ruiz et al., 2022) [11]. Figures 8(a) and 8(b) show the load and displacement curves and stress and strain curves for both GFRP twisted and sand-coated rebars after the alkaline exposure, respectively.

5.3. Saline Exposure

The test results presented herein provide samples' aged physio-mechanical properties under evaluation post-standard accelerated saline conditioning exposure. The saline (NaCl - 3.5%) solution was set to a constant temperature of 60 ± 3°C (140 ± 5°F) for 180 days (4320 hrs). This solution reproduces the marine environment, while the high temperature aims to accelerate any potential degradation mechanisms in the composite rebars. After exposure, a visual inspection was conducted immediately after removing the specimens from the saline solutions.

Before physical and mechanical testing, a lengthy recovery period was established so that the samples reached moisture equilibrium with laboratory testing conditions (minimum 72 hours). Samples were then prepared and tested per each standard test method of reference. Table 9 shows the mechanical properties of both GFRP twisted and sand-coated rebars after saline exposure.

It should be emphasized that there is a decrease in tensile strength of 23.95% and 17.75% for GFRP - Twisted and Sand-coated rebars, respectively. The results indicate that Sand-coated rebars outperformed Twisted rebars by 7.6% in direct tension, resulting in a lower reduction of tensile force in the sand-coated rebars. The tensile strength of GFRP bars decreases by 0 to 20 percent when exposed to a saline solution at room temperature and subjected to cyclic freezing-and-thawing temperatures.

The citation (Vijay et al., 1998) is provided. Figures 9(a) and 9(b) show the load and displacement curves and stress and strain curves for both GFRP twisted and sand-coated rebars after the saline exposure, respectively.

Table 9. Tensile strength retention on GFRP rebars due to saline exposure

Bar Type	Bar Mark	Diameter mm	F_{U1} KN	F_{U2} KN	RA= (F_{U1}/ F_{U2}) *100	Elastic Modulus E GPa	Strain %	RU= Ret_T/ Ret_{sc}
Twisted	Tw1	12	62.50	47.20	75.520	44.070	1.260	0.924
	Tw2			47.80	76.480	44.160	1.280	
	Tw3			47.60	76.160	44.120	1.280	
			MEAN	47.53	76.053	44.117	1.273	
			SD	0.249	0.399	0.037	0.009	
			COV	0.525	0.525	0.083	0.740	
Sand coated	Scw1	12.7	62.50	51.35	82.160	49.810	1.370	1.000
	Scw2			51.75	82.800	49.830	1.390	
	Scw3			51.15	81.840	49.710	1.360	
			MEAN	51.42	82.267	49.783	1.373	
			SD	0.249	0.399	0.052	0.012	
			COV	0.485	0.485	0.105	0.908	

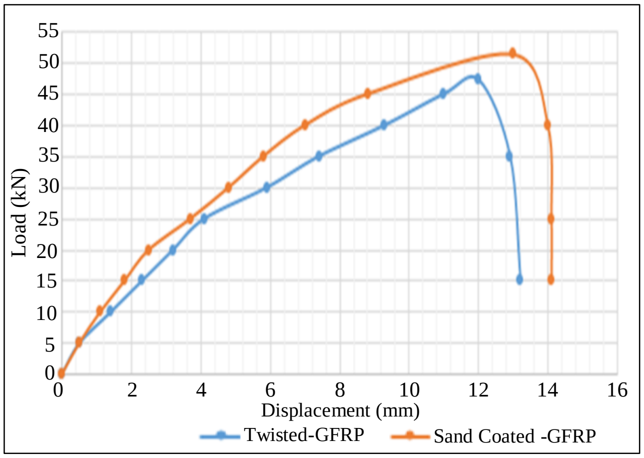


Fig. 9(a) Load vs. Displacement curve for GFRP rebar after saline exposure

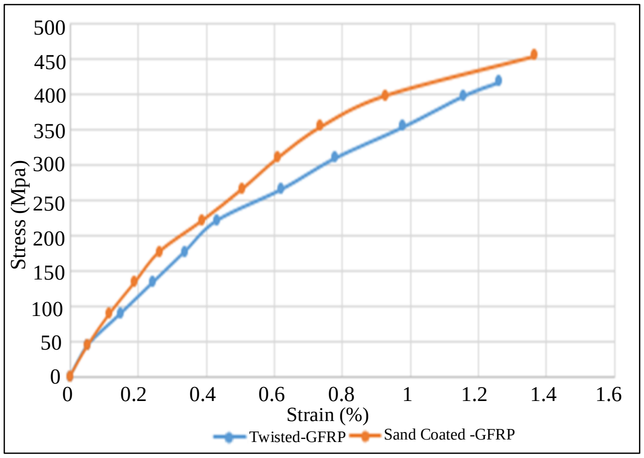


Fig. 9(b) Stress vs. Strain curve for GFRP rebar after saline exposure

Table 10 compares the tensile load capacity of both GFRP twisted and sand-coated rebars after the moisture, alkaline and saline exposures.

Table 10. Comparison of tensile strength reduction on GFRP rebars due to moisture/alkaline/saline exposure

Rebar Type	Exposure Conditions		
	Moisture	**Alkaline**	**Saline**
Twisted GFRP	13.7 %	33.5%	23.95%
Sand-Coated GFRP	8.8 %	21.0%	17.75%
Efficiency	36%	33%	26%

6. Research Findings

To address the reduction in tensile strength capacity of Glass Fiber-Reinforced Polymer (GFRP) rebars over time in the design of reinforced concrete structures, the ACI 440.1R-15 (ACI440.1, 2015) standard introduces an environmental reduction factor (CE).

This factor is applied by multiplying it with the guaranteed tensile strength to obtain the design strength. The value of this factor, determined through the consensus of the ACI committee, is set at 0.7 (retention of 70%) or 1.0 (retention of 100%) for GFRP rebars, depending on the exposure conditions. Specifically, a CE of 0.7 is recommended for concrete structures exposed to earth and water, while a CE of 1.0 is suggested for structures without such exposure.

According to Alvaro Ruiz et al.'s findings in 2022, the primary cause of degradation is the fibre/resin contact, as indicated by the strength retention values and failure modes. Nevertheless, to establish a precise CE value, it is important to verify these forecasts by comparing them with data collected from established structures that have been in operation for a considerable duration. It is crucial to compare the proposed CE values with real-world data to guarantee their trustworthiness and applicability in genuine engineering contexts.

7. Conclusion

GFRP rebars of type Twisted and Sand-coated subjected to moisture, saline, and alkaline environmental conditions exhibit a reduction in tensile strength capacities ranging between 10% and 30% when exposed to 180 days at accelerated conditions. GFRP sand-coated rebars demonstrate superior tensile strength performance than twisted rebars, particularly when subjected to saline and alkaline exposure conditions. The tensile strength capacity efficiency factor for GFRP sand-coated rebars was calculated and found to be 26% and 36% compared to GFRP twisted rebars. Based on the test mentioned above results, talks, and discoveries, the following conclusions can be drawn:

- The longevity of GFRP rebars appears to be linked to their ability to absorb moisture: greater moisture absorption leads to more degradation, making moisture absorption measurements a reliable indicator of long-term performance.
- Both Twisted and Sand-coated rebar varieties exceeded the minimum requirements outlined in the acceptance criteria of ASTM D7957. Exposing GFRP rebars to water at a regulated temperature causes a decrease in their tensile strength, which is in the range of 13.7% (Retention of 86.3%) and 8.8% (Retention of 91.2%) for Twisted and Sand-coated GFRP rebars respectively.
- Alkaline exposure under the controlled temperature leads to tensile strength reduction in the GFRP rebars, which is in the range of 33.5% (Retention of 66.5%) and 21.0% (Retention of 79.0%) for Twisted and Sand-coated GFRP rebars respectively.
- Sea water/Saline exposure under the controlled temperature leads to tensile strength reduction in the GFRP rebars, which is in the range of 23.95% (Retention of 76.05%) and 17.75% (Retention of 82.25%) for Twisted and Sand-coated GFRP rebars respectively.
- Under three different (water, Alkaline and Saline) environmental conditions, it is observed that GFRP sand-coated rebars tensile retention capacity is better than GFRP twisted rebars and the average efficiency factor was calculated in the range of 26-36%.
- Environmental reduction factor C_E in the design of FRP concrete structures should be reviewed and validated based on the GFRP rebar type and resin type.

References

[1] Brahim Benmokrane et al., "Effects of Diameter on the Durability of Glass Fibre-Reinforced Polymer Bars Conditioned in Alkaline Solution," *Journal of Composites for Construction*, vol. 21, no. 5, pp. 1-12, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[2] Hyeong-Yeol Kim et al., "Short-Term Durability Test for GFRP Rods under Various Environmental Conditions," *Composite Structures*, vol. 83, no. 1, pp. 37-47, 2008. [CrossRef] [Google Scholar] [Publisher Link]

[3] Daoguang Jia et al., "Durability of Glass Fibre-Reinforced Polymer (GFRP) Bars Embedded in Concrete under Various Environments. I: Experiments and Analysis," *Composite Structures*, vol. 234, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[4] Jianwei Tu, Hua Xie, and Kui Gao, "Prediction of the Long-Term Performance and Durability of GFRP Bars under the Combined Effect of a Sustained Load and Severe Environments," *Materials*, vol. 13, no. 10, pp. 1-18, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[5] N. Garg, and S. Shrivastava, "Environmental and Economic Comparison of FRP Reinforcements and Steel Reinforcements in Concrete Beams Based on Design Strength Parameter," *Proceedings of the UKIERI Concrete Congress*, Jalandhar, India, pp. 1-9, 2019. [Google Scholar] [Publisher Link]

[6] Hamed Fergani et al., "Characterization and Durability Study of GFRP Bars Exposed to Severe Environments and under Sustained Loads," *Proceedings of the Fifth International Conference on Durability of Fiber Reinforced Polymer (FRP) Composites for Construction and Rehabilitation of Structures*, pp. 1-9, 2017. [Google Scholar]

[7] Carlos N. Morales et al., "Durability of GFRP Reinforcing Bars in Seawater Concrete," *Construction and Building Materials*, vol. 270, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[8] Antonio Nanni, "*Guide Test Methods for Fiber Reinforced Polymers for Reinforcing or Strengthening Concrete Structures*," Technical Report, Manual of Concrete Practice, American Concrete Institute, 2004. [Google Scholar] [Publisher Link]

[9] Canadian Standards Association, Design and Construction of Building Components with Fibre-Reinforced Polymers (CAN/CSA S806-02), 2022. [Online]. Available: https://www.csagroup.org/store/product/2415292/

[10] Francesco Micelli, and Antonio Nanni, "Durability of FRP Rods for Concrete Structures," *Construction and Building Materials*, vol. 18, no. 7, pp. 491-503, 2004. [CrossRef] [Google Scholar] [Publisher Link]

[11] Alvaro Ruiz Emparanza et al., "Durability Assessment of GFRP Rebars in Marine Environments," *Construction and Building Materials*, vol. 329, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[12] ASTM International, "*Standard Specification for Solid Round Glass Fibre Reinforced Polymer Bars for Concrete Reinforcement*," Technical Report, ASTM D7957/D7957M-22, ASTM, 2017. [Google Scholar] [Publisher Link]

[13] Iwao Sasaki et al., "Durability Evaluation of FRP Cables by Exposure Tests," *Non-Metallic (FRP) Reinforcement for Concrete Structures: The Third International Symposium Proceedings*, vol. 2, pp. 131-137, 2004. [Google Scholar]

[14] T. Uomoto, "Durability of FRP as Reinforcement for Concrete Structures," *Advanced Composite Materials in Buildings and Structures 3rd International Conference*, Ontario, Canada, pp. 3-14, 2000. [Google Scholar]

[15] Abdeldjelil Belarbi, and Huanzi Wang, "Bond Durability of FRP Bars Embedded in Fibre-Reinforced Concrete," *Journal of Composites for Construction*, vol. 16, no. 4, pp. 371-380, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[16] P.V. Vijay, H.V.S. GangaRao, and Rajesh Kalluri, "Hygrothermal Response of GFRP Bars under Different Conditioning Schemes," *The Proceedings of the 1st International Conference on Durability of Fiber Reinforced Polymer for Construction (CDCC'98)*, Sherbrooke, Canada, pp. 243-252, 1998. [Google Scholar]

[17] International Concrete Abstracts Portal, "*440.1R-06: Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars*," Technical Report, American Concrete Institute, pp. 1-44, 2006. [Google Scholar] [Publisher Link]

Appendix

Nomenclature

A	Area of specimen (m^2)
L	Length of specimen (m)
C_E	Environmental strength reduction factor (dimensionless)
D	Diameter of rod (m)
E	Modulus of elasticity (MPa)
F_1, F_2	Tension capacity at 50% and 20%
f_{ck}	Characteristic compressive strength of concrete (MPa)
f_u	Tensile strength (MPa)
F_{u1}	Tensile capacity before immersion (kN)
F_{u2}	Tensile capacity after immersion (kN)
R_{et}	Tensile capacity Retention (%)
T	Temperature (deg C)
W_1	Mass of the specimen after immersion for some time (g)
W_0	Initial mass of the specimen before immersion (g)
ε_u	Ultimate strain (dimensionless)
ε_1, ε_2	Strain at 50% and 20% of tensile capacity (dimensionless)