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*Original Article*

# Evaluation of Bond Strength on Fiber Reinforced Concrete (FRC) with GFRP Rebars under Marine Environmental Conditions - An Experimental Investigation

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***Abstract*** *- Researchers examined how Glass Fiber Reinforced Polymer (GFRP) bars bond with standard and Fiber-Reinforced Concrete (FRC) when exposed to marine conditions at 45°C.Thirty-six specimens with 12 mm diameter GFRP rebars featuring twisted and sand-coated surfaces were embedded in 100 mm concrete cubes and subjected to direct tension pullout tests per ASTM D 7913. Results show that surface treatment significantly influences bond-slip relationships and durability. Sand-coated GFRP rebars exhibited superior performance, achieving bond stresses of 11.77 MPa in plain concrete and 13.66 MPa in FRC, compared to 9.89 MPa and 12.39 MPa for twisted rebars, respectively. Durability assessment revealed lower bond strength reductions for sand-coated rebars (7% in plain concrete, 13.5% in FRC) compared to twisted rebars. These findings provide crucial insights for designing corrosion-resistant concrete structures using GFRP reinforcement.*

***Keywords*** *- GFRP, Fiber Reinforced Concrete (FRC), Sand-coated, Twisted, Bond strength, Slip.*

## 1. Introduction

This research examines the long-term bonding characteristics of two systems: FRP bars in Fiber-Reinforced Concrete (FRC) and FRP bars in plain concrete. The main goal is to provide a qualitative assessment of the advantages of incorporating fibers into concrete reinforced with FRP bars, building on previous studies showing improved bond stress-slip behavior in such systems [1]. Our study focuses on a single fiber volume fraction, as exploring the effects of different fiber concentrations was beyond the scope of this investigation. We conducted an experimental program using two common GFRP bar types in combination with synthetic fibers, extending the work of researchers who have evaluated bond behavior under various conditions [2]. Our analysis is based on direct pullout tests, which we used to evaluate how rebar surface treatments interact with a 1% volume fraction of synthetic fibers. This approach is intended to redress the current lack of clear methods of measuring and quantifying the improvements in ductility in the interfacial zone of the friction between the FRP rebars and the fibre-reinforced cementitious matrices [3]. While previous research has demonstrated that Incorporating fibers into the concrete mixture can improve two key aspects of rebar performance: the bearing force between the rebar and the encapsulating concrete and, finally, the stand that the rebar displayed at the time of failure. This fiber reinforcement results in an improved interface strength and enables improved deformation capacity before the failure of the bonding interface, which increases the concrete structure's overall element strength and safety with fiber reinforcement. To our knowledge, [4] provides a long-term performance analysis in the context of the European crisis, and thus, our study seems to be the first one to fill this gap. This information is important for assessing the behaviour and performance of FRP/FRC hybrid systems under different conditions, especially when previous studies have shown that adding short polypropylene fibers and GFRP rebars to concrete structures can enhance their performance [5].

## 2. Research Significance

Therefore, this study seeks to analyze the behavior of bond strength between Plain Concrete and Fiber Reinforced Concrete (FRC) while using various types of GFRP rebar, including sand-coated and twined forms. Besides, it aimed to evaluate the long-term stability of the concrete-rebar interface, considering that it was subjected to a simulated harsh saline environment. In this assessment, emphasis was placed on the capacity of a bond between the reinforcement and concrete matrix to withstand severe exposure to highly saline conditions for a relatively long time to elicit interfacial integrity in conditions with higher corrosion risks. For the purpose of identifying factors that define the bond between Plain Concrete and FRC in terms of the combination with sand-coated and twisted GFRP rebars. With this in mind, this research was done to put more information in the database regarding the durability and long-term behaviour of structures made of Fiber Reinforced Concrete and reinforced with GFRP rebars. The findings of this study usher information that will be precious in future designs to enhance the reliability and durability of the structures made from these materials. Hence, the conclusions of this research will enrich the existing literature on concrete structures reinforced with GFRP especially under the hostile environment condition. This knowledge will ensure engineers and designers, especially those in charge of the construction of structures, that corrosion aspects are of paramount importance when structures are to be located near the sea or any water body.

## 3. Methodology

In this research, the searches were done per the interfacial adhesion of concrete and two different types of commercially available Glass Fiber Reinforced Polymer (GFRP) rebar. The pullout test method was carried out for these GFRG rebars as per ASTM D7913 to evaluate the bond performance of this GFRG rebar to the concrete matrix. They adopted a widely recognized procedure that carries the title “Bond Strength of fiber reinforced polymer matrix composite bars to concrete by Pullout Testing”, which provided befitting guidelines to measure the bond properties [11].

To investigate the bond strength behavior and durability of the Fiber Reinforced Concrete (FRC)/GFRP hybrid system, the research design incorporated two distinct GFRP rebar types: sand-coated and rolled. The conditioning regimen used with the test group was to expose it to the saltwater solution at 45° C for a period of 180 days. This early sign of corrosion was to mimic the deterioration of the bond between the GFRP rebars and concrete due to the effects of an aggressive marine environment for a longer period than that used in the test.

Altogether, it was intended to assess through comparing the result of both the control and test group prudent to this research as to the effect of time of saltwater immersing on the bond strength and durability of various types of GFRP rebar integrated into plain and fiber-reinforced concrete. The presented research approach allows for evaluating the sustainability and lifetime of concrete structures with the reinforcement of GFRP in an aggressive environment.

## 4. Experimental Program

### *4.1. Materials*

#### *4.1.1. GFRP Rebars*

Our research examines two distinct varieties of Glass Fiber Reinforced Polymer (GFRP) reinforcing bars: This faces one has a twisted surface, while the other is covered by sand. Each type of bar is pultruded, which is a method commonly applied in composite product manufacturing [6]. The main components of these reinforcing bars, therefore, include E-glass fibers and a vinyl ester resin. These two kinds of materials comprise the structural framework of the reinforcement system. The GFRP bars are curved shaped or twisted with a helical outer layer, which involves undulations on the exterior surface to increase the adhesion characteristics of the concrete. This design is based on prior studies showing surface roughness can adversely influence bond strength [7].

As for the sand-coated GFRP bars, the bars have to be treated by applying coarse silica particles on the surface of the bars, a process that complies with the guidelines in the ACI440. 3-03 (2003) for enhancing bar concrete interfaces [8]. Images of these GFRP bars are shown in Figure 1, while Table 1 presents a summary of the mechanical characteristics of GFRP bars. This data presentation is consistent with conventions used in the materials science literature in terms of the clarity of the characteristics presented here [9].

Thus, examining these two types of GFRP bars will allow us to assess and contrast bonding efficiency and encompassing performance of concrete structures. We can compare the performance of the helically wrapped surface and the sand-coated surface where all other factors are kept constant so that we can understand how the nature of the surface influences the bond strength and durability, especially in adverse conditions. This approach builds upon the prior work done in our previous papers concerning the interaction between GFRP-Concrete [10, 11].

Thus, the comparative study will help establish the extent to which the performance of reinforced concrete is affected by different designs of GFRP bars. Perhaps such insights may help the material selection process that is more appropriate for certain construction applications to make construction structures more durable and efficient. The presented research supports further development of GFRP reinforcement for concrete structures and can be considered a significant contribution to the constantly progressing area of civil engineering [12].

**Fig. 1 GFRP rebars (Twisted and sand-coated)**

**Table 1. Properties of GFRP rebars**

| Description | Plain Concrete | FRC |
|---|---|---|
| Cement | 360kg/$m^3$ | 360kg/$m^3$ |
| CoarseAggregates–20mm | 718kg/$m^3$ | 718kg/$m^3$ |
| CoarseAggregates–10mm | 478kg/$m^3$ | 478kg/$m^3$ |
| River Sand | 752kg/$m^3$ | 752kg/$m^3$ |
| Macro Synthetic Fibre (1%) (L/D=74) | - | 4.0kg/$m^3$ |
| W/C | 0.35 | 0.35 |
| Super Plasticizer | 1.0% | 1.5% |
| Mix Ratio | 1:2.09:3.32 | 1:2.09:3.32 |

**Table 2. Properties of polypropylene fibers**

| Description | Details |
|---|---|
| Category | Twisted/sand Coated |
| Dia | 12/12.7mm |
| EM | 43GPa |
| BULK Density | 1.9g/cc |
| Fiber Content | 78% |
| Weight | 0.21kg/m |
| UTL | 550MPa |
| UTS | 89.36KN |
| UE | 3% |
| Co.eff of Thermal Expansion-Longitudinal | 8*10-6perdegC |
| Co.eff of Thermal Expansion-Transverse | 26*10-6perdegC |

### *4.1.2. Polypropylene Fiber*

In accordance with the non-metallic components included in the composition of the presented mixtures for this research, polypropylene fibers are included in line with the recommendations of ACI Committee 544 (2009) [13, 14]. Among all fiber types, polypropylene fibers are selected, taking into account the research objectives and playing a decisive role in the performance characteristics of the material.

The reinforcement of the concrete matrix under investigation is characterized by the distinct mechanical properties of polypropylene fibers. These fibers significantly enhance several characteristics of the composite material's functioning and actual lifespan. For the purpose of giving a clear picture of the type of fibers utilized, the main characteristics of polypropylene fibers used in the concrete mix are given below in Table 2. This table provides further analysis of the fibers in terms of their physical and mechanical properties, something as fiber length, fiber diameter, tensile strength and elastic modulus, among others. Thus, the research intends to develop and investigate the use of polypropylene fibers for the FRP in general and the effect on the performance of the fiber-reinforced concrete, especially in association with the GFRP reinforcing bars. This approach makes it possible to analyze the influence of the incorporation of non-metallic fibres and GFRP reinforcement on the characteristics of the concrete and how it may impact durability and performance under adverse conditions.

### *4.1.3. Concrete*

In this present research, normal-strength concrete was used with desired characteristic compressive strength of 45 MPa at 28 days. In selecting its mixture proportions, the Fiber-Reinforced Concrete (FRC) was intended to be similar to that of plain concrete in which the fibers can easily be incorporated without compromising workability. In the FRC mix, a high-range water-reducing admixture was used to ensure sufficient workability in the presence of fibers. Table 3 presents a detailed overview of the constituents of a concrete mix in a common application in the present study and the exact composition and proportions of the materials in plain and fiber-reinforced concrete matrices.

Keeping the general proportions of the two concrete types close to each other, including incorporating the water-reducing admixture only in the FRC matrix, the study will seek to identify the effects of fiber incorporation on the behavior and compatibility between the FRC and GFRP reinforcement. This approach allows a better comparison between both types of concrete and their behavior in conjunction with distinct variants of GFRP rebar, which makes it possible to perform a deep analysis of the concrete characteristics and of the bond behavior of concrete with GFRP rebar under various conditions due to the inclusion of fibers.

**Table 3. Concrete mix design for plain cement and FRC concrete**

| Description | Details |
|---|---|
| Length, mm | 51 |
| Diameter | 0.69 mm |
| Aspect Ratio | 74 |
| Volume fraction | 1.0% |
| Specific Gravity | 0.92 |
| Elastic Modulus, GPa | 9.5 |
| Tensile Strength, MPa | 600 |

Non-destructive evaluations of the cured concrete were conducted using Ultrasonic Pulse Velocity and Rebound Hammer tests. Additionally, the 28-day compressive strength was determined. The results of these qualitative and quantitative assessments are presented in the accompanying table.

### *4.1.4. Specimens*

As per ASTM D7913 (ASTM International 2014) [11], the authors performed pullout tests on as many as 36 specimens. Characteristic features of both ends of the GFRP rebar specimens were taken into account during preparation. On the loaded end, where force was applied, a 300 mm long steel pipe enveloped the rebar to prevent it from being damaged by grips since it has negligible transverse load-bearing capacity. The free end of the specimen was placed vertically into an acrylic resin concrete cube with a dimension of 100×100×100 mm. Of the 100 mm bar length embedded in concrete, only 50 mm, which is four times the diameter of the bar, was meant to have a bond with the concrete.

The other 50 mm within the cube was also treated to not bond with the core, as shown in Figure 2 (JSCE-E 539, 1996) [12]. That arrangement made it possible to have a controlled bonding channel that would provide accurate test results. Sample preparation consisted in pouring the samples into individual molds made from plywood, as indicated in Figure 2 left. It has been considered important to place fresh concrete in two layers and compact them using a vibrator to enhance the material's consolidation.

The samples were demoulded after 48 hours of setting period and exposed to the natural environment for a period of 28 days before testing or exposure to aging conditions. This logical procedure to prepare and analyze the specimens made it easier to ensure repeatability, enabling proper comparison of all the GFRP rebar types and the different concrete mixtures. It is implied that the strict regulation of bonding length and curing conditions create a benchmark for measuring the bond strength and life cycle of GFRG rebars in plain and fiber-reinforced concrete with respect to the environment.

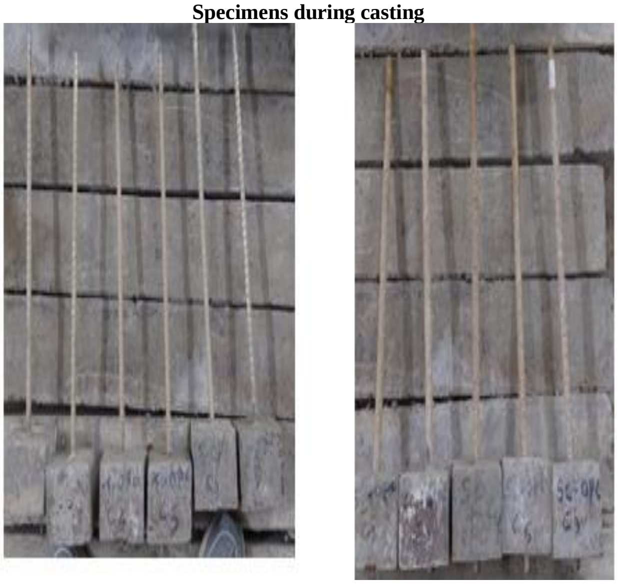
**Table 4. Concrete properties**

| Description | Plain Concrete | FRC |
|---|---|---|
| UPV, km/sec | 4.08 | 4.49 |
| Rebound Number, no | 38 | 42 |
| Compressive strength, MPa | 46.0 | 49.0 |

**Table 5. Cube with rebar details**

| Rebar Type | Diameter, mm ($d_b$) | Beam Size, mm (bx D x L) | Rebar Embedded length, mm ($L_b$) |
|---|---|---|---|
| GFRP - Twisted | 12.0 | 100x 100 x100 | 100 |
| GFRP- Sand Coated | 12.7 | 150x100 x100 | 100 |

**Specimens during casting**



**Specimens after 180 Days of exposure to chlorine GFRP rebar twisted, GFRP rebars and coated**
**Fig. 2 Pullout specimen details**

**Table 6. Exposure conditions**

| Exposure Type | Details |
|---|---|
| **Marine Exposure (S)** | |
| Sodium Chloride (NaCl) | 3.5 % (38.39 g/ Litres) |
| Calcium Chloride ($CaCl_2$) | 0.24 % (2.435 g/ Litres) |
| Magnesium Chloride ($MgCl_2$) | 1.90 % (19.06 g/ Litres) |
| Sodium Sulphate ($Na_2SO_4$) | 0.52 % (5.26 g/ Litres) |
| Sodium bi Carbonate ($NaHSO_3$) | 0.026 % (0.265 g/ Litres) |
| **Conventional Exposure©** | 45 deg C Temperature |
| Normal Water | Control Specimens |
| Duration of Exposure | 180 days |

For the purpose of casting the specimens, the concrete was prepared for mixing with the help of a laboratory drum mixer. Altogether, 32 cubes with varying GFRP rebars and 12 control cube specimens of 100 x 100 x 100 mm were prepared for crushing test. The specimens were compacted in two layers, or three layers, with an internal vibrator. All the specimens mentioned above were allowed to be set at room temperature for 24 hours. After demoulding, they were treated in a tank for twenty-four hours at room temperature, followed by a curing period of twenty-eight days.

As for the next procedure, after the first curing period, the reinforced cubes were exposed to either saline conditions or normal exposure, depending on the curing tank they were placed in before testing [15]. These specimens were of 180 days of age at the time of testing. As for capturing the bond behavior of the FRC/GFRP hybrid system under investigation, these specimens also went through the above-mentioned tests on the reinforced concrete specimens. A specific notation system was developed to identify each specimen:

- The first letter indicates the concrete type, Where “P” stands for Plain concrete and “F” stands for Fiber-reinforced concrete.
- The second letter denotes the GFRP rebar type: This is why beverage cans may be labeled “T” for Twisted or “SC” for Sand-coated.
- The third letter specifies the exposure condition: SEA exposure, which is defined as “S” for Sea exposure, and “Conventional” exposure, which is marked as “C”.

The specimen preparation, curing and identification strategies proposed above give a systematic approach towards assessing bond behaviour between various types of GFRP rebar and concrete mix proportions in different environmental conditions [16].

The use of both plain concrete and concrete with fiber reinforcement together with the exposure conditions gives a good understanding of the long-term performance of concrete structures reinforced with GFRP under various conditions.

### 4.2. Test Setup and Procedure

Cube specimens were subjected to pullout load testing, as shown in figure 3.

**Table 7. Exposure conditions and its types**

| SpecimenID | Concrete Type | GFRP Rebar Type | Exposure Type |
|---|---|---|---|
| PTS1,PTS2 | Plain | Twisted | Marine/ Chlorine |
| FTS1,FTS2 | FRC | | |
| PTC1,PTC2 | Plain | | Conventional |
| FTC1,FTC2 | FRC | | |
| PSCS1,PSCS2 | Plain | SandCoated | Marine/ Chlorine |
| FSCS1,FSCS2 | FRC | | |
| PSCC1,PSCC2 | Plain | | Conventional |
| FSCC1,FSCC2 | FRC | | |

**Fig. 3 Pullout test setup**

In the experiment, the test arrangement involved a specially constructed test configuration for cubic specimens in which the bar’s long end rested on a rigid reference plane and anchored by rounded end wedges. A 2,000 kN universal testing machine evaluated the pullout behaviors of GFRP bars, both with and without fiber addition. Displacement measurements were taken at the loaded and free ends of the embedded rebar to analyze bond slip, following industry guidelines. Concurrent compressive strength tests on cylindrical specimens provided context for the concrete’s properties. This comprehensive approach allowed for a detailed analysis of bond behavior between GFRP rebars and concrete under various conditions, capturing the full range of bond-slip characteristics and revealing insights into how fiber addition and different GFRP rebar types affect bonding in concrete structures. The inclusion of compressive strength data enriched the overall understanding of material performance.

## 5. Test Results and Discussions

The environmental conditioning process resulted in noticeable changes to the specimens. Surface deterioration was evident across most samples, with the concrete exhibiting signs of scaling. More significant damage was observed in specific areas, particularly at the corners of the specimens. The degradation was severe in some cases, leading to substantial concrete fragmentation. These effects are visually documented in the accompanying image.

**Fig. 4 Plain concrete specimens with GFRP rebar exposed to chlorine**

### *5.1. Fiber-Reinforced Concrete Specimens*

The environmental exposure primarily affected the outer layers of the samples. As the concrete surface eroded, the underlying fibers became visible. Despite this surface deterioration, all Fiber Reinforced Concrete (FRC) specimens maintained their structural integrity, as depicted in the accompanying image. Compared to their non-reinforced counterparts, the FRC samples demonstrated superior resistance to environmental degradation, showcasing the protective benefits of fiber reinforcement against harsh conditions.

**Fig. 5 FRC specimens with GFRP rebar exposed to chlorine**

### *5.2. Plain Cement Concrete (PCC)*

This section examines the effects of bar type (Sand-Coated and Twisted), exposure conditions, and the addition of polypropylene fibers on the interfacial bond behavior between GFRP rebars and concrete. The study defines bar pullout failure as the point when the applied load reaches its maximum value. To quantify the bond performance, the research determines the maximum nominal bond stress and its corresponding slip at the point of failure. At the same time, it acknowledges that in pullout tests, the stress distribution at the interface between the reinforcing bar and the concrete matrix varies along the embedded length. Researchers employ a simplified approach to address this non-uniformity by calculating an average bond strength.

This average bond strength is determined using the following equation:

$$\tau avg = Fmax / (\pi * d * L)$$

Where:

This average of these bond strengths is symbolically represented as τavg, as provided in Equation 2.

Fmax is defined as the amount of force by which a screwdriver blade can be pulled out of a stock screw head.

D is the outer diameter of a reinforcing bar.

The other properties of the concrete mix are the following: L is the length of the bar to be introduced.

This considers the multitier stress usually applied for the real pull out of the bond, thus making this method reasonable for estimating the bond performance. This approach offers a scientific methodology in assessing the performance of bonds with no regard to the nature of the particular bond specimen as well as the exposure class.

According to these parameters, the research will aim to find out more about how a number of these parameters affect the characteristic of the bond between the GFRP rebars and the concrete, whereby the effect of the incorporation of the fibre on the bond strength and the required durability will also be determined. Therefore, it becomes possible to do a probability analysis of the bond strength systematically, which will enable one to assess the effects of bar type, exposure conditions, and fibre incorporation into the bond behaviour of the GFRP reinforced concrete structures.

#### *5.2.1. Plain Cement Concrete (PCC)*

Table 8 shows the Ultimate Bond stress results after Chlorine/Marine exposure conditions for a 180-day time period for Plain Concrete specimens with GFRP rebars.

From Table 8, It is found that Sand-coated GFRP rebar reached maximum bond stress of 11.77 MPa under Marine exposure and 13.62 MPa under Conventional exposure conditions, whereas Twisted GFRP rebar attained maximum bond stress values of 9.89 MPa and 12.05 MPa after Marine and Conventional conditions after 180 days of exposure at 45 deg C temperature conditions. The maximum bond stress for both GFRP rebars was more than the average bond stress of 8.58 MPa as per ACI 440.1R -15 requirements. Reduction in bond stress values was observed at 13.54% for sand-coated GFRP rebars and 17.91% for GFRP twisted rebars, respectively, when compared to unaged specimens. Figure 6 shows the bond stress for both sand-coated and twisted GFRP rebars with PCC under chlorine and conventional exposure conditions.

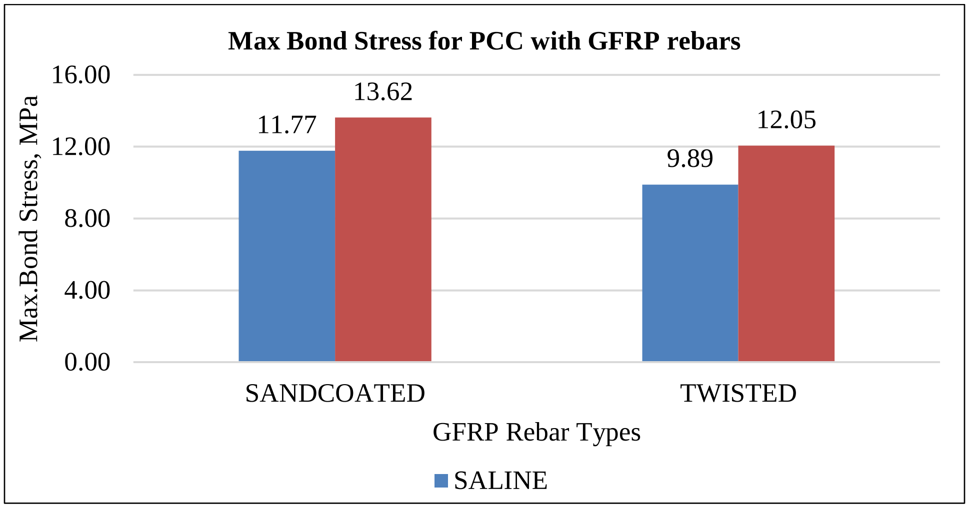


**Fig. 6 Bond Stress for PCC Specimens with GFRP rebar exposed to chlorine/conventional conditions**

**Table 8. Bond stress values for plain concrete with GFRP rebars**

| **Ultimate Bond Stress Values for Plain Concrete with GFRP Rebars** | | | | | | | |
|---|---|---|---|---|---|---|---|
| Exp | Bar Type | Specimen | Db | $P_{ult}$ | $\tau_{max} = P_u/(\pi * d_b * l_b)$ | Failure Mode | % Bond Stress Reduction (η = τA/ τc) |
| | | | mm | KN | MPa | | |
| Chorine Exposure(Marine) | Sandcoated | PSCS1 | 12.7 | 47.250 | 11.849 | Rebar Elongation /Split | 13.54% |
| | | PSCS2 | | 46.650 | 11.698 | | |
| | | PSCS3 | | 46.950 | 11.773 | | |
| | | | MEAN | 46.950 | 11.773 > 8.58 ($\tau_{ave}$) | | |
| | | | SD | 0.245 | 0.061 | | |
| | Twisted | PTS1 | 12 | 37.250 | 9.886 | Slip | 17.91% |
| | | PTS2 | | 37.450 | 9.939 | | |
| | | PTS3 | | 37.150 | 9.859 | | |
| | | | MEAN | 37.283 | 9.895 > 8.58 ($\tau_{ave}$ ) | | |
| | | | SD | 0.125 | 0.033 | | |
| Conventional Exposure | Sandcoated | PSCC1 | 12.7 | 54.500 | 13.667 | Rebar Elongation /Split | - |
| | | PSCC2 | | 54.100 | 13.566 | | |
| | | PSCC3 | | 54.300 | 13.617 | | |
| | | | MEAN | 54.300 | 13.617 > 8.58 ($\tau_{ave}$ ) | | |
| | | | SD | 0.163 | 0.041 | | |
| | Twisted | PTC1 | 12 | 45.250 | 12.009 | Slip | - |
| | | PTC2 | | 45.450 | 12.062 | | |
| | | PTC3 | | 45.550 | 12.089 | | |
| | | | MEAN | 45.417 | 12.053 > 8.58 ($\tau_{ave}$ ) | | |
| | | | SD | 0.125 | 0.033 | | |

### *5.2.2. Fiber Reinforced Concrete (FRC)*

However, in the pullout bond tests, there was a process that was noticed whereby the concrete at the loaded end experienced compaction under compression. This compaction could potentially lead to an increase in load and, subsequently, an overestimation of the measured slip at the loaded end. On the other hand, the slip measurements at the free end were immune to this compaction effect. To achieve the objectives and provide a comparison with previous research work on steel reinforcement, the present study followed a specific criterion for the determination of net bond strength. This criterion is centered on the bond strength, which is associated with a 0. It was observed that at the free end of the specimen, the average slip was of the order of 05 mm. When using the free-end slip measurement as a benchmark, the research avoids the errors arising from the compaction effect in the loaded end. This approach helps in arriving at a more accurate and conservative measure of bond strength and makes the assessment of GFRP rebar performance a lot closer to the standard set for traditional steel rebar. This methodology gives a common testing reference by which the performance of the GFRP rebars in the concrete matrix in terms of bond strength can be compared with equivalency for differing specimen shapes, various exposure climates, and other ordinary reinforcement materials. It is consistent with a detailed consideration with regard to the specific characteristics of pullout behaviour of GFRP-reinforced concrete understood in the context of the given study and confirms the practical, applicable outcomes of the research directed towards its applications in design. Table 9 shows the Bond stress values after Chlorine/Marine exposure conditions for specimens with FRC for a 180-day time period.

From Table 9, It is found that Sand-coated GFRP rebar achieves maximum bond stress of 13.66 MPa and 14.70 MPa, whereas Twisted GFRP rebar attained maximum bond stress values of 12.39 MPa and 13.94 MPa after exposure to Marine and Conventional conditions after 180 days of exposure at 45 deg C temperature conditions. Reduction in bond stress values was observed at 7.08% for sand-coated GFRP rebars and 11.15% for GFRP twisted rebars, respectively. Figure 7 shows the bond stress for both sand-coated and twisted GFRP rebars with FRC under chlorine and conventional exposure conditions.

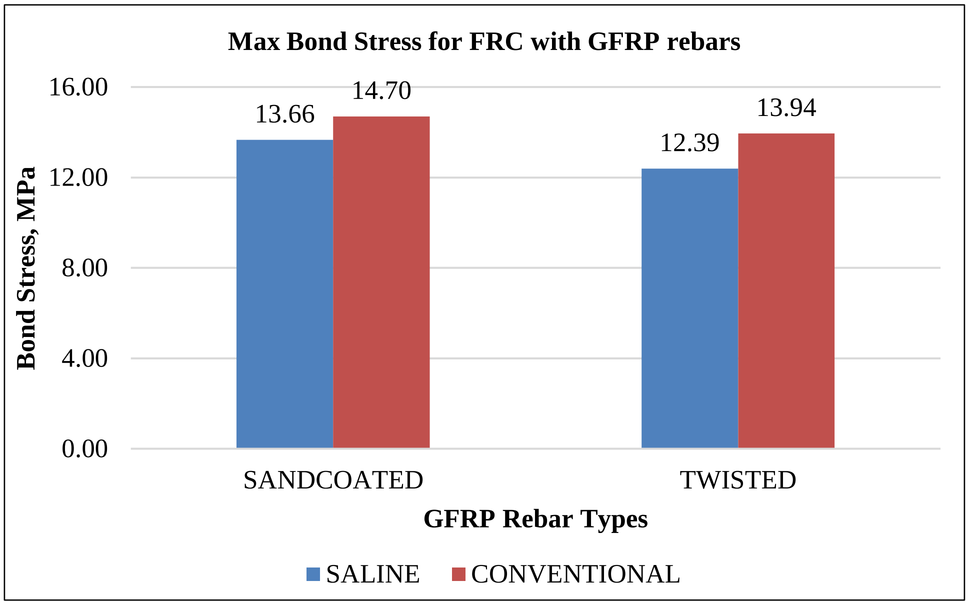


**Fig. 7 Bond Stress for FRC Specimens with GFRP rebar exposed to Chlorine/Conventional conditions**

A study of the bond strength reduction, as depicted in carry out of Figure 8, showed that FRC coupons were characterized by lower reduction compared with the PCC coupons. In PCC samples, the average bond strength reduction was 14% for sand-coated rebars and 18% for twisted GFRP rebars.

However, FRC samples contained lesser degradation values of about 7% for sand-coated positions and 11% for twisted rebars. This observed reduction in bond strength is indicative of possible material degradation of the FRP bars, a fact confirmed by Chen et al. (2007) [17]. These findings confirmed previous studies that indicated the inclusion of fibers improved bond strength and durability and provided an indication that fiber reinforcement could alleviate bond degradation due to environmental conditioning.

In the course of environmental exposure, cracks or voids may occur on surfaces such as concrete. Despite most of the research indicating that fiber addition does not elevate the first cracking load, it limits crack extension arising from water reaction or movement of the reinforcement bar. By investigating the FRC specimens' performance enhancement shown in the test results, the less the concrete damage after environmental conditioning. The comparative evaluation of bond stress reduction of both FRC and PCC has been depicted in Figure 8 in the presence of two different types of GFRP rebar exposed to marine environmental conditions. This diagram helps convey the message of how fiber inclusion helps maintain bond strength in an aggressive environment. These results indicate that the integration of fiber-reinforced concrete matrices together with GFRP rebars can prove advantageous in structures that are subjected to severe marine weather conditions. The increase in specimens' durability and decrease in bond strength degradation of FRC in the present study indicate that this combination may contribute to an increase in concrete structures' reliability and service life in aggressive and severe environments.

**Table 9. Bond stress values for FRC concrete with GFRP rebars**

| **Ultimate Bond Stress Values for Fiber Reinforced Concrete with GFRP Rebars** | | | | | | | |
|---|---|---|---|---|---|---|---|
| Exp | Bar Type | Specimen | Db | $P_{ult}$ | $\tau_{max} = P_u/(\pi * d_b * l_b)$ | Failure Mode | % Bond Stress Reduction ($\eta = \tau A/\tau c$) |
| | | | mm | KN | MPa | | |
| Chlorine Exposure(Marine) | **Sandcoated** | FSCS1 | 12.7 | 54.810 | 13.744 | Rebar Elongation /Split | 7.08% |
| | | FSCS2 | | 54.114 | 13.570 | | |
| | | FSCS3 | | 54.462 | 13.657 | | |
| | | | MEAN | **54.462** | **13.657 > 8.58 ($\tau_{ave}$)** | | |
| | | | SD | 0.284 | 0.071 | | |
| | **Twisted** | FTS1 | 12 | 46.850 | 12.434 | Slip | 11.15% |
| | | FTS2 | | 46.650 | 12.381 | | |
| | | FTS3 | | 46.550 | 12.354 | | |
| | | | Mean | **46.683** | **12.389 > 8.58 ($\tau_{ave}$)** | | |
| | | | SD | 0.125 | 0.033 | | |
| Conventional Exposure | **Sandcoated** | FSCC1 | 12.7 | 58.840 | 14.755 | Rebar Split | - |
| | | FSCC2 | | 58.550 | 14.682 | | |
| | | FSCC3 | | 58.450 | 14.657 | | |
| | | | Mean | **58.613** | **14.698 > 8.58 ($\tau_{ave}$)** | | |
| | | | SD | 0.165 | 0.041 | | |
| | **Twisted** | FTC1 | 12 | 52.640 | 13.970 | Slip | - |
| | | FTC2 | | 52.440 | 13.917 | | |
| | | FTC3 | | 52.550 | 13.946 | | |
| | | | Mean | **52.543** | **13.945 > 8.58 ($\tau_{ave}$)** | | |
| | | | SD | 0.082 | 0.022 | | |

### *5.3. Bond - Slip Response*

The normalized interfacial bond stress-slip curve indicates a steep initial linear region representing the elastic slip within a small slip, followed by a nonlinear softening behavior due to interface deterioration near the embedded bar. It was also found that the post-peak behaviour of the load-slip curves depends on the type of fibre reinforcement and the type of rebar used in the work. They are able to shed light on how different material pairings behave after the first signs of debonding and reveal their intrinsic mechanical characteristics and interface behavior. This difference in post-peak trend clearly demonstrates that the response of concrete matrix, fiber reinforcement, and GFRP rebar surface treatments is interdependent and gives some understanding of their performance in various structural uses and environmental situations.

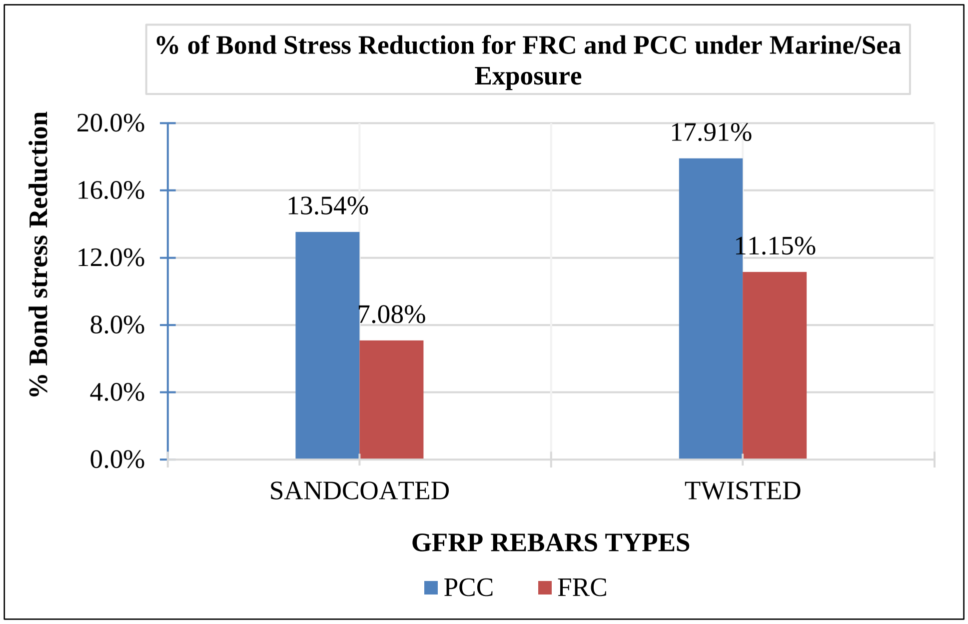


**Fig. 8** Reduction of bond stress for FRC and PCC specimens with GFRP rebar exposed to chlorine/conventional conditions

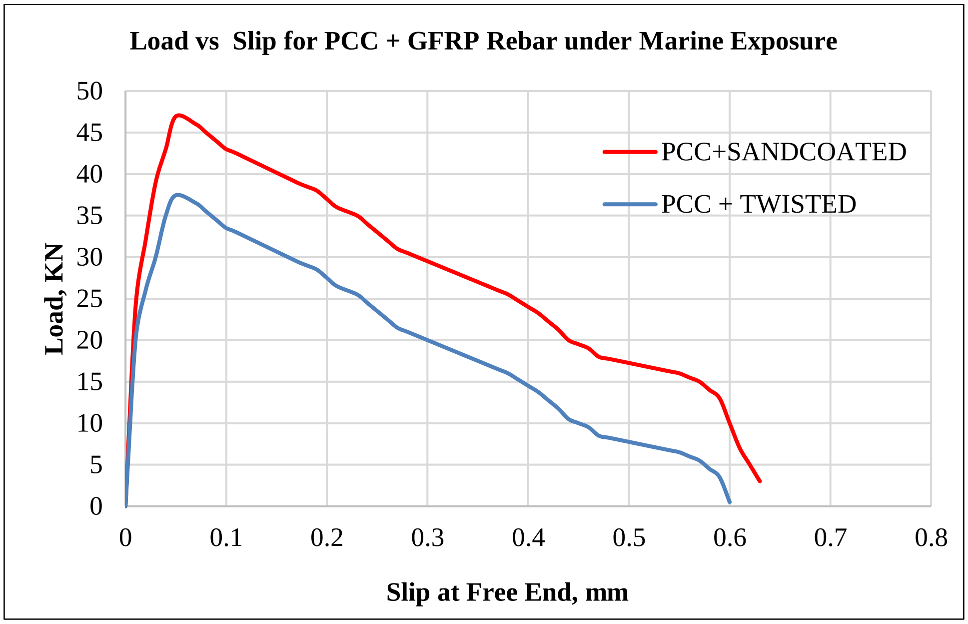


**Fig. 9** Load vs Slip for PCC specimens with GFRP rebar exposed to marine conditions

### *5.3.1. Plain Cement Concrete (PCC)*

Specimens tested under prescribed conditions yielded periodic values, while the specimens exposed to environmental conditioning displayed higher variations in the values, probably because the degradation process is random in nature. Before testing, visual observations showed that the plain concrete specimens exposed to severe damage were associated with low bond strength [18]. All tested specimens evidenced a reduction in the severity of their bond-slip curves after the environmental exposure, as evidenced in the figure depicting bond stress against slip relationship for plain concrete specimens exposed to chlorine/marine environment for 180 days. These observations draw attention to the multiple impacts of environmental deterioration on GFRP-reinforced concrete structures. Regarding bond-slip curves and concrete damage to bond strength, particular attention should be given to the effects of various environmental conditions or the durability of such structures, mainly in marine or chlorine-exposed atmospheres.

Specimens tested under standard conditions showed consistent results, while those exposed to environmental conditioning exhibited greater variability, likely due to the random nature of degradation processes. Visual assessments revealed a correlation between concrete damage severity and reduced bond strength, with the most severely damaged plain concrete specimens showing very low bond strengths. All tested specimens displayed softening of their bond-slip curves after environmental exposure, as illustrated in the figure showing bond stress versus slip curves for plain concrete specimens after 180 days in chlorine/marine conditions. These observations highlight the complex effects of environmental degradation on GFRP-reinforced concrete structures [19]. The softening of bond-slip curves and the relationship between concrete damage and bond strength emphasize the importance of considering environmental factors in the design and durability assessment of such structures, particularly in aggressive environments like marine or chlorine-rich settings.

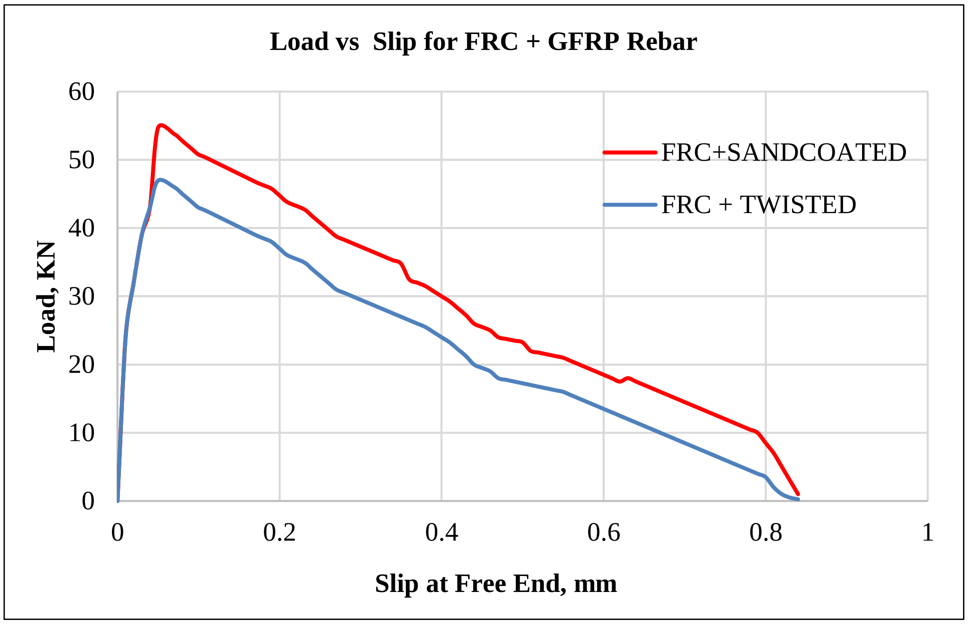


**Fig. 10 Load Vs Slip for FRC specimens with GFRP rebar exposed to marine conditions**

### *5.3.2. Fiber Reinforced Concrete (FRC)*

The specimens tested under standard conditions had relatively similar test results, while the ones that were exposed to environmental conditioning had higher variability of the test results, likely because of the random nature of the degradation process. Samples of plain concrete as well as DC concrete were also submitted to interface bond strength testing, and it was ascertained that concrete which was more deteriorated resulted in lower bond strength and plain concrete samples which displayed severe deterioration registered the lowest values of bonding strength.

The graph of bond stress versus slip for plain concrete samples after six months in chlorine/marine environments showed that environmental exposure resulted in the softening of the bond-slip curves for all the specimens tested [20]. These findings demonstrate the complex relationship between the environment and GFRP-reinforced concrete structures.

The general patterns of the bond-slip curves, together with the dependency between the concrete properties and the bond strength, prove the fact that environmental issues should be taken into consideration for such structures and durability assessments of the structures when they will be exposed to severe environments like marine or chlorine.

Failure modes: These composites' bond failure mechanisms contrast in some aspects of concrete. In all the diameters that were tested, GFRP bars had a consistent failure at the bar-concrete interface location [9]. External WEAR Barrier, or discrete layer outside of the bar, including a helical aramid fiber wrapping and a quartz sand coating. Getting this detachment provided the section of the bar that had been in contact with the concrete to be absolutely smooth.

Pullout tests reveal two primary failure modes for steel rebars: concrete crushing localized between the ribs, resulting in shear crack and splitting failure due to exces-sive radially acting stress. GFRP rebars show similar trends but have specific failure modes with regard to their surface coatings.

The introduction of fiber in the last mix significantly reduces the pull-out fails by limiting crack nucleation and propagation. This changed failure mechanism is easy to discern in the interface failure modes of rebars in FRC, as illustrated in the picture below. The results of this research underscore the complex issue of bonds in concrete with GFRP reinforcement and present the potential of fiber addition with respect to the bond efficiency and failure mode. A fundamental understanding of all these diverse failure mechanisms is crucial in order to improve the design and performance of structures with GFRP concrete reinforcement, particularly where durability is a key requirement.

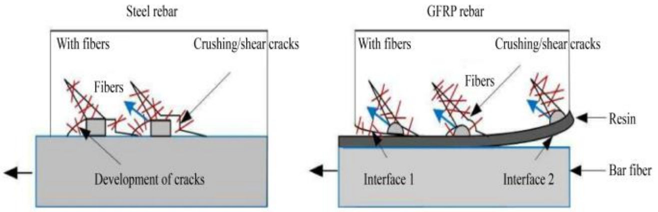


**Fig. 11 Idealized interfacial failure modes**

The current experimental results indicate that the majority of the specimens had failure characteristics similar to those observed in samples that were not exposed to moisture. Nevertheless, significant shifts in failure modes were identified, particularly for the Sand-coated and twisted GFRP rebar specimens, which underwent environmental conditioning. These changes in failure characteristics imply that these specific GFRP rebar forms could be more vulnerable to variations in bond behavior from the weathering procedures that they undergo.

Twisted GFRP did not rise to the challenge in the reinforcement pullout test, while sand-coated rebar failed in rebar elongation or splitting of the rebar. The failure modes of the GFRP rebar are discussed below and presented in Figure 12.

**Fig. 12 Failures modes of GFRP (Sand-coated/Twisted) rebars@ direct pull out test after 180 days of exposure under marine/conventional exposure conditions**

## 6. Conclusion

This study investigated the long-term bond performance between GFRP bars and Fiber Reinforced Concrete (FRC), comparing it with GFRP bars in plain concrete. Accelerated aging tests were conducted by submerging specimens in salt solutions for 180 days at 45°C. The research yielded several key findings:

- GFRP twisted rebars exhibited lower bond strengths compared to sand-coated rebars, with a 16% reduction in plain concrete and a 9% reduction in FRC specimens.
- Sand-coated GFRP rebars demonstrated superior bond resistance under marine exposure conditions compared to twisted rebars.
- FRC specimens showed better integrity and resistance to environmental attack compared to plain concrete specimens.
- The addition of polypropylene fibers increased bond strength by 40-50% compared to normal concrete specimens.
- Fiber inclusion altered the failure mode of GFRP bars from partial resin debonding to complete failure.
- Discrete fiber or transverse reinforcement proved effective in increasing the bond strength between GFRP bars and concrete.
- Chlorine solution exposure led to significant losses in both tensile and bond strength, indicating a need for further studies on combined environmental effects.

Polypropylene fiber addition significantly improved bond durability by restricting crack development at the interface. Plain concrete specimens showed an average 18% reduction in design bond strength of FRP bars due to aging, while FRC specimens experienced only a 7% reduction.

These findings highlight the potential benefits of using fiber-reinforced concrete with GFRP rebars in marine environments, demonstrating improved durability and bond performance compared to traditional plain concrete reinforcement systems.

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