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EFFECT OF CORROSIVE ENVIRONMENT ON BOND STRENGTH OF FRP BARS IN DIFFERENT GRADE OF CONCRETE

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Abstract: Corrosion of steel reinforcement severely compromises the longevity of concrete infrastructure in aggressive environments. Fiber-Reinforced Polymer (FRP) bars offer a corrosion-resistant alternative; however, maintaining exceptional bond integrity at the bar–concrete interface is critical for overall structural stability. This study systematically evaluates the impact of aggressive environmental conditioning on the compressive and bond strength of FRP bars embedded across three ordinary concrete grades: M30, M35, and M40. Pull-out specimens and cubes were subjected to accelerated curing in marine (3.5% NaCl) and industrial acidic (3.5% HCl) solutions for up to 28 days. Destructive testing revealed that acidic exposure inflicted the most severe deterioration, reducing bond strength by up to 30% and causing high susceptibility in lower-grade (M30) mixes. Conversely, higher-grade concrete (M40) demonstrated superior mechanical resilience due to its dense microstructural matrix, which effectively limited degradation, preserved critical confinement pressure, and ensured long-term interfacial load transfer efficiency.

Keywords: FRP bars, Bond strength, Corrosive environment, Concrete grade, Pull-out test, Compressive strength, Durability, Marine exposure, Acidic degradation, Structural performance.

I. INTRODUCTION

Reinforced concrete is a dominant global construction material, but conventional structures face severe durability challenges in aggressive environments. In coastal regions, marine infrastructure, and chemical plants, the intrusion of chloride ions and acids destroys the alkaline protection of concrete, triggering electrochemical steel corrosion. As steel rusts, its volumetric expansion generates internal tensile stresses, causing micro-cracking, spalling, and a catastrophic loss of the interfacial bond required for effective composite action.

To eliminate this degradation mechanism, Fiber-Reinforced Polymer (FRP) bars have emerged as an excellent non-corrosive alternative due to their high tensile strength, lightweight nature, and absolute immunity to electrochemical rusting. However, the long-term structural safety of FRP-reinforced systems relies entirely on the bond strength at the bar–concrete interface. While FRP bars do not rust, prolonged exposure to harsh chemicals can potentially degrade the surrounding concrete matrix and alter the surface interlocking mechanisms of the composite bar.

This research investigates the degradation of this critical interface by evaluating the bond performance of FRP bars embedded in three distinct concrete grades: M30, M35, and M40. Specimens were subjected to accelerated environmental conditioning via submersion in a marine-simulating saline solution ($3.5\%\text{ NaCl}$) and an industrial acidic medium ($3.5\%\text{ HCl}$) for up to 28 days. By analyzing changes in compressive strength, pull-out capacity, and localized failure modes, this study clarifies how matrix density and environmental aggressiveness interact to influence the long-term bond retention and durability of FRP-reinforced concrete.

II. PROBLEM STATEMENT

The premature degradation of reinforced concrete structures due to conventional steel corrosion incurs massive global maintenance costs and poses severe structural safety risks, particularly in marine and industrial environments. While Fiber-Reinforced Polymer (FRP) bars have emerged as a highly viable, corrosion-resistant alternative to traditional steel, the overall structural integrity of any reinforced concrete member relies fundamentally on the continuous transfer of stresses across the bar–concrete interface.

The primary challenge lies in the fact that this critical interfacial bond is not inert; it remains highly vulnerable to aggressive chemical conditioning. Marine environments (saline solutions) and industrial pollution (acidic mediums) systematically attack the surrounding concrete matrix, inducing microstructural damage, altering concrete confinement pressure, and potentially degrading the surface interlocking mechanisms of the FRP bars.

Currently, there is a lack of comprehensive data regarding how different strengths or grades of concrete (such as M30, M35, and M40) interact with FRP bars to preserve or lose this crucial bond capacity under accelerated chemical attacks. Without a clear quantification of these degradation rates, structural engineers cannot safely predict the service life, residual bond capacity, or transitioning failure modes of FRP-reinforced systems deployed in highly corrosive, real-world environments.

III. LITERATURE REVIEW

The structural efficacy of Fiber-Reinforced Polymer (FRP) reinforced concrete elements relies fundamentally on the continuous transfer of stresses across the bar–concrete interface, which is governed by chemical adhesion, surface friction, and mechanical interlock. While traditional steel reinforcement suffers from severe electrochemical corrosion that generates internal tensile stresses and cracks the surrounding concrete matrix, FRP bars offer an immune alternative due to their non-corrosive composite nature. However, existing literature establishes that this critical interfacial bond remains highly vulnerable to aggressive environmental conditioning.

When subjected to marine conditioning (saline solutions), moisture and chloride ion diffusion can induce matrix swelling, plasticization, and hydrolysis within the polymer resin, alongside a mild chemical softening of the surrounding concrete paste. Conversely, industrial acidic conditioning (HCl) exerts a far more destructive impact by directly attacking the calcium hydroxide and calcium-silicate-hydrate gel within the cement matrix, increasing localized porosity and severely stripping away the concrete's confinement pressure.

A critical factor in mitigating this chemical degradation is the compressive strength grade of the concrete mix. Higher-grade concretes feature a dense microstructure and a tightly packed Interfacial Transition Zone, which provides superior mechanical interlocking and limits chemical permeability. While past studies have evaluated the standalone chemical degradation of composites, there remains a critical research gap in directly comparing how distinct concrete grades (such as M30, M35, and M40) interact with FRP bars to preserve residual bond capacity and alter shifting failure modes under localized chemical attacks.

IV. METHODOLOGY

The experimental program was structured systematically to evaluate the mechanical and interfacial degradation of Fiber-Reinforced Polymer (FRP) reinforced concrete systems exposed to aggressive chemical environments. The experimental matrix involved preparing two distinct categories of test specimens: standard 150 mm concrete cubes to determine compressive strength, and specialized concrete blocks with a single FRP rebar centrally embedded to assess localized bond integrity. These specimens were cast using three distinct mix designs proportioned for M30, M35, and M40 grades, incorporating a 10 % wastage allowance. Fresh concrete was placed inside steel moulds, compacted thoroughly using standard tamping rods to eliminate voids, and meticulously troweled smooth. Following an initial 24-hour setting period, specimens were demoulded, labeled, and transferred into three isolated chemical storage tanks for accelerated deterioration conditioning. The environmental exposure tracks included a normal tap water curing medium to monitor baseline hydration strength development, a marine simulation environment consisting of continuous immersion in a 3.5 % Sodium Chloride (NaCl) solution, and an industrial chemical attack medium consisting of continuous immersion in a 3.5 % Hydrochloric Acid (HCl) solution.

Upon reaching targeted exposure durations of 14 and 28 days, destructive testing was carried out immediately. Compressive strength was evaluated by centrally loading the cube blocks into a Compression Testing Machine until crushing failure occurred to record the ultimate peak load. Concurrently, direct pull-out testing was performed using a Universal Testing Machine equipped with a specialized loading frame that anchored the concrete block while applying a direct, controlled tensile force to the protruding end of the FRP bar. The maximum peak pull-out force was recorded to evaluate the ultimate bond stress, while final failure modes such as pure bar slip or sudden concrete splitting—were carefully monitored and categorized to understand the changing mechanics of the deteriorated interface.

Table: I Sample preparation details

Experimental stage	**Specimen type**	**Main variable**	**Output**
Stage 1: Concrete matrix test	150 mm cube	Concrete grade and exposure condition	Compressive strength
Stage 2: Bond test	Cube with centrally embedded FRP bar	Concrete grade and exposure condition	Peak pull-out load and bond stress

V. RESULTS AND DISCUSSION

The experimental results clearly demonstrate that both concrete grade and exposure condition influence the compressive strength and bond strength of FRP-reinforced specimens. In all cases, specimens cured in normal water achieved higher strengths than those exposed to NaCl and HCl solutions, confirming that aggressive media reduce both the quality of the concrete matrix and the effectiveness of the FRP–concrete bond. Among the three grades, M40 concrete consistently showed the highest resistance to strength loss, followed by M35 and M30, which indicates that higher-grade mixes provide better protection to the embedded FRP bars.

The compressive strength values presented in Table 2 show that all three concrete grades gained strength with age; however, the detrimental effect of corrosive exposure is evident at both 7 and 28 days. Specimens stored in HCl exhibited the largest reduction in compressive strength for each grade, while NaCl-exposed specimens showed an intermediate level of strength loss compared with the normal water controls. This behaviour highlights that acidic attack is more severe than saline exposure for the concrete matrix, and any reduction in compressive strength is expected to have a direct impact on the bond performance of FRP bars embedded in the same concrete.

Table:2 Compressive strength results

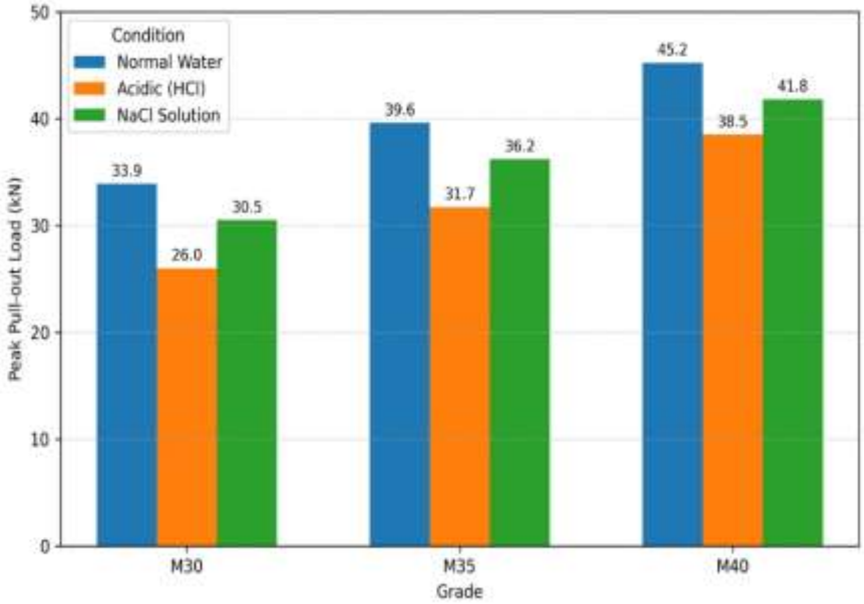
Concrete grade	**7 days Normal**	**7 days NaCl**	**7 days HCl**	**28 days Normal**	**28 days NaCl**	**28 days HCl**
M30	21.0	19.8	18.5	34.2	30.8	26.5
M35	24.5	22.4	20.1	39.5	35.2	31.0
M40	28.0	26.2	23.5	45.1	41.5	36.8

The pull-out bond strength results in Table 3 follow a similar trend to the compressive strength data. For all three grades, the highest bond stresses were recorded for specimens cured in normal water, with progressively lower values for NaCl and HCl conditioning at both 14 and 28 days. M40 concrete again provided the highest bond strength and the smallest relative loss under corrosive exposure, which can be attributed to the denser microstructure and improved confinement around the FRP bar in the higher-grade mix. The observed reduction in bond capacity under NaCl and HCl exposure is mainly associated with matrix softening, micro-cracking in the cover region and weakening of mechanical interlock at the bar–concrete interface.

Table:3 FRP pull-out bond strength results

Concrete grade	**14 days Normal**	**14 days NaCl**	**14 days HCl**	**28 days Normal**	**28 days NaCl**	**28 days HCl**
M30	15.0	13.5	11.5	17.0	15.0	12.5
M35	17.5	16.0	14.0	20.5	18.5	15.5
M40	20.0	18.5	17.0	25.0	23.0	20.5

Changes in failure mode with exposure condition further support these observations. Lower-grade concretes and specimens subjected to acidic attack tended to fail by splitting and premature bond failure, indicating that the cracked and weakened cover could not sustain the stresses developed around the FRP bar. In contrast, higher-grade specimens more frequently exhibited pull-out or interfacial shear failure, suggesting that stronger and denser concrete delays splitting and maintains bond performance for a longer period under aggressive environments. Overall, the graphical trends in Graphs 1 and 2 confirm that M40 concrete offers the most favourable bond behaviour for FRP bars in all exposure conditions.



Graph 1: FRP bond strength by grade and condition for 14 days

The corrosion weight-loss results in Table 4 provide additional insight into the relative durability of glass-FRP and steel bars under the same solutions. Glass-FRP bars showed negligible weight change in normal water and NaCl solution, with only a slight loss and surface dullness in HCl, while both Fe250 and Fe500 steel bars experienced significant mass loss and severe surface damage in the corrosive media. The observations of uniform diameter reduction, heavy scaling and deep pitting on steel bars, particularly in acidic and saline solutions, contrast sharply with the almost unchanged condition of FRP bars and illustrate the corrosion-free nature of FRP reinforcement. These findings reinforce the motivation for using FRP bars in structures exposed to aggressive environments, provided that their bond with concrete is adequately ensured.

Table:4 Corrosion Test [Weight Loss]

Sr no.	Solution Environment	Bar Type	Initial Weight (g)	Final Weight (g)	Net Weight Loss (g)	Specific Structural Observation
1.	Normal Tap Water (Control)	Glass-FRP	22.91	22.91	0.00	No visual or structural change.
2.	Normal Tap Water (Control)	Fe250 Mild Steel	90.18	89.44	0.74	Uniform light orange layer of surface rust.
3.	Normal Tap Water (Control)	Fe500 TMT Steel	90.25	89.81	0.44	Minor pinpoint rust spots on the outer ribs.
4.	3.5% HCl Solution (Acidic Attack)	Glass-FRP	22.88	22.74	0.14	Outer epoxy glossy finish turned dull and whitish.
5.	3.5% HCl Solution (Acidic Attack)	Fe250 Mild Steel	90.21	66.85	23.36	Severe, uniform diameter reduction; heavy scaling.
6.	3.5% HCl Solution (Acidic Attack)	Fe500 TMT Steel	90.14	77.21	12.93	Deep, irregular rough etching across entire surface.
7.	3.5% NaCl Solution (Marine Simulation)	Glass-FRP	22.93	22.93	0.00	Zero reaction; physical properties intact.

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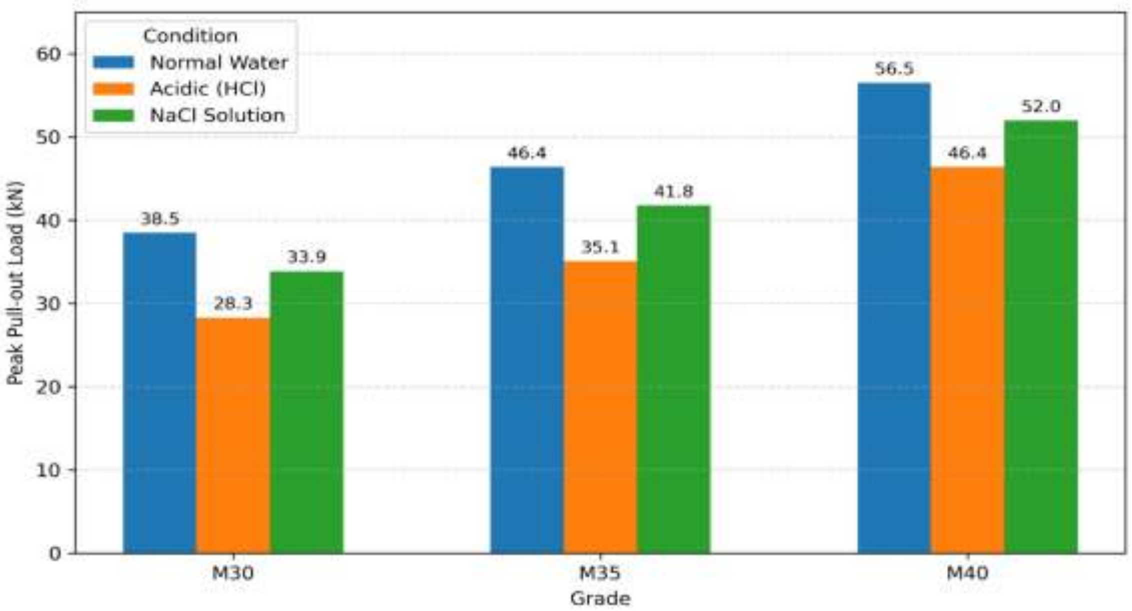
8.	3.5% NaCl Solution (Marine Simulation)	Fe250 Mild Steel	90.23	85.41	4.82	Heavy dark-brown flaky rust; severe pitting.
9.	3.5% NaCl Solution (Marine Simulation)	Fe500 TMT Steel	90.17	87.53	2.64	Dark blackish oxides; localized macro-pitting.

The percentage bond strength loss and retention values presented in Table 5 summarise the combined effect of concrete grade and exposure condition at 14 and 28 days. For all grades, bond strength retention was higher in NaCl solution than in HCl solution, confirming that acidic exposure is more damaging to the FRP–concrete bond than saline exposure. M40 concrete consistently exhibited the smallest percentage loss and the highest retention, with values remaining above those of M35 and M30 at both ages and in both corrosive media. The trends plotted in Graphs 3 and 4 therefore indicate that increasing concrete grade leads to improved bond durability, and that the negative impact of prolonged exposure is most pronounced in lower-strength mixes.

In summary, the results show that FRP bars themselves are highly resistant to corrosion, but their bond performance is strongly affected by the quality of the surrounding concrete and the nature of the exposure environment. Higher-grade concrete, particularly M40, enhances the anchorage around the FRP bar and mitigates bond degradation under NaCl and

Table:5 Percentage Bond Strength Loss of FRP Bars at 14 and 28 Days

Grade	**14 Days NaCl Loss**	**14 Days HCl Loss**	**28 Days NaCl Loss**	**28 Days HCl Loss**	**14 Days NaCl Retention**	**14 Days HCl Retention**	**28 Days NaCl Retention**	**28 Days HCl Retention**
M30	10.00%	23.33%	11.76%	26.47%	90.00%	76.67%	88.24%	73.53%
M35	8.57%	20.00%	9.76%	24.39%	91.43%	80.00%	90.24%	75.61%
M40	7.50%	15.00%	8.00%	18.00%	92.50%	85.00%	92.00%	82.00%



Graph 2: FRP bond strength by grade and condition for 28 days

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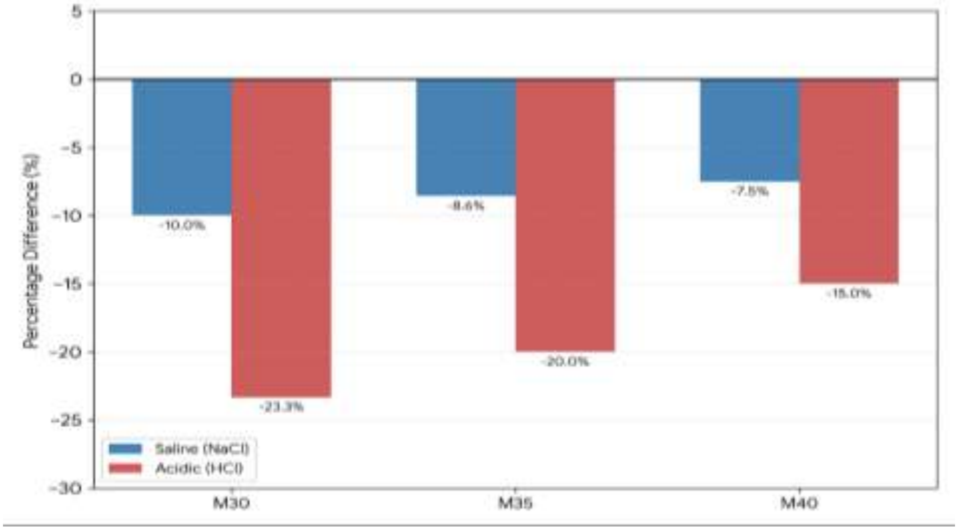
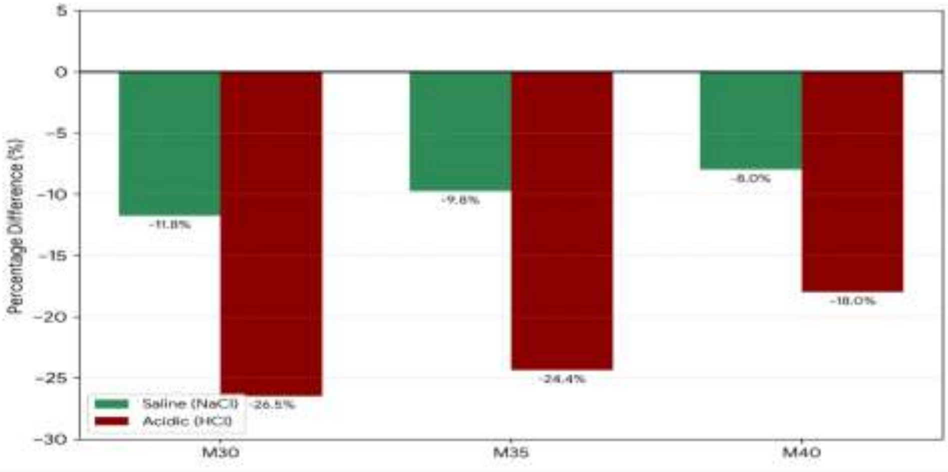
Figure 4.3: Specimen after Exposure



Graph 3: 28 Days Bond Strength Percentage Variance (Compared to Normal Water Baseline)

Graph 3 illustrates the 28-day bond strength percentage variation relative to the normal water baseline. All specimens conditioned in corrosive media exhibited a reduction in bond strength, with HCl producing the greatest loss and NaClcausing a comparatively smaller decrease, indicating that higher-grade concrete provides better resistance to bond degradation at 28 days



Graph 4: 14 Days Bond Strength Percentage Variance (Compared to Normal Water Baseline)

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Graph 4 presents the 14-day bond strength percentage variation with respect to the normal water baseline. Conditioning in corrosive media reduced bond strength for all three concrete grades, with HCl causing the greatest reduction and NaCl producing a comparatively smaller decrease. Among the mixes, M40 exhibited the highest bond retention, followed by M35 and M30, confirming that higher-grade concrete provides better resistance to bond degradation at 14 days.

VI. CONCLUSION

The experimental investigation demonstrates that the structural durability and load-transfer capacity of Fiber-Reinforced Polymer (FRP) reinforced systems are profoundly dictated by the interaction between the surrounding concrete matrix and the aggressiveness of the chemical environment. Higher concrete grades provide vastly superior protection against corrosive environments, as the denser microstructure, tightly packed particle matrix, and significantly reduced permeability inherent to the M40 mix effectively restrict the depth and rate of aggressive chemical diffusion to shield the inner bar interface. Conversely, industrial acidic conditioning (3.5 % HCl) proves to be the most destructive exposure medium, severely disrupting the matrix's structural hydration integrity to reduce concrete compressive strength by 18 % to 25 % and strip ultimate bond capacity by up to 30 % over 28 days, while marine simulation (3.5 % NaCl) causes comparatively moderate deterioration with compressive losses limited between 8 % and 12 % and maximum bond drops of 15 %. Ultimately, lower-grade M30 concrete displays the highest environmental susceptibility by losing up to 26.5 % of its ultimate bond capacity under acidic attack, whereas the M40 grade demonstrates excellent mechanical resilience by retaining up to 92 % of its baseline bond strength in saline and 82 % in acidic solutions. This chemical degradation fundamentally alters post-peak mechanical behavior, shifting the failure mode from a progressive, relatively ductile bar pull-out mechanism seen in the high-resilience M40 and control specimens to sudden, brittle concrete splitting in the degraded M30 and M35 blocks due to a critical loss of matrix tensile capacity and radial confinement pressure.

Overall, the findings indicate that although FRP bars themselves are essentially corrosion-resistant, their structural performance still depends on maintaining an adequate bond with the surrounding concrete when the member is exposed to harsh media. Among the grades studied, M40 concrete offered the best combination of strength and bond durability under NaCl and HCl exposure, followed by M35 and then M30, which supports the use of higher-grade concrete for FRP-reinforced elements in coastal and chemically aggressive conditions. Proper selection of concrete grade, appropriate curing and measures to limit contact with aggressive solutions are therefore essential to ensure durable and reliable performance of FRP-reinforced concrete structures

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