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Bond Durability of GFRP Bars in Alkaline Environment

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A B S T R A C T

Marine infrastructure is highly vulnerable to corrosion due to chloride rich environment that poses severe durability and serviceability issues. Glass Fibre-Reinforced Polymer (GFRP) bars provide an excellent alternative to steel to eliminate corrosion related issues. However, the durability of GFRP bars in concrete's highly alkaline environment remains a concern. This study evaluates the effects of alkaline exposure on the bond performance of 8, 10, and 12 mm GFRP bars. Pullout specimens were cast and immersed in simulated alkaline solution for a duration of 90 and 180 days. Pullout tests conducted after 90 and 180 days revealed minimal bond deterioration at 90 days, while a 3–4% reduction was observed after 180 days compared to control specimens. The findings offer significant contribution in developing design models to predict service life of GFRP bars in alkaline environment.

Keywords: *GFRP bars, bond retention, alkali exposure, bond stress, free end slip, failure modes.*

1 Introduction

Corrosion of steel reinforcement significantly compromises the durability and serviceability of RC structures by reducing bar cross-section and degrading steel–concrete bond performance [1]. As an alternative to corrosion issue of steel rebars, Glass Fibre-Reinforced Polymer (GFRP) bars have gained prominence due to their lightweight nature, cost-effectiveness, and favourable mechanical properties [2]–[5]. Despite these advantages, concerns regarding the long-term durability of GFRP bars persist, primarily due to the susceptibility of the glass fibre–resin matrix to degradation in concrete's highly alkaline environment.

GFRP bars, manufactured via pultrusion, exhibit excellent tensile strength, however, the resin matrix undergoes hydrolytic degradation in moist, alkaline conditions [6]. The schematic representation of degradation process is shown in Figure 1. Factors such as fibre and resin type, bar diameter, and exposure environment influence degradation behaviour of GFRP bars [7]–[9]. Studies indicate that though GFRP bars performs slightly better in saline environments due to protective salt layer formation [5]-[6] they tend to deteriorate in alkaline environment. Hydrolysis of ester bonds by hydroxyl ions drives this degradation process [10]-[11], which over time weakens the fiber-resin matrix resulting disintegration of fibers.

Bond behaviour is essentially critical for long term structural performance. Unlike steel, GFRP bond strength varies with bar surface condition, resin system, concrete strength, and diameter [12]-[14]]. Carbon–epoxy GFRP bars exhibit better bond performance than glass–vinyl ester bars [15], though overall bond capacity remains lower than steel due to surface damage and slip under radial stresses [16]. Surface enhancements such as helical wrapping combined with sand coating; significantly improve bond strength [17], while larger diameters tend to reduce it. Research on bond degradation under alkaline exposure is limited and the existing results could not assess the actual degradation of bond in alkaline environment. Some studies report minimal reduction after conditioning at elevated temperatures [18],[19], while others observe 15–20% bond loss under prolonged exposure [20],[21], attributed to alkali ion ingress and interfacial damage. These discrepancies underscore the need for systematic investigation.

This study addresses existing gaps by examining bond durability of smaller-diameter (8, 10, and 12 mm) GFRP bars in alkaline environments. Pull-out tests were performed after 90 and 180 days of alkaline exposure. The experimental findings offer quantitative insight into bond retention mechanisms and support the development of reliable design guidelines for GFRP-reinforced concrete structures.

2 Experimental program

2.1 Materials

The GFRP bars of diameter 8, 10 and 12 mm were used in the current study supplied by local manufacturer in India. GFRP bars are made of E Glass fibers (71%) and epoxy resin. Anchors at ends of GFRP bars are prepared based on ASTM D7205 (2016) [22] using resin and

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hardener. The mechanical properties of GFRP bars are provided in Table 1.

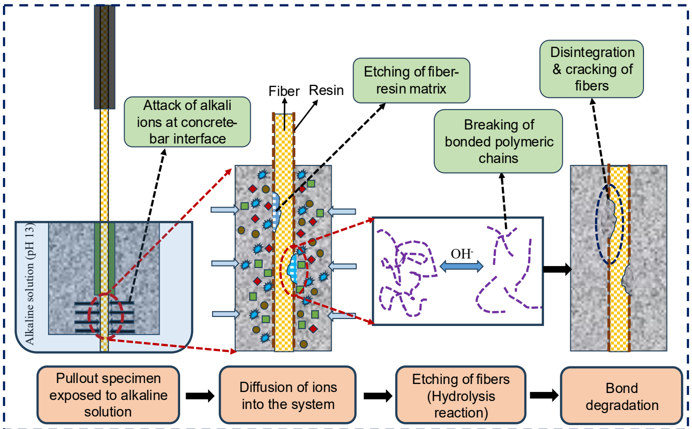

Figure 1 Degradation process of GFRP pull-out specimen under alkaline exposure

Table 1 Mechanical properties of GFRP bars

Type of bar	Nominal Diameter (mm)	C/s area (mm^2)	Ultimate strength (MPa)	Elastic modulus (MPa)	Ultimate strain (%)
GFRP	8	50.3	671	38	2.2
	10	78.5	648	54	2.8
	12	113.05	733	84	2.8

2.2 Specimen configurations

2.2.1 Specimen preparation for pullout specimens

The specimen configuration of the pull-out specimens to investigate the bond durability in alkaline environment, is shown in Table 2. The prepared pull-out specimens for bond test are shown in Figure 2. The grade of concrete used for the current study is M40 whose compressive strength results are given in Table 3.

2.2.2 Test Setups

The test setups used to test pull-out specimens after alkali exposure is shown in Figure 3.

Figure 2 Pull-out specimens

Table 3 Compressive strength of concrete cubes

Exposure duration	Compressive strength			Average
	Cube 1	Cube 2	Cube 3	
28	45.56	49.85	48.12	47.84
90	52.89	56.14	51.96	53.66
180	55.98	52.88	54.13	54.33

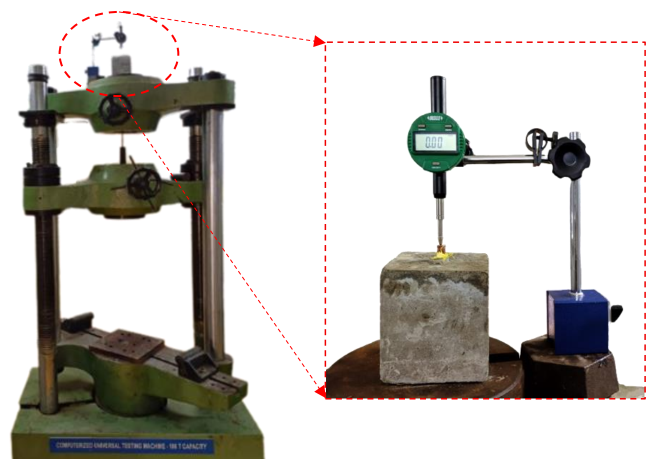

Figure 3 Pul-lout test setup

3 Results

The bond strength results and its retention (%) after alkaline exposure for 90 and 180 days are presented in the Table 4. The failure mode of pullout specimens is shown in Figure 4.

Table 2 Specimen details of pull-out specimens

Diameter of bar (d_b) (mm)	Length of specimen (l) (mm)	Anchorage length (l_a) (mm)	Steel sleeves diameter (mm)	Embedment length (l_e) (mm)	No. of specimens for alkaline exposure		
					0 days	90 days	180 days
8	815	300	33.4	32	3	3	3
10	815	300	33.4	40	3	3	3
12	865	350	41.5	48	3	3	3

Table 4 Bond results of tested pull-out specimens

Exposure time (days)	Dia. of bar	8 mm				10 mm				12 mm			
	Specimen ID.	8-1	8-2	8-3	Avg.	10-1	10-2	10-3	Avg.	12-1	12-2	12-3	Avg.
28	P_u (kN)	Premature failure	10.44	13.96	12.1	18.08	17.20	18.58	17.9	23.30	30.02	18.68	24
	τ (MPa)		12.98	17.31	15.1	14.4	13.7	14.8	14.3	12.88	16.6	10.28	13.2
	S (mm)		6.42	9.33	7.87	2.61	1.64	1.64	1.93	1.2	0.73	1.24	1.05
	$\tau/\sqrt{f_{ck}}$		1.87	2.5	2.18	2.08	1.98	2.13	2.05	1.86	2.4	1.48	1.91
	BSR (%)		-	-	100	-	-	-	100	-	-	-	100
	Failure mode	P	P	P		S	S	S		S	S	S	
90	P_u (kN)	15.11	16.07	12.78	13.3	20.34	19.09	21.35	20.2	20.43	27.12	29.66	25.7
	τ (MPa)	16.5	18.4	15.9	16.9	16.2	15.2	17	16.1	11.3	15	16.4	14.2
	S (mm)	3.35	2.91	4.73	3.66	1.41	2.07	2.90	2.12	0.91	1.56	1.81	1.42
	$\tau/\sqrt{f_{ck}}$	2.25	2.51	2.17	2.31	2.21	2.07	2.32	2.2	1.54	2.04	2.23	1.93
	BSR (%)	-	-	-	111	-	-	-	112	-	-	-	1.07
	Failure mode	P	P	S		S	S	P		S	S	S	
180	P_u (kN)	12.53	10.53	Premature failure	11.5	18.33	16.83	14.82	16.6	18.26	26.76	23.51	22.8
	τ (MPa)	15.6	13.1		14.3	14.6	13.4	11.8	13.5	10.1	14.8	13	12.6
	S (mm)	5.01	4.78		4.89	2.81	2.62	2.23	2.55	1.01	1.62	1.02	1.21
	$\tau/\sqrt{f_{ck}}$	2.11	1.77		1.94	1.98	1.81	1.60	1.79	1.37	2	1.76	1.71
	BSR (%)	-	-		94	-	-	-	94.5	-	-	-	95
	Failure mode	P	P	P		P	S	P		S	S	S	

Note: Specimen ID – 8-1 means 8 stands for bar diameter and 1 stands for specimen number, P_u – Ultimate load of failure, τ – Bond stress S – Slip, $\tau/\sqrt{f_{ck}}$ – Normalised bond, BSR – Bond strength retention (%), P – Pullout failure, S – Split failure

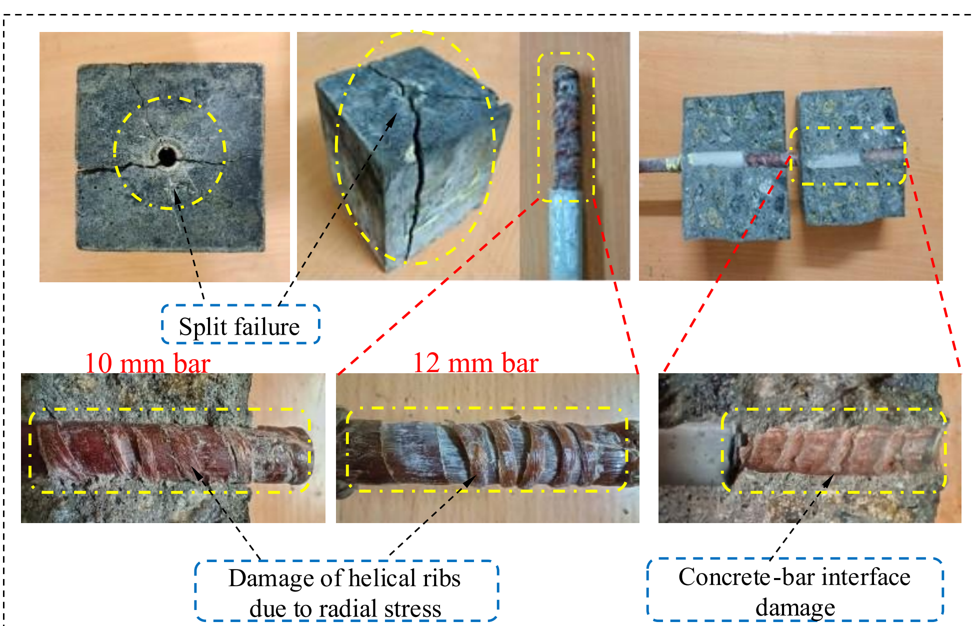

Figure 4 Failure modes of pullout specimens

4 Conclusions

The effect of diameter and alkaline exposure on bond strength and failure patterns are vividly studied, and its conclusions are as follows.

- The bond strength of 90 days conditioned specimens is higher than control specimens by 7-12%.
- The actual bond degradation noticed after 180 days of exposure showing a drop in bond strength by 4-6% over control specimens. Bond strength from the experimental results for both conditioned and unconditioned were 1.7 to 2 times the minimum bond strength required by CAN/CSA S807-19 and ASTM D7957-17.
- Failure mode of the lower diameter bars was found to be pull out failure while the higher diameter bars were failed by the splitting of concrete. The radial stress developed on the surface of the bar causes the splitting of the concrete and this radial stress is found to be greater for higher diameter bars.

5 Data Availability

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Conflicts of Interest

The authors declare no conflict of interest.

Authors contribution:

Mavoori Hitesh Kumar – Data curation, Conceptualization, Software, Supervision, Original draft preparation. Muhammed Riyas K.P – Investigation, Conceptualization, Methodology, Software. Jallu Sriharsha - Investigation, Conceptualization, Methodology, Software. Prabha Mohandoss - Supervision, Original draft preparation, Reviewing and Editing.

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