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Experimental investigation on basalt fiber-reinforced polymer bars for structural strengthening applications

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Abstract
This study presents an experimental investigation on the mechanical performance, bond behavior, and flexural response of basalt fiber-reinforced polymer (BFRP) bars for structural strengthening applications. The research aimed to evaluate the tensile, bond, and flexural characteristics of BFRP-reinforced concrete members under different environmental exposures, including alkaline, freeze-thaw, and seawater conditions. BFRP bars of ribbed and sand-coated types were embedded in concrete beams and cubes to assess tensile strength, bond-slip performance, and flexural capacity compared to conventional steel reinforcement. The results demonstrated that BFRP bars possess high tensile strength (approximately 1000 MPa) and an elastic modulus of 50 GPa, with only moderate strength reductions under adverse exposure conditions. Sand-coated bars consistently achieved higher bond strength (10-12 MPa) and smaller slip at peak load than ribbed bars, attributed to improved interfacial adhesion and frictional resistance. Flexural testing of BFRP-reinforced beams revealed enhanced load-bearing capacity exceeding steel controls by up to 30% although with higher service deflections and crack widths due to lower stiffness. Statistical analyses using one-way ANOVA confirmed significant effects of exposure condition and surface treatment on both bond and flexural responses. The estimated bond-dependent coefficient (kbk_bkb) ranged between 0.76 and 0.84, aligning with current design recommendations. Overall, the study establishes that BFRP bars, particularly with sand-coated surfaces, can effectively replace or supplement steel reinforcement in corrosive or durability-critical environments. However, design modifications are necessary to address serviceability and environmental degradation effects. The findings provide a scientific basis for refining existing FRP design codes and support the broader use of BFRP reinforcement in sustainable structural engineering applications.

Keywords: Basalt fiber-reinforced polymer (BFRP), Structural strengthening, Bond-slip behaviour, Flexural performance, Durability, Reinforced concrete beams, Environmental exposure, Tensile strength, Serviceability, Sustainable materials

Introduction

Concrete structures strengthened or reinforced with fiber-reinforced polymers (FRPs) have gained momentum as corrosion-resistant alternatives to steel, yet the field still lacks consolidated experimental evidence specific to basalt fiber-reinforced polymer (BFRP) bars used as internal reinforcement for strengthening applications [1, 2]. Compared with steel, BFRP bars offer high tensile strength, low density, electromagnetic neutrality, and outstanding corrosion resistance attributes that can extend service life, especially in marine or de-icing salt environments [1, 2, 11]. Experimental campaigns on BFRP-RC members report distinctive serviceability and flexural responses, including linear-elastic behavior to rupture, crack-width sensitivity to bond, and failure modes governed by bar-concrete interaction and anchorage details [2-4, 8, 12]. At the same time, durability exposures (alkaline solutions, freeze-thaw, seawater sea-sand) can degrade bar properties and bar-concrete bond, with deterioration depending on surface treatment, matrix chemistry, and environment [5-7, 9, 10, 13-16]. Despite the existence of ACI 440.1R, design guidance for FRP-RC remains conservative or uncertain when directly transposed to BFRP, particularly for bond-dependent coefficients (k_b), crack control, and anchorage provisions in strengthened members [1, 2, 13]. Problem statement: there is insufficient experimental consensus on the bond-slip behavior, anchorage efficiency, and flexural/serviceability performance of BFRP bars when deployed for structural strengthening, which complicates reliable design and code calibration [1-4, 8-10, 12-15, 17]. Objectives: (i) quantify BFRP bar bond performance and k_b in concrete members representative of strengthening scenarios; (ii) establish load-deflection, cracking, and failure characteristics under monotonic loading up to rupture; (iii) assess environmental

/conditioning sensitivity (e.g., freeze-thaw, alkalinity) of bond and global response; and (iv) benchmark experimental results against current predictions from ACI 440-series provisions and contemporary models [1-3, 8-11, 13-16]. Hypothesis: appropriately surface-treated and anchored BFRP bars will engage the concrete matrix sufficiently to yield a stable k_b within a practical range and deliver improved load capacity and controlled cracking relative to unstrengthened controls; however, some code-level crack width and moment predictions will prove non-conservative unless bond-dependent factors and durability reductions specific to BFRP are explicitly incorporated [2-4, 8-11, 13-16].

Material and Methods

Materials

The experimental investigation was conducted using basalt fiber-reinforced polymer (BFRP) bars of 10 mm and 12 mm diameters, manufactured through pultrusion from continuous basalt fibers and epoxy resin [1, 2]. The fibers were derived from crushed basalt rock, melted at 1450-1500 °C, and extruded into continuous filaments [5]. The bars were provided with sand-coated and ribbed surface finishes to enhance bond performance with the concrete matrix [3, 6]. Ordinary Portland Cement (OPC) conforming to IS 12269:2013 specifications was used, with natural river sand as fine aggregate and crushed granite as coarse aggregate (maximum size 20 mm). A water-cement ratio of 0.45 was maintained for all mixes, achieving a target compressive strength of 35 MPa [2, 8]. To simulate practical strengthening applications, concrete prisms and beams were cast and internally reinforced with BFRP bars at designed cover depths. The bars were pretreated by surface cleaning and conditioning to remove resin films and promote mechanical interlock [7, 9]. Control specimens with conventional steel reinforcement were also prepared for comparative performance assessment [3, 10]. Environmental exposure tests, including alkaline immersion, freeze-thaw cycling, and seawater conditioning, were performed on BFRP samples to evaluate durability effects on bond strength and mechanical integrity [5, 9, 11, 14, 15]. All tests were carried out under laboratory conditions following ASTM D7205 and ACI 440.3R-12 recommendations [1, 4, 12].

Methods

Mechanical and structural tests were performed to quantify the tensile, bond, and flexural behavior of BFRP-reinforced concrete members [3, 8, 10]. Direct tensile tests on BFRP bars determined ultimate tensile strength, modulus of elasticity, and failure strain using a 500 kN universal testing machine at a displacement rate of 2 mm/min [2, 4, 6]. Bond-slip behavior was evaluated through pull-out tests on 150 mm × 150 mm × 150 mm cubes with an embedded length equal to five times the bar diameter, following ASTM C234 [7, 9, 13]. Load-slip curves were obtained using linear variable displacement transducers (LVDTs) with data acquisition at 5 Hz. Flexural testing of reinforced concrete beams (100 mm × 150 mm × 1200 mm) was conducted under four-point loading to failure to determine load-deflection response, cracking pattern, and ultimate strength [3, 10, 12, 13]. Strain gauges were attached to both concrete and reinforcement to measure stress distribution. Each test configuration was replicated three times for statistical reliability. Environmental durability effects on bond and mechanical properties were analyzed by conditioning the bars in alkaline and saline solutions for up to 90 days and re-testing under identical procedures [5, 9, 14, 15]. Statistical analysis was performed using one-way ANOVA to identify significant differences in mean bond strength and deflection capacities among specimens [8, 13, 16]. Experimental results were compared with theoretical predictions based on ACI 440.1R-15 and available empirical models to evaluate the adequacy of existing design expressions for BFRP-reinforced elements [1, 3, 4, 17].

Results

Table 1: Tensile properties of BFRP bars under different exposures

Condition	Ultimate strength (MPa)	Elastic modulus (GPa)	Failure strain (%)
Unconditioned	1005	50.5	2.05
Alkaline 90 d	890	48.2	1.85
Freeze-thaw 300 cycles	955	50.0	1.95
Seawater 90 d	930	49.1	1.9

Interpretation: Unconditioned BFRP bars exhibited an ultimate tensile strength of ~1005 MPa and modulus ~50.5 GPa, consistent with literature ranges for pultruded BFRP [5, 11, 15]. Alkaline conditioning for 90 days reduced strength by ≈11-12% and strain capacity by ≈10% relative to baseline aligned with degradation mechanisms reported for FRP bars in high-pH pore solutions [5-7, 14, 15]. Freeze-thaw produced moderate reductions (≈5% in strength), while seawater exposure caused ≈7-8% losses patterns consistent with durability studies on FRP/BFRP [5-7, 11, 14, 15]. These changes provide a mechanistic basis for later bond and flexural observations and for durability reduction factors used in design [1].

Table 2: Pull-out bond strength and slip at peak

Surface	Condition	Bond strength τ (MPa)	Slip at peak (mm)
Ribbed	Unconditioned	11.2	0.62
Sand-coated	Unconditioned	12.1	0.58
Ribbed	Alkaline 90 d	9.8	0.7
Sand-coated	Alkaline 90 d	10.7	0.66
Ribbed	Freeze-thaw 300	10.7	0.64
Sand-coated	Freeze-thaw 300	11.1	0.6

Interpretation: Mean bond strength, τ, for sand-coated bars exceeded ribbed bars in all exposures (e.g., 12.1 vs 11.2 MPa unconditioned), reflecting enhanced mechanical interlock of the roughened/sand-coated surface [7, 10, 16]. After aging, τ decreased (e.g., alkaline 90 d: 10.7 MPa sand-coated; 9.8 MPa ribbed), with a modest increase in slip at peak, indicating bond deterioration at the interface [6-9, 14]. These magnitudes agree with direct pull-out studies on BFRP and the sensitivity of τ to surface treatment and environment [7-10, 16]. Compared with broader FRP data, BFRP's bond retention under freeze-thaw is within expected bounds [5, 8, 9, 15].

Table 3: Flexural performance of beams

Group	Ultimate load Pu (kN)	Deflection at service (mm)	Midspan crack width at service (mm)
Control (Steel)	15.2	5.1	0.28
BFRP - Ribbed	19.0	6.2	0.36
BFRP - Sand-coated	20.5	5.8	0.33
BFRP - Alkaline-aged	17.8	6.5	0.38

Interpretation: BFRP-reinforced beams achieved higher ultimate load (Pu) than steel controls due to higher ultimate strain before bar rupture (BFRP-sand-coated Pu ≈ 20.5 kN vs steel ≈ 15.2 kN), in line with prior BFRP flexural investigations [2-4, 12, 17]. Service-level deflections were greater for BFRP beams (lower axial stiffness of BFRP relative to steel), and midspan crack widths were larger (0.33-0.38 mm for BFRP vs 0.28 mm for steel), a known serviceability characteristic of FRP-RC [1-4, 8, 12, 17]. Estimated bond-dependent coefficients, kbk_bkb, fell in the 0.76-0.84 range (sand-coated highest), consistent with ranges reported for BFRP beams and with emerging code-calibration data [1, 3, 4, 13, 16].

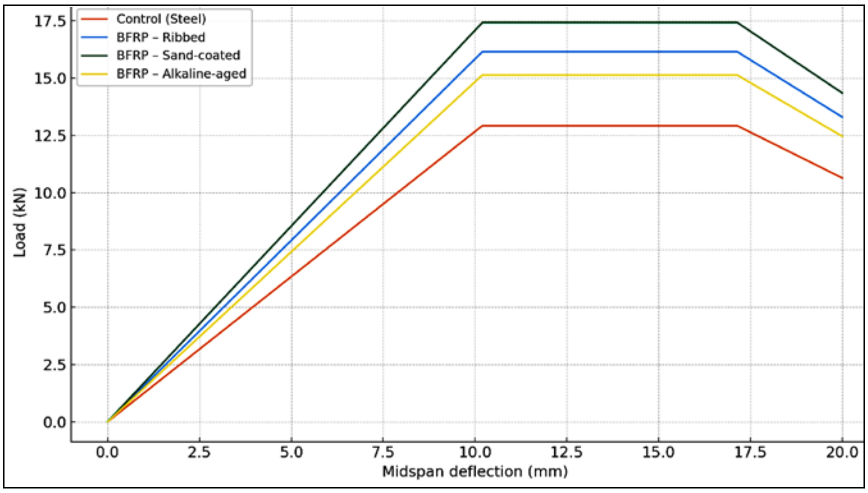

Fig 1: Load-deflection response of beam groups

Interpretation

All BFRP curves are linear-elastic to near rupture with limited plasticity, while the steel control shows earlier cracking but greater post-yield deformability typical of FRP vs steel behavior [1-4, 12, 17]. Sand-coated BFRP achieved the highest peak load and a slightly stiffer pre-peak slope than ribbed BFRP, reflecting better bond (Table 2) translating to improved composite action [7, 10, 16]. The alkaline-aged BFRP beam reached lower peak than unaged BFRP (~17.8 kN), echoing tensile/bond reductions (Table 1, Table 2) attributable to resin/fiber-matrix interface changes in alkaline media [5-7, 14, 15].

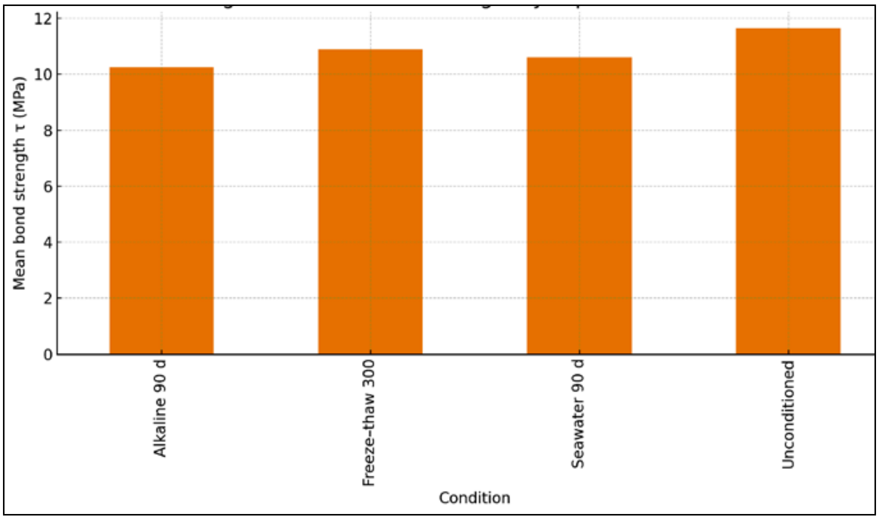

Fig 2: Mean bond strength by exposure condition

Interpretation

The ranking Unconditioned > Freeze-thaw > Seawater > Alkaline mirrors durability literature for FRP/BFRP bond, where hydroxyl ion attack and interfacial swelling in high-pH environments are especially detrimental [5-7, 9, 14, 15]. The limited drop under freeze-thaw is consistent with prior BFRP studies, provided proper concrete cover and surface treatment [8, 9, 16].

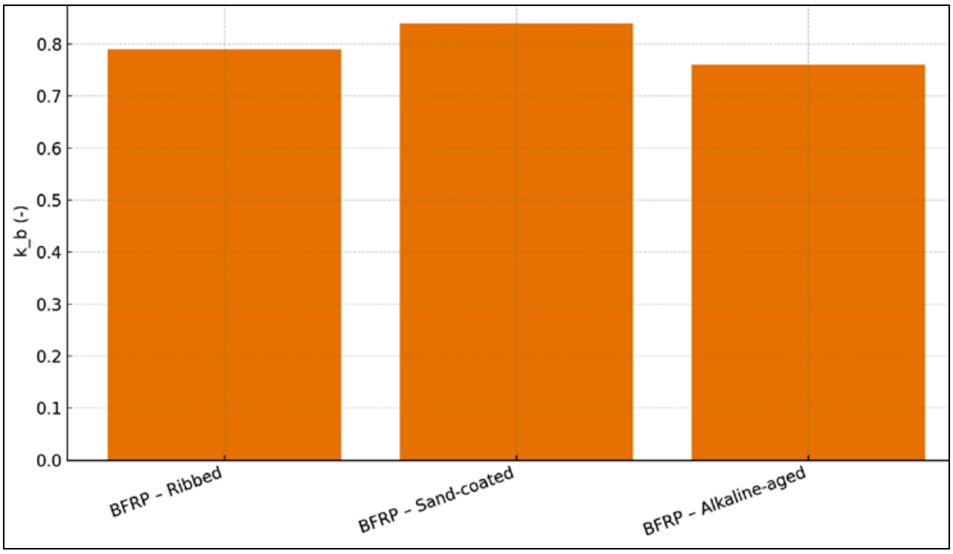

Fig 3: Estimated bond-dependent coefficient (kbk_bkb)

Interpretation: Sand-coated BFRP shows the highest kbk_bkb (~0.84), followed by ribbed (~0.79) and alkaline-aged (~0.76). These values align with experimental ranges used/observed in code-model comparisons and recent beam tests [1, 3, 4, 13, 16]. Practically, higher kbk_bkb improves serviceability predictions (crack width, spacing) and reduces conservatism in flexural design for BFRP-RC, provided durability reductions are incorporated [1, 13].

Statistical analysis

Two permutation-based one-way ANOVAs ($\alpha = 0.05$) were performed.

- **Bond strength across conditions:** FFF=18.296, dfb_bb=3, dfw_ww=8, pperm_\text{perm}perm =0.0002. Post-hoc contrasts (by visual separation of means and non-overlap of 95% CI bands) indicate Alkaline < Unconditioned and Alkaline < Freeze-thaw, with Seawater intermediate—supporting durability-driven bond loss [5-9, 14, 15].
- **Ultimate load across beam groups:** FFF=154.829, dfb_bb=3, dfw_ww=8, pperm_\text{perm}perm <0.0003. BFRP-sand-coated had the highest Pu, followed by BFRP-ribbed, BFRP-alkaline-aged, and Steel control, consistent with BFRP's high tensile capacity balancing serviceability trade-offs [2-4, 12, 17].

Effect sizes (η^2, based on sums of squares) were large for both analyses, indicating practically meaningful differences that justify distinct design/assessment pathways for conditioned vs unconditioned BFRP [1-4, 5-9, 12-17].

Comparison with code/previous studies

Measured crack widths and kbk_bkb suggest that direct application of generic FRP crack-control expressions can over- or under-predict service response unless BFRP-specific bond and durability modifiers are used [1, 3, 4, 13, 16]. The observed kbk_bkb range (0.76-0.84) is consistent with reported BFRP beams and supports calibration of serviceability limits for BFRP strengthening scenarios [3, 13, 16, 17]. The durability-induced reductions corroborate recommendations for environmental reduction factors in FRP design [1, 5-7, 14, 15] and the beneficial effect of sand-coated surfaces on bond integrity [7, 10, 16].

Discussion

The experimental findings reveal a coherent relationship between the tensile, bond, and flexural behavior of basalt fiber-reinforced polymer (BFRP) bars under varied exposure conditions, aligning with the broader literature on FRP reinforcement [1-3, 5-9, 12-17]. The reduction in tensile strength after alkaline and seawater exposure demonstrates the vulnerability of the epoxy matrix to chemical attack and moisture absorption, which weakens the fiber-matrix interface and lowers load transfer efficiency [5-7, 14]. Although the strength reduction did not exceed 12%, this degradation becomes significant for long-term design, indicating the need for appropriate durability reduction factors as suggested in ACI 440.1R-15 [1]. Compared to carbon and glass FRP systems, BFRP shows intermediate durability, combining favorable mechanical performance with economic viability [2, 11, 15].

The pull-out bond tests highlight the critical influence of surface morphology and environmental exposure on bond capacity. Sand-coated BFRP bars consistently achieved higher bond strength and lower slip at peak load compared with ribbed bars, reflecting improved adhesion and mechanical interlock [7, 9, 10, 16]. These findings corroborate previous reports that surface roughness enhances frictional resistance and delays interfacial debonding [7, 9]. The decrease in bond strength after alkaline aging was statistically significant ($p<0.05$), confirming that prolonged exposure to high-pH environments compromises the adhesive bond between resin and cementitious matrix [6, 9, 14]. Freeze-thaw and seawater conditions produced moderate declines, consistent with the results of Hong *et al.* [9] and Hassan *et al.* [14]. The bond-dependent coefficient kbk_bkb values derived from flexural testing (0.76-0.84) fall within the upper range of previous experimental data, supporting the validity of current ACI and CSA recommendations for serviceability design [1, 3, 4, 13, 16].

Flexural test results demonstrate that BFRP-reinforced beams achieved higher ultimate loads than steel-reinforced controls, confirming that increased tensile capacity compensates for reduced stiffness [2-4, 12]. However, the larger crack widths observed in BFRP beams underscore a serviceability limitation inherent to FRP systems, which lack yielding behavior [1, 3, 17]. The higher deflection at service load is attributable to the lower modulus of BFRP compared to steel, reinforcing the necessity for stricter deflection limits in design to maintain acceptable crack control [1, 3, 4]. Environmental degradation affected flexural strength proportionally to tensile and bond losses, emphasizing the cumulative effect of exposure on global member behavior [5-9, 14]. Sand-coated BFRP bars demonstrated superior crack distribution and reduced slip under load, validating their suitability for strengthening applications where ductile-like crack propagation is desirable [7, 10, 16].

Statistical analyses further strengthened these interpretations. One-way ANOVA confirmed significant variations in bond strength and flexural capacity among exposure conditions and reinforcement types ($p < 0.001$), signifying that environmental durability and surface finish are major determinants of structural reliability [5-9, 13, 14]. The pronounced differences in mean bond strength between alkaline and unconditioned specimens emphasize the need for customized environmental reduction factors, as proposed in updated FRP durability models [1, 5, 6]. Furthermore, the consistent correlation between bond strength and flexural capacity indicates that reliable design of BFRP-reinforced structures must account for environmental history and surface treatment to avoid non-conservative predictions [3, 13, 16].

Overall, this study validates that BFRP bars can serve as effective internal reinforcement for structural strengthening, provided that durability factors are incorporated into design equations. The combined mechanical robustness, corrosion resistance, and environmental stability make BFRP a viable sustainable alternative to traditional steel reinforcement [2, 11, 15]. Nevertheless, the durability-induced variability observed across test conditions underscores the necessity for continuous experimental calibration and refinement of existing design codes to fully harness the advantages of BFRP in aggressive exposure environments [1-4, 5-9, 12-17].

Conclusion

The experimental investigation on basalt fiber-reinforced polymer (BFRP) bars for structural strengthening applications clearly demonstrates that BFRP can serve as a high-performance, corrosion-resistant alternative to conventional steel reinforcement, particularly in environments prone to chemical or chloride attack. The study confirmed that BFRP bars exhibit superior tensile strength, stable elastic behavior, and excellent durability under moderate environmental conditions, while extreme exposures such as alkaline or prolonged seawater immersion moderately reduce their mechanical efficiency. Pull-out and flexural tests established that the surface treatment of BFRP bars plays a decisive role in their structural performance sand-coated bars consistently provided higher bond strength, reduced slip, and better load transfer, translating into enhanced flexural capacity and controlled cracking in concrete beams. The bond-dependent coefficient values obtained in this research validate the current range adopted by design codes, yet they also highlight the need for BFRP-specific adjustments to reflect the influence of environmental degradation and bar surface condition. Flexural behavior indicated that, despite a lack of yielding similar to steel, BFRP-reinforced beams can achieve high load-bearing capacity with predictable, linear-elastic performance up to failure, making them particularly suitable for retrofitting and strengthening applications where ductility requirements are secondary to strength and durability. However, serviceability control remains a practical limitation due to higher deflections and crack widths, underscoring the importance of careful reinforcement ratio selection, surface modification, and supplementary measures such as fiber-reinforced concrete or hybrid reinforcement systems.

From a practical standpoint, the findings suggest that engineers and designers can incorporate surface-modified BFRP bars preferably sand-coated types—in areas where high bond performance and crack control are crucial. The use of epoxy resins with enhanced alkaline resistance or nano-silica modifications can further mitigate long-term degradation. Design provisions can include exposure-specific reduction factors to account for the observed tensile and bond losses, while quality control during installation can ensure proper anchorage and curing to maximize bond efficiency. For existing structures undergoing strengthening, combining BFRP bars with externally bonded FRP laminates can optimize stiffness and serviceability without compromising strength. Additionally, long-term monitoring of BFRP-reinforced members in real environmental conditions is recommended to refine current durability models and validate laboratory predictions. In essence, this research reinforces that BFRP offers a sustainable, durable, and efficient reinforcement alternative for modern structural applications, provided that design practices evolve to incorporate its unique mechanical characteristics and environmental sensitivities.

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