

Article

Investigating the Bond Performance of FRP Bars and Concrete Under Dynamic Loading Conditions

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Abstract: With growing emphasis on sustainable construction, fiber-reinforced polymer (FRP) bars are increasingly being used as alternatives to steel rebars due to their high strength-to-weight ratio, corrosion resistance, and environmental benefits. This study has investigated the bond behavior between FRP bars and concrete of different strength grades under dynamic loading conditions. To analyze the microscopic properties of FRP bar surfaces, the study employs a variety of techniques, including scanning electron microscopy (SEM), atomic force microscopy (AFM), and non-contact surface profilometry. In addition, X-ray photoelectron spectroscopy (XPS), water contact angle (WCA) measurements, and energy dispersive spectrometry (EDS) are used to further investigate surface characteristics. The results reveal a direct correlation between the resin surface roughness of FRP bars and their wettability characteristics, which in turn influence the cement hydration process. Pull-out tests under different loading rates and concrete strength grades have been conducted to evaluate the bond–slip behavior and failure modes. The results indicate that bond strength increases with increasing concrete strength. Dynamic pull-out tests further reveal that higher loading rates generate heterogeneous stress fields, which limit the deformation of FRP bars and consequently diminish the contribution of mechanical interlock to interfacial bonding.

Keywords: FRP bars; concrete; surface microstructure; dynamic loading; interfacial bonding; pull-out test



Academic Editor: Andrea Nobili

Received: 12 April 2025

Revised: 10 June 2025

Accepted: 12 June 2025

Published: 13 June 2025

Citation: Bao, W.; Tan, Y.; Li, H.; Liang, C.; Chen, H.; Fu, C. Investigating the Bond Performance of FRP Bars and Concrete Under Dynamic Loading Conditions. *Coatings* **2025**, *15*, 716. <https://doi.org/10.3390/coatings15060716>

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1. Introduction

With the increasing demand for energy and environmental conservation, eco-friendly materials are increasingly being sought to replace petroleum-based materials for sustainable development [1–3]. In structural applications, fiber-reinforced polymer (FRP) bars are typically fabricated using a polymer matrix, such as epoxy, vinyl ester, or polyester, and reinforced with fibers like carbon, glass, basalt, and/or aramid [4]. These bars are commonly produced using techniques such as pultrusion. FRP bars offer several advantages over traditional steel rebars [5,6], including high specific strength, stiffness, corrosion resistance, superior fatigue resistance, and environmentally friendly characteristics [7]. However, despite these attractive features, FRP bars still face challenges in the modern construction industry due to their high fire risk, inherent viscoelastic behavior, and fiber–matrix interface degradation [8]. These issues can negatively impact the bonding characteristics between FRP bars and concrete [9–12]. The FRP bar–concrete interface bond performance significantly affects the serviceability and bearing capacity of structures.

Over the past decades, extensive research has been conducted to investigate various factors influencing the bond behavior between concrete and FRP bars, as illustrated in Figure 1. These factors encompass FRP material types, resin formulations, embedment lengths, and the surface morphologies of the bars, among others [13]. For example, Xiong et al. [14] evaluated the bond performance between recycled aggregate concrete and FRP bars, focusing on the influence of interface characteristics, concrete type, bar diameter, and surface morphology. Their findings revealed that the R-type surface exhibited superior bonding behavior. Furthermore, bond strength showed a non-linear trend with increasing bar diameter, initially rising before declining, while bond stiffness decreased and residual bond strength increased in a linear fashion. Li and co-workers [15] investigated the effects of concrete strength, bar diameter, FRP bar surface morphology, and stress levels on the fatigue bond performance of FRP bars embedded in seawater sea-sand concrete. Wang and co-workers [16] investigated the impact of various FRP bar surface textures on bonding characteristics by compiling a database of 407 pull-out test outcomes from prior research, covering sand-coated (SC), helically wrapped (HW), ribbed (RB), and indented (IN) surface types. Findings indicate that for the SC type, factors such as concrete compressive strength, concrete cover, embedment length, and bar diameter exert a minimal effect on bond performance. Although the bonding mechanism of FRP bars with concrete is similar to that of steel rebars, the failure modes include bar pullout and concrete splitting failure, but in certain cases, the FRP bars may also experience fiber–resin matrix separation [17]. The bond strength consists of three components: chemical adhesion, friction, and mechanical interlock [18,19]. However, few studies have investigated the chemical adhesion between FRP bars and concrete, indicating that more work is needed to develop an in-depth understanding of this field. This is mainly because chemical adhesion occurs at the initial stage of pull-out testing, and its contribution to bonding strength is weak. Chen et al. [20] studied three types of bars (i.e., steel bars, glass fiber-reinforced polymer (GFRP) bars, and basalt fiber-reinforced polymer (BFRP) bars) with different surface conditions. The results showed that adhesion and friction between concrete and the BFRP bars and the GFRP bars were much greater than for steel bars due to their rougher surface. The contributions of adhesion and friction for bond strength were 40%, 28.7%, and 16.7%, respectively. Additionally, surface properties affect the degradation mechanisms of FRP bars. Extensive studies have been conducted on FRP bar–concrete bond performance exposed to various harsh environments, e.g., alkaline and acidic solutions and freeze–thaw cycles [21]. Degradation occurs when FRP bar-reinforced concrete is subjected to the coupling effect of continuous loading and special environments, resulting in interfacial microcracks and voids in the FRP bar surface [22]. Microscopic imperfections in the surface lead to the rapid penetration of Cl^- , OH^- , and H_2O into the FRP bars and accelerated damage [23]. The study by Hamed et al. [24] demonstrated that alterations in the matrix microstructure and fiber/matrix debonding primarily influence the durability of the mechanical properties of FRP bars over time. Studies further verify that the synergistic effect of the concrete’s alkaline environment and the salt ions present in seawater and sea sand accelerates resin degradation and fiber–resin interface separation, especially in BFRP bars [25]. Based on experiments, Feng et al. [26] examined the mechanical characteristics and degradation processes of FRP bars. They assessed the deterioration of the mechanical properties when exposed to water, seawater, and alkaline solutions, as well as the effects of dry, wet, and freeze–thaw cycling conditions. They found that the degradation processes could be divided into three stages: matrix permeability cracking, interface debonding, and delamination. Overall, compared with other factors, the alkaline environment has the most serious effect on FRP bar degradation due to the presence of H_2O and OH^- . There is no doubt that most existing research has focused on bond performance under static rate

loadings, while relatively little attention has been given to its behavior under high-strain rate loading conditions.

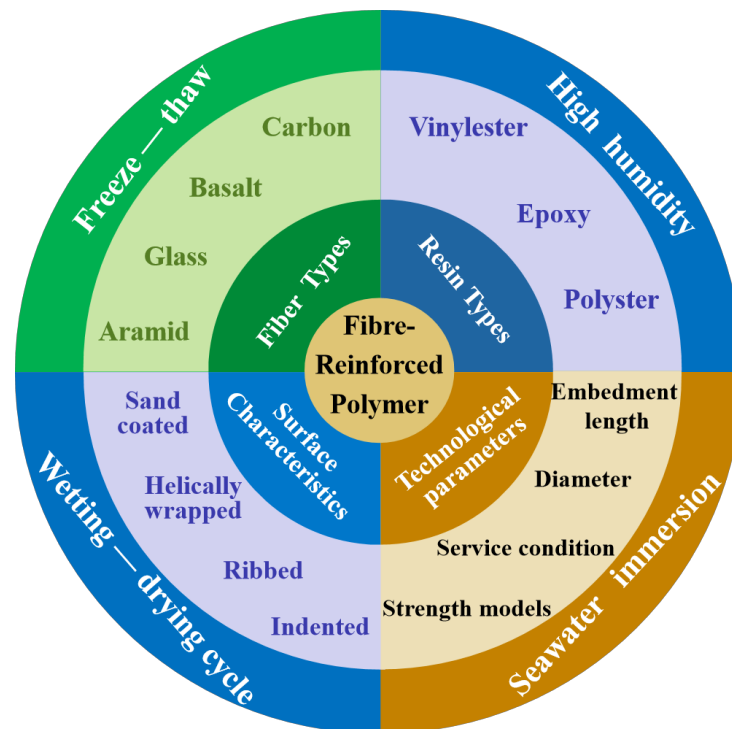


Figure 1. Schematic representation of fiber-reinforced polymer (FRP) bars.

In reality, the dynamic performance of concrete structures under impact loads has drawn much attention due to extreme events such as accidental explosions, falling objects, vehicle or ship collisions, tsunamis, and earthquakes [27]. Several researchers have conducted studies on FRP bar reinforcements under impact loads. Liu et al. [28] indicated that as the strain rate increased, both the peak stress and peak strain of concrete also increased. Li et al. [29] observed that the tensile strength and elongation of GFRP bars significantly increased with a loading rate of 2–15 mm/min, whereas the elastic modulus remained practically constant. Xu et al. [30] studied the pull-out performance of high-strength fibers in ultra-high performance concrete, obtaining the speed sensitivities of different types of fibers at loading rates in the range of 0.025–25 mm/s. Vos et al. [31] demonstrated that the loading rate has a significant influence on the bond strength between deformed steel bars and concrete. Their results indicated that higher strain rates contribute to improved bond strength and bond stiffness. Huo et al. [32] reported that the strain gradient in CFRP sheets subjected to impact loading exceeded that under static conditions, highlighting the significant effect of the loading rate on bond performance. Chen et al. [33] investigated the dynamic bond behavior between BFRP bars and concrete through 16 groups of pull-out tests. The results indicate that the loading rate significantly affects the bond strength of the BFRP bar-to-concrete interface, which increases logarithmically with the displacement rate. By introducing a Dynamic Increase Factor (DIF) into the static bond strength, the dynamic bond strength can be effectively predicted. Apparently, the performance of FRP materials and the complexity of their interaction with concrete require further research to better understand their interactions.

Building on this context, the present study aims to explore how the microstructural features of FRP bar surfaces influence their wettability and cement hydration behavior [34]. Furthermore, pull-out tests at various loading rates were carried out to evaluate the bond performance between FRP bars and concrete. Initially, surface characterization was con-

ducted using scanning electron microscopy (SEM) combined with energy dispersive spectrometry (EDS), water contact angle (WCA) analysis, and X-ray photoelectron spectroscopy (XPS). Quantitative surface roughness assessments were achieved through direct measurement techniques, including atomic force microscopy (AFM) and non-contact surface profilometry. Subsequently, the dynamic bond behavior of FRP bars embedded in concrete was examined via pull-out testing, during which bond–slip relationships, failure modes, and interface characteristics were systematically recorded.

2. Materials and Methods

2.1. Materials

In this study, the ribbed texture on the surface of the FRP bars was created by tightly winding strands around the bars during the pultrusion process, which were subsequently removed upon completion of manufacturing. The fiber volume fraction was approximately 70%, while the resin accounted for about 30%. The experimental program utilized externally ribbed GFRP-, BFRP-, and carbon fiber-reinforced polymer (CFRP) bars, all with a diameter of 12 mm. The geometric characteristics of the ribs—including rib width, spacing, and height—are illustrated in Figure 2. Detailed specifications of the FRP bars are summarized in Table 1. All specimens were sourced from Jiangsu Fiber Composite Co., Ltd. (Nanjing, China).

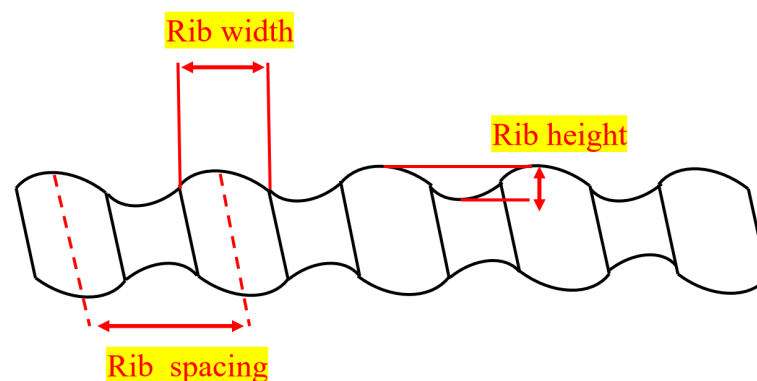


Figure 2. Definition of rib properties.

Table 1. Properties of the FRP bars used in this study.

Types of Bars	Diameter (mm)	Surface Condition	Rib Height (mm)	Rib Width (mm)	Rib Spacing (mm)	Tensile Strength (MPa)	Elastic Modulus (GPa)
GFRP	12 mm	rib	1.1	5	6	758	46
BFRP	12 mm	rib	1.5	5	6	1000	48
CFRP	12 mm	Shallow rib	0.7	5	6	2068	124

2.2. Specimen Preparation

The concrete mix was prepared using 42.5-grade Portland cement, natural sand, cobble aggregates, water, and a water-reducing admixture. A water-to-cement ratio of 0.56 was adopted to achieve a target compressive strength of 40 MPa. During casting, the reinforcement bars were pre-positioned at the center of the mold, and concrete was poured accordingly. Each specimen was a cube measuring 150 × 150 × 150 mm. In the domain of the concrete specimen, the bond length of the FRP bar was set as five times its diameter [34]. To define the debonded region, a smooth copper sleeve was applied to isolate the bar from the surrounding concrete. Epoxy resin was used to seal the interface between the bar and

the copper tube, ensuring waterproofing. After casting, the specimens were demolded after seven days and then subjected to air curing. Both the material characterization and pull-out tests were performed after a 28-day curing period.

2.3. Micro-Morphology and Surface Roughness Tests

A scanning electron microscope (SEM) with an energy dispersive X-ray spectroscopy (EDX) detector was used to study the surface morphologies of different bars and the interfacial transition zone between the bars and the cements. The SEM worked with an accelerating voltage of 20 kV. The working distance was around 10.0 mm. Atomic force microscopy (AFM) (tap mode, scanning area = $300 \times 300 \text{ nm}^2$) and 3D non-contact surface profilometry were used to investigate the surface morphology and roughness. Three points were selected for each sample, and the focus moving synthesis method, which is used for samples with concave and convex textures, was used. The contact angles were measured with 5 μL of deionized water droplets at room temperature using an optical contact angle meter (Hitachi, CA-A) [35].

2.4. EDX Analysis

The specimen preparation procedure was conducted in accordance with the method outlined in previous studies [36] and is summarized as follows: Cement and water were first weighed separately according to the required proportions. The cement was initially mixed at medium speed for 15 s, followed by the gradual addition of water while mixing continued for an additional 90 s. The bowl's sides and bottom were scraped using a spatula to ensure uniform blending. The mixture was then further mixed for 90 s at the same speed. A 10 cm segment of FRP bar was vertically positioned at the base of a plastic container. Upon completion of mixing, the fresh cement paste was poured into plastic cylindrical molds and sealed at 24 °C for initial curing. After 24 h, the molds were removed, surface moisture was gently wiped off, and the specimens were sealed in plastic bags and stored at 24 °C until testing. To verify compressive strength development, the samples were tested at 28 days. Subsequently, they were sectioned using a diamond saw and polished in preparation for EDX analysis [37].

2.5. Pull-Out Test

In this paper, a universal material testing machine was employed to conduct the direct pull-out specimen test [38–43]. The pull-out tests were conducted following the guidelines provided in the relevant literature and international recommendations [16]. The anchorage length ranged from 4 to 15 times the bar diameter, with 76.7% of the specimens adopting an anchorage length of 5 times the diameter, which corresponds to the recommended value specified in most current design codes, such as CSA S806-12 [44], ACI 440.3R-12 [45], and ASTM D7913/D7913M-14 [46]. This length (5d) is commonly adopted because it ensures a relatively uniform bond stress distribution along the embedded length and helps prevent premature interfacial failure. In total, 27 specimens with 9 groups were designed for the test, considering the influences of the fiber type and the three loading speeds: 5 mm/min represents the static load, and 10 mm/min and 15 mm/min represent the dynamic load [29]. All the pull-out tests were conducted using a universal testing machine manufactured by Jinan Chenda, with a load capacity of 2500 kN and sampling frequency of 100 Hz. The tensile load (P) and displacement (s) were recorded using the universal material testing machine. The bond length (l) was set as 5d. Using Equation (1), the bond stress (τ) corresponding to the different loading speeds was calculated, as shown in Table S3.

$$\tau = \frac{P}{\pi dl} \quad (1)$$

3. Results

3.1. Bar Surface Morphology

SEM was applied to study the morphology structure of the FRP bars. As seen in Figure 3a,d, the GFRP bars exhibit a light white color due to the properties of the glass itself. The fibers are closely arranged without pore spaces due to the transparent epoxy resin layer covering. The surface of the resin is relatively smooth, and there are some pits of different sizes. No interface gaps are apparent between the fiber and the resin. A higher magnification image shows an obvious high affinity fiber–matrix interface (Figure 3d). In the process of manufacturing GFRP bars, glass fiber is usually coated with a surface modifier to improve the wettability with resin. This enables the formation of a tight interface layer between the fiber and the resin to increase bond strength and eliminate interface stress. In contrast to the GFRP bars, the mechanical properties of basalt and glass fibers are quite similar, but basalt fiber can reach a higher tensile strength. Figure 3b,e shows the longitudinal surface morphology of the BFRP bars. The surface of the BFRP bars is visibly brown. The fiber layer is clearly visible because the resin layer is thin, and the diameter of a single fiber is 10~20 μm . There are obvious cracks in the fiber layer due to debonding between the interfaces. Basalt fiber has a smooth surface, low surface energy, and strong chemical stability, so it is difficult for the fiber and resin to have good wettability and interfacial bonding strength. Compared with the BFRP bars, the CFRP bars exhibit a bright black color (Figure 3c). Carbon fiber has a smooth surface and almost no defects. In addition, there are a small number of white spots on the surface, which may be small substances introduced by the processing process or other impurities that are sticky during transportation. In its production, carbon fiber needs to be carbonized at a high temperature, and the C-C structure of its surface has a poor anchoring effect with the resin. The surface grooves are very clear, the texture is deepened, and the axial alignment of the fiber bundles creates an uneven, rough surface (Figure 3f). In conclusion, although the distribution of resin on the fiber surface is uneven, the resin coatings enabled effective interconnections among the single filaments, leading to better load transmission among the fibers [47].

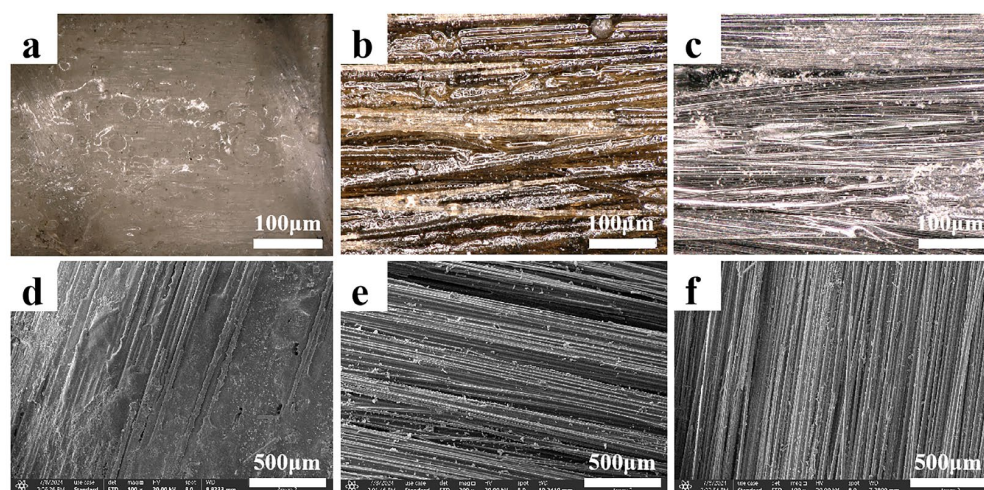


Figure 3. Morphology of the FRP bars: (a,d) GFRP, (b,e) BFRP, (c,f) CFRP.

3.2. Bar Surface Roughness and Water Contact Angle

The wettability performance of FRP bars is primarily determined by their surface roughness and chemical composition [48]. To observe the surface roughness, the as-prepared samples were examined using non-contact surface profilometry and AFM. Figure 4a–c displays the 3D scan images of the FRP bars. The color in the images represents the height variation of the test area, with red indicating areas above the horizontal

line and blue indicating areas below it. The surface roughness of the GFRP bars, with a value of $1.531\text{ }\mu\text{m}$, is the lowest, indicating that the voids between the fibers are filled with resin (Figure 4a). In contrast, the roughness of the BFRP and CFRP bars is significantly higher, at $2.325\text{ }\mu\text{m}$ and $2.363\text{ }\mu\text{m}$, respectively. The color alternation in the 3D scan images reveals folds and furrows formed by the parallel arrangement of fibers (Figure 4b,c).

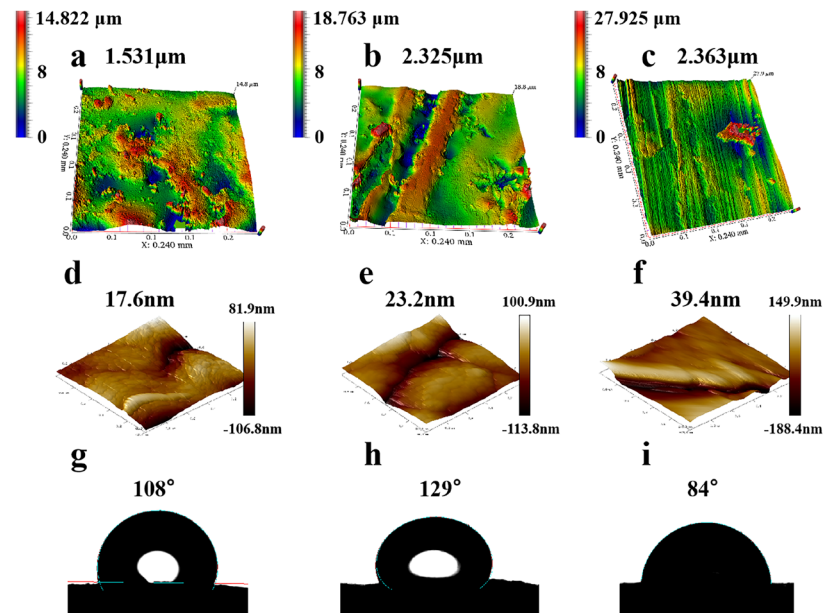


Figure 4. Three-dimensional scan and AFM topography image of the FRP bars: GFRP (a,d), BFRP (b,e), CFRP (c,f). Water contact angle profile test results of GFRP (g), BFRP (h), and CFRP (i).

To further examine the surface microstructure of the FRP bars, AFM tests were conducted to assess surface roughness. AFM also provides useful interfacial information regarding the morphologies, viscoelasticity, texture, elemental concentration, and surface depth profile based on the interaction between the sample atoms and the AFM tip [49]. The AFM images shown in Figure 4d,e are consistent with the 3D scan results. The average roughness of the CFRP bars is the highest, while that of the GFRP bars is the lowest. Specifically, the CFRP bar surface presents pronounced peaks and valleys, characterized by high hills and deep valleys, ranging from approximately -188 nm to 149 nm in the representative scan area shown in Figure 4f. The large roughness parameters indicate a rougher surface on the CFRP bars, contributing to a stronger interfacial bonding strength. In contrast, the GFRP bar surface is flatter and smoother, with a granular texture. The height variation between the deepest valley and highest peak is approximately 186 nm (ranging from -106 nm to 80 nm), representing a 55% reduction compared to CFRP.

Furthermore, to investigate the wettability behavior of the FRP bars, contact angle tests were performed to assess the wettability properties of their longitudinal surfaces. The FRP bars are primarily made of commercial epoxy resins, which are hydrophilic due to the presence of polar functional groups such as $-\text{OH}$, $-\text{CONH}_2$, $-\text{NO}_2$, and $-\text{NH}_2$ on the surface. As shown in Figure 4g–i, the water contact angle for the GFRP bars changed only slightly compared to the BFRP bars, whereas the contact angle for the CFRP bars significantly decreased from 129° to 84° . This indicates that increased roughness improves the hydrophilicity of the CFRP surface. Wettability affects the porosity and chemical composition of the interfacial transition zone between the concrete matrix and the FRP bar surface, thereby influencing the chemical bonding force [35,50].

3.3. The Chemical Composition of the Bar and Its Interfacial Properties with Cement

The surface composition of the FRP bars is a key factor in determining their bonding properties [51]. Figure 5 presents the XPS analysis of the surfaces of the GFRP, BFRP, and CFRP specimens. The results show that C, O, and N are the main elements on the specimen surfaces, with C, O, and N originating from the surface resin and fiber-containing contaminants [4]. The C1s spectrum primarily consists of C-C, C-H, and C-N groups. The O1s spectrum, in contrast, is composed of C-O/C-OH and C=O groups. Oxygen-containing functional groups are crucial for enhancing the adhesion properties between the adhesive and the adherend. These chemically activated groups not only improve the wettability and affinity of the adherend but also form covalent bonds with the adhesive, thus enhancing the bonding strength [52]. Table 2 shows the dominant elemental components and their proportions on the surface of the FRP bars. Compared to CFRP, the surface C1s content of the GFRP and BFRP samples increases to varying extents, while the O content decreases significantly. A higher O/C ratio leads to increased surface polarity and hydrophilicity, which enhances the bonding strength [53].

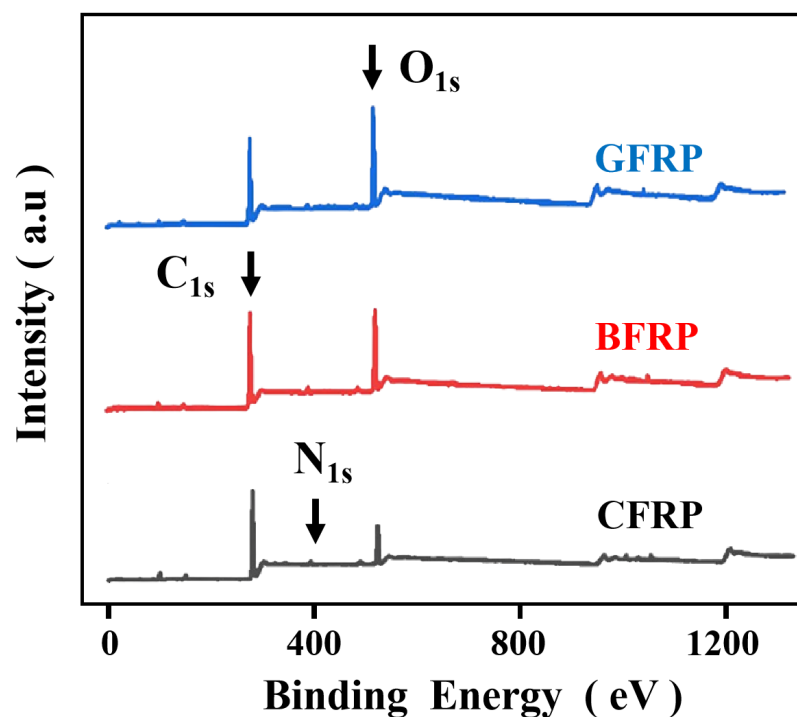


Figure 5. XPS spectra of three types of FRP bars.

Table 2. Surface chemical composition and elemental proportions of the FRP bars.

Specimens	C1s	O1s	N1s	Si2p	O1s/C1s
GFRP	73.67	18.74	3.57	4.02	25.43
BFRP	72.21	18.54	5.78	3.47	25.67
CFRP	70.09	21.87	2.86	3.18	31.20

In general, the bonding strength between FRP bars and cement is influenced by the wetting properties of the surface resin, which are determined by surface roughness and the functional groups [54]. Hydrophilic functional groups on the resin surface, such as -OH and -COOH, can form ionic bonds with Ca^{2+} in $\text{Ca}(\text{OH})_2$ or covalent bonds with C-S-H gel in cement [55]. The C-S-H gel constitutes up to 70% of the final volume and is primarily responsible for the cohesion and mechanical strength of cement pastes [56].

Figure 6 presents the numerical EDX results and analysis for the interfaces of three different FRP bars with cement [57]. The results indicate that the C/S ratio in the interfacial zone significantly changes for CFRP and BFRP, while it remains nearly constant for regular C-S-H gel samples. This difference is mainly attributed to the variation in wettability caused by surface roughness. The resin layer creates a rougher surface, increasing water absorption [58]. Additionally, the polar groups introduced by the epoxy resin enhance the likelihood of water interacting through hydrogen bonding [59]. The increase in the Ca fraction leads to a denser interfacial microstructure, primarily due to the reaction between the resin surface and cement hydrates, forming ettringite [60,61].

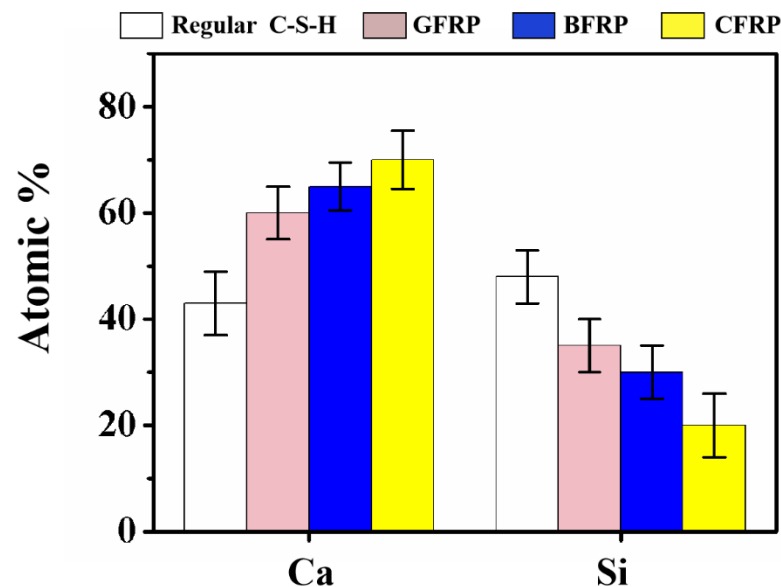


Figure 6. A comparison of the EDX results between the regular C–S–H gel samples and the FRP bar/C–S–H gel interface samples.

3.4. Bond Peak Tension Force–Slip Curves of the FRP Bar–Concrete Interface

To investigate the relationships between the material properties of concrete, the geometric configuration of FRP bars, and the loading rate with respect to bond behavior, pull-out tests were conducted. Figure 7 shows the peak tensile load–slip curves of the pull-out specimens. For comparative analysis, specimens with peak tensile loads closest to the average within each group were chosen to reflect the typical bond response of the FRP bar–concrete interface under diverse loading scenarios. Typically, failure of FRP bars embedded in concrete manifests as either (i) splitting failure of the adjacent concrete or (ii) pull-out failure of the reinforcement bar [62]. In addition, a special failure mode is the rupture of the reinforcement, which typically occurs in steel bars. Compared to steel, FRP bars possess higher tensile strength and superior elongation capacity, allowing them to sustain greater loads. In this investigation, the majority of specimens exhibited pull-out failure under both static and dynamic loading conditions once the tensile force attained its peak value [63]. In specimens exhibiting pull-out failure, shear failure mainly took place within the bond ribs of the FRP bars, leading to a reduction in friction and mechanical interlock between the bars and the surrounding concrete. The peak tension force–slip curves for specimens undergoing pull-out failure can be segmented into three distinct stages (Figure 7c,f,i). During the initial slip stage, the displacement of the FRP bars is minimal, and the bond strength exhibits a linear proportionality [64]. As the load increases, the system enters the second stage, where the convex ribs of the FRP bars undergo shear failure. This results in a gradual decrease in mechanical interlock, and the slope of the curve decreases until it approaches zero. The third stage is the descending phase, where,

after the peak load is reached, the bond stress decreases. This phenomenon indicates that the work performed by the applied load is gradually dissipated through the friction between the FRP bars and the surrounding concrete, ultimately leading to pull-out failure. Correspondingly, the splitting failure mode exhibits a two-stage load–slip curve: an initial slip stage where the load increases linearly with the slip, followed by a sudden drop in the curve once the peak load is reached (Figure 7e,h). This behavior is primarily attributed to the circumferential stress exceeding the tensile strength of the concrete. These two failure modes correspond to different material behaviors: the former represents a ductile failure of the FRP bar, while the latter corresponds to a brittle failure of the concrete.

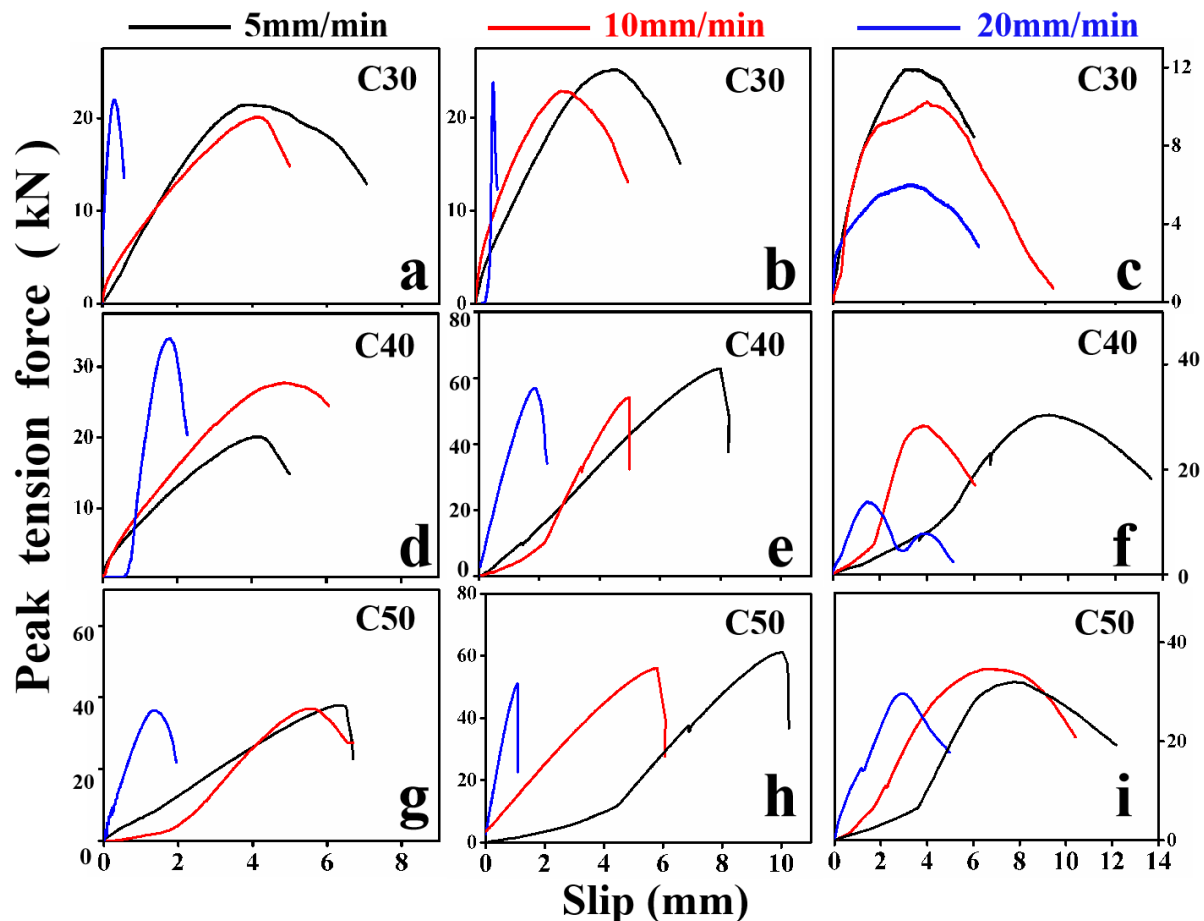


Figure 7. Pull-out test results of the bond performance between the FRP bars and three grades of concrete (C30, C40, and C50) under different loading rates: (a,d,g) GFRP, (b,e,h) BFRP, (c,f,i) CFRP.

Figure 7 illustrates the influence of different concrete strength grades on bond strength. Clearly, the bond strength between the FRP bars and the concrete increases with the compressive strength of the cementation matrix. Under static loading conditions, the peak load of GFRP, BFRP, and CFRP increased by 76.4%, 131%, and 142%, respectively, as the concrete strength grade increased from C30 to C50. This is mainly because higher-strength concrete can form a better adhesive interface with FRP bars, providing stronger mechanical interlocking during the slip process and enhancing resistance to external damage. Similarly, under dynamic loading conditions, the peak load of all three types of FRP bars also increased within the range of 73% to 220%.

Meanwhile, the geometric morphology of the three types of FRP bars also has a particularly significant effect on bond strength. Under static loading conditions, when the concrete grade is C30, the peak loads of GFRP, BFRP, and CFRP are 22.23 kN, 25.97 kN, and 12.51 kN, respectively. The differences in peak load values among them are not pronounced,

mainly because the low concrete strength grade provides insufficient confinement to the FRP bars during the slip stage, thereby diminishing the influence of the FRP bars' geometry on the peak load performance. When the concrete strength is C50, the peak load of BFRP is 53% higher than that of GFRP, and both exhibit significantly higher load values than CFRP. This is primarily due to the lower rib height of the CFRP bars, which results in a lower proportion of mechanical interlocking caused by interactions between the ribs and the surrounding concrete.

The effect of the loading rate on bond strength can be analyzed in conjunction with Table 3 and Figure 7. Under dynamic loading, most of the specimens failed in splitting mode, with the BFRP specimens being the most representative. When subjected to loading rates of 10 mm/min and 20 mm/min, both the failure time and peak load of the FRP bars significantly decrease as the loading rate increases. The splitting failure is accompanied by the sudden release of energy as cracks propagate through the concrete specimen. This phenomenon is attributed to dynamic effects that induce a non-uniform distribution of bond stress under identical loading conditions, leading to diminished deformation and a subsequent reduction in mechanical interlocking forces. At a loading rate of 20 mm/s, the bond strengths of BFRP in the C30, C40, and C50 concrete are 10.39 MPa, 25.69 MPa, and 22.58 MPa, respectively. Compared with static loading conditions, the bond strength decreases by 9.4%, 5.1%, and 15.17%, respectively. Similarly, the bond strength of the carbon fiber bars decreases by 5%–43% under the same conditions. The BFRP bar specimens exhibit relatively high peak loads compared to the GFRP and CFRP specimens under both static and dynamic loading. This is primarily attributed to the greater rib depth of the BFRP bars, which enhances the contact interface with the concrete, thereby strengthening the mechanical interlock. The CFRP bars exhibit the lowest peak tension, characterized by a smoother curve lacking a distinct inflection point, indicating that friction predominantly governs the bonding mechanism.

Table 3. Experimental results of bond strength for different concrete strength grades (C30, C40, C50) under dynamic loading. The values in parentheses represent the standard deviation of each sample group.

Sample	Concrete Grade	Peak Tension Force (kN)		Peak Tension Force (kN)		Peak Tension Force (kN)	
		5 mm/min	$\tau_{\max}$	10 mm/min	$\tau_{\max}$	20 mm/min	$\tau_{\max}$
GFRP	C30	22.23 (1.62)	9.83	21.06 (1.38)	9.31	22.36 (3.82)	9.89
BFRP		25.97 (3.14)	11.48	22.63 (2.65)	10.01	23.51 (4.03)	10.39
CFRP		12.51 (2.75)	5.53	10.39 (0.96)	4.59	6.39 (1.67)	2.82
GFRP	C40	21.7 (1.98)	9.59	27.6 (3.19)	12.21	33.7 (4.33)	14.9
BFRP		61.2 (2.32)	27.05	57.6 (2.48)	25.47	58.1 (5.66)	25.69
CFRP		28.61 (3.12)	12.65	28.3 (2.02)	12.51	16.2 (3.24)	7.16
GFRP	C50	39.22 (2.37)	17.34	39.1 (4.19)	17.29	38.74 (2.49)	17.13
BFRP		62.2 (4.81)	27.51	58.7 (5.13)	25.96	51.06 (4.41)	22.58
CFRP		30.29 (2.34)	13.39	34.78 (3.38)	15.38	28.74 (3.97)	12.71

3.5. Interfacial Bond Failure Modes

Figure 8 illustrates the interfacial damage between the FRP bars and the C40 concrete under varying loading rates. The failure mode observed during dynamic pull-out testing aligns with that under static loading, predominantly characterized by pull-out failure. At a loading rate of 5 mm/min, the interfacial damage on the pull-out FRP bars displays uniform features, as depicted in Figure 8(a1,b1,c1). The roots of the ribs on the FRP bars exhibit significant wear, penetrating deeply into the bar core. Residual concrete remains adhered to the fiber–resin interface, especially evident in the GFRP and BFRP specimens. Conversely, the CFRP bars show less pronounced rib protrusions, with more consistent

concrete coverage on their surfaces, indicating damage mainly due to friction, as shown in Figure 8(c1).

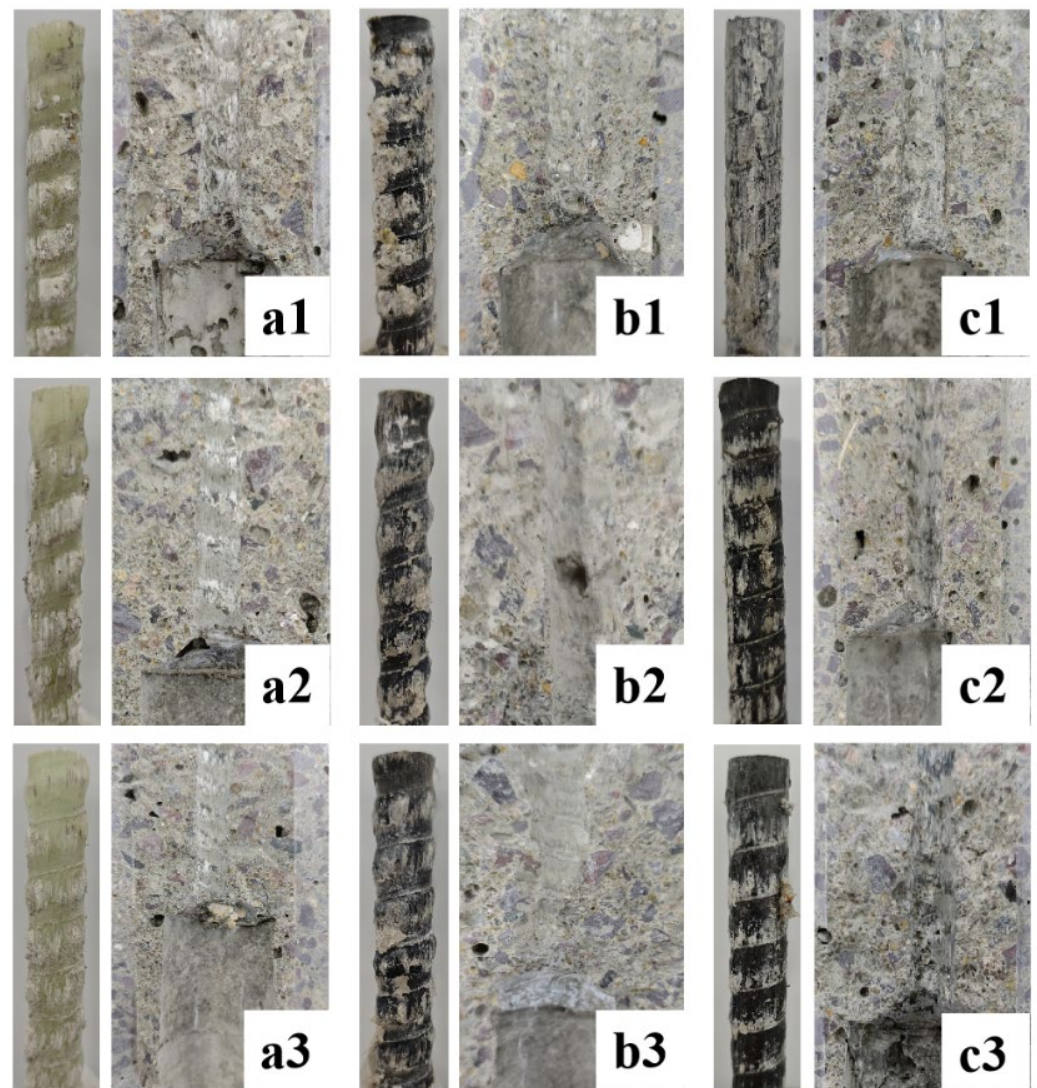


Figure 8. Interface damage between FRP bars and concrete: (a) GFRP, (b) BFRP, (c) CFRP. Loading rates (v): 5 mm/min (a1,b1,c1), 10 mm/min (a2,b2,c2), 20 mm/min (a3,b3,c3), respectively.

The concrete surfaces are severely damaged, with the original rib texture almost completely worn away. Generally, during a stable, static loading process, chemical adhesion first develops, followed by friction, and finally, mechanical interlocking occurs due to the relative slip between the FRP bar and the concrete. Among these mechanisms, mechanical interlocking plays the most significant role in the bonding force [65]. This mechanical interlock chiefly arises from the shear forces acting at the rib roots of the FRP bars and the adjacent concrete surface. Stress within the fiber layers is conveyed to the bonding interface via shear strain in the epoxy resin. The uniform surface damage of the FRP bars suggests that bond strength is predominantly governed by the static shear capacity of the fiber layers. Therefore, the bonding force reaches its full potential under static loading conditions.

When the loading rate is 10 mm/min, the interface damage of the pull-out FRP bar exhibits non-uniform damage characteristics, as shown in Figure 8(a2,b2,c2). The residual concrete on the surface of the fiber layer is less than that observed under static loading. The mechanical locking effect appears to weaken with the increase in loading rate, being replaced by uneven friction. There are few fibers remaining on the damaged area

interface surface of the concrete due to the severe cutting off of the convex ribs, as shown in Figure 8(a2). The difference between dynamic and static loading lies in the introduction of dynamic effects [66]. These dynamic effects increase the dynamic elastic modulus of the FRP bars. As a result, when the FRP bar is subjected to the same load, its deformation decreases with the increase in loading speed, leading to a reduction in the effective area of mechanical interlock. Consequently, the proportion of mechanical interlocking contributing to the bond force decreases. This is an important reason for the uneven surface damage of the FRP bars. When the loading rate is 20 mm/min, the non-uniformity of the FRP bar interface damage becomes more pronounced. The front interface damage to the GFRP and BFRP bars exhibits shear failure, as shown in Figure 8(a3,b3). The increase in dynamic effects results in the rapid transfer of the load to the bonding area of the FRP bars. Due to the hysteresis effect, the stress distribution within the bonding area becomes uneven, causing the bonding area to be divided into non-deforming and relative slip regions. In the non-deforming region, the bonding force exists in the form of friction or dynamic shear force. With the increase in the dynamic elastic modulus and shear modulus of the epoxy resin, the impact stress transmitted from the FRP bar surface to its core material is enhanced. Under these conditions, the bonding behavior in pull-out specimens is primarily controlled by the shear strength of the fiber layers. Moreover, in the relative slip region near the distal end of the FRP bars, the bond force is predominantly influenced by mechanical interlocking [67]. The site of damage is chiefly determined by the comparative shear strength at the interface between the FRP bars and the concrete.

4. Conclusions

This study investigated the bond performance between FRP bars and concrete, with a focus on the effects of surface microstructure and dynamic loading conditions. A variety of techniques, including SEM, AFM, XPS, WCA, EDS measurements, and non-contact surface profilometry, were employed to assess the microscopic properties and surface characteristics of the FRP bars. Pull-out tests with varying loading rates were conducted to evaluate bond–slip curves and failure modes. The key findings and conclusions are summarized as follows:

1. The wettability of the FRP bars' surface is determined by the roughness and chemical composition. The results show that the WCA of the CFRP bars is the highest, reaching 84°.
2. The surface of the FRP bars is primarily composed of three chemical elements: carbon, hydrogen, and oxygen. The O/C ratio of the CFRP bars is the highest, reaching 31.20. Firstly, the higher this value is, the stronger the surface polarity and hydrophilicity, which helps enhance the bonding strength. Secondly, the surface hydrophilicity aids in the formation of the covalent bond to C–S–H.
3. The results of the pull-out tests indicate that under C50 concrete conditions, the BFRP bars exhibited the highest bond strength of 27.51 MPa at a loading rate of 5 mm/min. This is due to their deeper rib structure, which enhances mechanical interlocking with concrete.
4. As the loading rate increases, the bonding strength of the FRP bars generally shows a decreasing trend. Under dynamic loading at 20 mm/s, the bond strength of the BFRP bars in C30, C40, and C50 concrete decreases by 9.4%, 5.1%, and 15.17%, respectively, compared to static conditions. The CFRP bars exhibit a more pronounced reduction in bond strength, ranging from 5% to 43%. This decrease is primarily due to the introduction of dynamic factors, which result in an uneven stress distribution. Consequently, this leads to a reduction in deformation and a decrease in the proportion of mechanical interlock.
5. FRP bars can extend the lifespan of concrete structures and reduce maintenance costs, but the environmental issues caused by their non-biodegradability, along with the

high initial cost and the lack of technical standards, limit their widespread application. Technological advancements are needed to address the economic and environmental challenges, thereby promoting sustainable development.

6. FRP bars offer advantages such as corrosion resistance, lightweight properties, and high durability, making them suitable for harsh environments like coastal or industrial areas. However, their high cost and the uncertainty regarding their long-term performance limit their widespread application, requiring further research breakthroughs.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/coatings15060716/s1>, Table S1. Comparative Properties of Glass fiber, Basalt Fiber, and Carbon Fiber. Table S2. Chemical Composition of Glass fiber, Basalt Fiber, and Carbon Fiber. Figure S1. The SEM images of the surfaces and cross-sections of (a,d) GFRP, (b,e) BFRP, (c,f) CFRP, respectively. Figure S2. The SEM images of the FRP bars surfaces after pulled out from the concrete (a,d) GFRP, (b,e) BFRP, (c,f) CFRP, respectively. Figure S3. Photograph of the physical test setup and schematic of the loading device mechanism. Figure S4. Photographs of the specimen preparation process. Figure S5. Photograph of the test system. Figure S6. Photograph of the test specimen after pull-out. Figure S7. Photographs of the four types of bars and a schematic diagram illustrating the geometric parameters of the deformed steel bar. Figure S8. Pull-out test results of the bond performance between deformed steel bars and C40 concrete under a loading rate of 5 mm/min.

Author Contributions: Conceptualization, W.B. and Y.T.; Data Curation, W.B.; Formal Analysis, W.B.; Investigation, C.L. and H.L.; Methodology, W.B. and H.C.; Project Administration, H.C.; Supervision, H.C. and C.F.; Validation, W.B. and H.C.; Visualization, H.C.; Writing—Original Draft, W.B. and Y.T.; Writing—Review and Editing, W.B. and Y.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Projects of the Zhejiang Provincial Federation of Social Sciences (Grant No. 2025B118).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available from the authors upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Zhang, K.; Zhang, Q.; Xiao, J. Durability of FRP bars and FRP bar reinforced seawater sea sand concrete structures in marine environments. *Constr. Build. Mater.* **2022**, *350*, 128898. [CrossRef]
2. Zwicky, D. Mechanical properties of organic-based lightweight concretes and their impact on economic and ecological performances. *Constr. Build. Mater.* **2020**, *245*, 118413. [CrossRef]
3. Sangmesh, B.; Patil, N.; Jaiswal, K.K.; Gowrishankar, T.; Selvakumar, K.K.; Jyothi, M.; Jyothilakshmi, R.; Kumar, S. Development of sustainable alternative materials for the construction of green buildings using agricultural residues: A review. *Constr. Build. Mater.* **2023**, *368*, 130457. [CrossRef]
4. Benmokrane, B.; Elgabbas, F.; Ahmed, E.A.; Cousin, P. Characterization and Comparative Durability Study of Glass/Vinylester, Basalt/Vinylester, and Basalt/Epoxy FRP Bars. *J. Compos. Constr.* **2015**, *19*, 04015008. [CrossRef]
5. Reis, E.; de Azevedo, R.; Christoforo, A.; Poggiali, F.; Bezerra, A. Bonding of steel bars in concrete: A systematic review of the literature. *Structures* **2023**, *49*, 508–519. [CrossRef]
6. Fang, C.; Lundgren, K.; Plos, M.; Gylltoft, K. Bond behaviour of corroded reinforcing steel bars in concrete. *Cem. Concr. Res.* **2006**, *36*, 1931–1938. [CrossRef]
7. Liang, X.; Peng, J.; Ren, R. A state-of-the-art review: Shear performance of the concrete beams reinforced with FRP bars. *Constr. Build. Mater.* **2022**, *364*, 129996. [CrossRef]
8. Ji, X.-L.; Chen, L.-J.; Liang, K.; Pan, W.; Su, R.K.-L. A review on FRP bars and supplementary cementitious materials for the next generation of sustainable and durable construction materials. *Constr. Build. Mater.* **2023**, *383*, 131403. [CrossRef]

9. Hosseini, S.-A.; Nematzadeh, M.; Chastre, C. Prediction of shear behavior of steel fiber-reinforced rubberized concrete beams reinforced with glass fiber-reinforced polymer (GFRP) bars. *Compos. Struct.* **2021**, *256*, 113010. [\[CrossRef\]](#)
10. Less, T.; Demir, A.; Sezen, H. Structural performance and corrosion resistance of fiber reinforced polymer wrapped steel reinforcing bars. *Constr. Build. Mater.* **2022**, *366*, 130176. [\[CrossRef\]](#)
11. Attia, M.M.; Ahmed, O.; Kobesy, O.; Malek, A.S. Behavior of FRP rods under uniaxial tensile strength with multiple materials as an alternative to steel rebar. *Case Stud. Constr. Mater.* **2022**, *17*, e01241. [\[CrossRef\]](#)
12. Sijavandi, K.; Sharbatdar, M.K.; Kheyroddin, A. Experimental evaluation of flexural behavior of High-Performance Fiber Reinforced Concrete Beams using GFRP and High Strength Steel Bars. *Structures* **2021**, *33*, 4256–4268. [\[CrossRef\]](#)
13. Sun, L.; Wang, C.; Zhang, C.; Yang, Z.; Li, C.; Qiao, P. Experimental investigation on the bond performance of sea sand coral concrete with FRP bar reinforcement for marine environments. *Adv. Struct. Eng.* **2022**, *26*, 533–546. [\[CrossRef\]](#)
14. Xiong, Z.; Wei, W.; Liu, F.; Cui, C.; Li, L.; Zou, R.; Zeng, Y. Bond behaviour of recycled aggregate concrete with basalt fibre-reinforced polymer bars. *Compos. Struct.* **2021**, *256*, 113078. [\[CrossRef\]](#)
15. Xiong, Z.; Mai, G.; Qiao, S.; He, S.; Zhang, B.; Wang, H.; Zhou, K.; Li, L. Fatigue bond behaviour between basalt fibre-reinforced polymer bars and seawater sea-sand concrete. *Ocean Coast. Manag.* **2022**, *218*, 106038. [\[CrossRef\]](#)
16. Wang, J.; Xiao, F.; Lai, Z.; Yang, J.; Tian, S. Bond of FRP bars with different surface characteristics to concrete. *Structures* **2023**, *59*, 105731. [\[CrossRef\]](#)
17. Li, H.; Li, L.; Li, L.; Zhou, J.; Mu, R.; Xu, M. Influence of fiber orientation on the microstructures of interfacial transition zones and pull-out behavior of steel fiber in cementitious composites. *Cem. Concr. Compos.* **2022**, *128*, 104459. [\[CrossRef\]](#)
18. Mazaheripour, H.; Barros, J.; Sena-Cruz, J.; Pepe, M.; Martinelli, E. Experimental study on bond performance of GFRP bars in self-compacting steel fiber reinforced concrete. *Compos. Struct.* **2013**, *95*, 202–212. [\[CrossRef\]](#)
19. Dvorkin, D.; Poursaei, A.; Peled, A.; Weiss, W. Influence of bundle coating on the tensile behavior, bonding, cracking and fluid transport of fabric cement-based composites. *Cem. Concr. Compos.* **2013**, *42*, 9–19. [\[CrossRef\]](#)
20. Chen, L.; Liang, K.; Shan, Z. Experimental and theoretical studies on bond behavior between concrete and FRP bars with different surface conditions. *Compos. Struct.* **2023**, *309*, 116721. [\[CrossRef\]](#)
21. Kim, H.-Y.; Park, Y.-H.; You, Y.-J.; Moon, C.-K. Short-term durability test for GFRP rods under various environmental conditions. *Compos. Struct.* **2008**, *83*, 37–47. [\[CrossRef\]](#)
22. Chen, Y.; Davalos, J.F.; Ray, I.; Kim, H.-Y. Accelerated aging tests for evaluations of durability performance of FRP reinforcing bars for concrete structures. *Compos. Struct.* **2007**, *78*, 101–111. [\[CrossRef\]](#)
23. Benmokrane, B.; Mousa, S.; Mohamed, K.; Sayed-Ahmed, M. Physical, mechanical, and durability characteristics of newly developed thermoplastic GFRP bars for reinforcing concrete structures. *Constr. Build. Mater.* **2021**, *276*, 122200. [\[CrossRef\]](#)
24. Fergani, H.; Di Benedetti, M.; Oller, C.M.; Lynsdale, C.; Guadagnini, M. Durability and degradation mechanisms of GFRP reinforcement subjected to severe environments and sustained stress. *Constr. Build. Mater.* **2018**, *170*, 637–648. [\[CrossRef\]](#)
25. Wang, T.; Razaqpur, A.G.; Chen, S. Durability of GFRP and CFRP Bars in the Pore Solution of Calcium Sulfoaluminate Cement Concrete Made with Fresh or Seawater. *Polymers* **2023**, *15*, 3306. [\[CrossRef\]](#)
26. Feng, G.; Zhu, D.; Guo, S.; Rahman, Z.; Jin, Z.; Shi, C. A review on mechanical properties and deterioration mechanisms of FRP bars under severe environmental and loading conditions. *Cem. Concr. Compos.* **2022**, *134*, 104758. [\[CrossRef\]](#)
27. Li, S.; Zhu, D.; Guo, S.; Xi, H.; Rahman, Z.; Yi, Y.; Fu, B.; Shi, C. Static and dynamic tensile behaviors of BFRP bars embedded in seawater sea sand concrete under marine environment. *Compos. Part B Eng.* **2022**, *242*, 110051. [\[CrossRef\]](#)
28. Liu, F.; Feng, W.; Xiong, Z.; Tu, G.; Li, L. Static and impact behaviour of recycled aggregate concrete under daily temperature variations. *J. Clean. Prod.* **2018**, *191*, 283–296. [\[CrossRef\]](#)
29. Li, G.; Wu, J.; Ge, W. Effect of loading rate and chemical corrosion on the mechanical properties of large diameter glass/basalt-glass FRP bars. *Constr. Build. Mater.* **2015**, *93*, 1059–1066. [\[CrossRef\]](#)
30. Xu, M.; Hallinan, B.; Wille, K. Effect of loading rates on pullout behavior of high strength steel fibers embedded in ultra-high performance concrete. *Cem. Concr. Compos.* **2016**, *70*, 98–109. [\[CrossRef\]](#)
31. Vos, E.; Reinhardt, H.W. Influence of loading rate on bond behaviour of reinforcing steel and prestressing strands. *Mater. Struct.* **1982**, *15*, 3–10. [\[CrossRef\]](#)
32. Huo, J.; Liu, J.; Dai, X.; Yang, J.; Lu, Y.; Xiao, Y.; Monti, G. Experimental Study on Dynamic Behavior of CFRP-to-Concrete Interface. *J. Compos. Constr.* **2016**, *20*, 04016026. [\[CrossRef\]](#)
33. Chen, W.; Meng, F.; Sun, H.; Guo, Z. Bond behaviors of BFRP bar-to-concrete interface under dynamic loading. *Constr. Build. Mater.* **2021**, *305*, 124812. [\[CrossRef\]](#)
34. BS EN 10080 2005; Steel for the Reinforcement of Concrete—Weldable Reinforcing Steel—General. Central Secretariat: Brussels, Belgium, 2005.
35. Espinal, M.; Kane, S.; Ryan, C.; Phillips, A.; Heveran, C. Evaluation of the bonding properties between low-value plastic fibers treated with microbially-induced calcium carbonate precipitation and cement mortar. *Constr. Build. Mater.* **2022**, *357*, 129331. [\[CrossRef\]](#)

36. Fataar, H.; Combrinck, R.; Boshoff, W. An experimental study on the fatigue failure of steel fibre reinforced concrete at a single fibre level. *Constr. Build. Mater.* **2021**, *299*, 123869. [\[CrossRef\]](#)
37. Abdulrahman, P.I.; Bzeni, D.K. Bond strength evaluation of polymer modified cement mortar incorporated with polypropylene fibers. *Case Stud. Constr. Mater.* **2022**, *17*, e01387. [\[CrossRef\]](#)
38. Kim, D.-J.; Kim, M.S.; Yun, G.Y.; Lee, Y.H. Bond strength of steel deformed rebars embedded in artificial lightweight aggregate concrete. *J. Adhes. Sci. Technol.* **2013**, *27*, 490–507. [\[CrossRef\]](#)
39. Liu, K.; Zou, C.; Yan, J.; Shan, X. Bond behavior of deformed steel bars in self-compacting concrete. *J. Adhes. Sci. Technol.* **2020**, *35*, 1518–1533. [\[CrossRef\]](#)
40. Li, L.; Chen, Z.; Ouyang, Y.; Zhu, J.; Chu, S.; Kwan, A. Synergistic effects of steel fibres and expansive agent on steel bar-concrete bond. *Cem. Concr. Compos.* **2019**, *104*, 103380. [\[CrossRef\]](#)
41. Al-Shannag, M.J.; Charif, A. Bond behavior of steel bars embedded in concretes made with natural lightweight aggregates. *J. King Saud Univ. Eng. Sci.* **2017**, *29*, 365–372. [\[CrossRef\]](#)
42. Zang, Y.; Zhan, Y.; Liang, S.; Guo, D.; Zhao, Q.; Cheng, Z.; Liu, W.; Ma, H.; Yu, H. Study on the effects of steel bar diameter and anchorage length on bond-slip characteristics of reinforced concrete under freeze-thaw cycles. *Constr. Build. Mater.* **2025**, *460*, 139786. [\[CrossRef\]](#)
43. Majain, N.; Rahman, A.B.A.; Adnan, A.; Mohamed, R.N. Bond behaviour of deformed steel bars in steel fibre high-strength self-compacting concrete. *Constr. Build. Mater.* **2022**, *318*, 125906. [\[CrossRef\]](#)
44. CSA S806-12; Design and Construction of Building Structures with Fibre Reinforced Polymers. Canadian Standards Association: Mississauga, ON, Canada, 2012.
45. ACI 440.3R-12; Guide Test Methods for Fiber-Reinforced Polymers (FRP) Composites for Reinforcing or Strengthening Concrete and Masonry Structures. American Concrete Institute: Farmington Hills, MI, USA, 2012.
46. ASTM D7913/D7913M-14; Standard Test Method for Bond Strength of Fiberreinforced Polymer Matrix Composite Bars to Concrete by Pullout Testing. ASTM International: Conshohocken, PA, USA, 2020.
47. Spagnuolo, S.; Rinaldi, Z.; Donnini, J.; Nanni, A. Physical, mechanical and durability properties of GFRP bars with modified acrylic resin (modar) matrix. *Compos. Struct.* **2021**, *262*, 113557. [\[CrossRef\]](#)
48. Castoldi, R.d.S.; Liebscher, M.; de Souza, L.M.S.; Mechtcherine, V.; Menezes, R.P.; Silva, F.d.A. Effect of polymeric fiber coating on the mechanical performance, water absorption, and interfacial bond with cement-based matrices. *Constr. Build. Mater.* **2023**, *404*, 133222. [\[CrossRef\]](#)
49. Chun, B.; Yoo, D.-Y.; Banthia, N. Achieving slip-hardening behavior of sanded straight steel fibers in ultra-high-performance concrete. *Cem. Concr. Compos.* **2020**, *113*, 103669. [\[CrossRef\]](#)
50. Gallinetti, S.; Mestres, G.; Canal, C.; Persson, C.; Ginebra, M.-P. A novel strategy to enhance interfacial adhesion in fiber-reinforced calcium phosphate cement. *J. Mech. Behav. Biomed. Mater.* **2017**, *75*, 495–503. [\[CrossRef\]](#)
51. Li, J.; Yang, L.; Xie, H.; Gao, J.; Zhang, F.; Chen, S.; Liu, Y.; Zhang, S. Experimental investigation on interfacial bonding performance between cluster basalt fiber and cement mortar. *Constr. Build. Mater.* **2023**, *411*, 134215. [\[CrossRef\]](#)
52. Benmokrane, B.; Ali, A.H.; Mohamed, H.M.; ElSafty, A.; Manalo, A. Laboratory assessment and durability performance of vinyl-ester, polyester, and epoxy glass-FRP bars for concrete structures. *Compos. Part B Eng.* **2017**, *114*, 163–174. [\[CrossRef\]](#)
53. Verma, C.; Olasunkanmi, L.O.; Akpan, E.D.; Quraishi, M.; Dagdag, O.; El Gouri, M.; Sherif, E.-S.M.; Ebenso, E.E. Epoxy resins as anticorrosive polymeric materials: A review. *React. Funct. Polym.* **2020**, *156*, 104741. [\[CrossRef\]](#)
54. Wu, B.; Qiu, J. Enhancing the hydrophobic PP fiber/cement matrix interface by coating nano-AlOOH to the fiber surface in a facile method. *Cem. Concr. Compos.* **2022**, *125*, 104297. [\[CrossRef\]](#)
55. Soyer-Uzun, S.; Chae, S.R.; Benmore, C.J.; Wenk, H.R.; Monteiro, P.J.M.; Brown, P. Compositional Evolution of Calcium Silicate Hydrate (C–S–H) Structures by TotalX-Ray Scattering. *J. Am. Ceram. Soc.* **2011**, *95*, 793–798. [\[CrossRef\]](#)
56. Antonova, A.; Eik, M.; Jokinen, V.; Puttonen, J. Effect of the roughness of steel fibre surface on its wettability and the cement paste close to fibre surface. *Constr. Build. Mater.* **2021**, *289*, 123139. [\[CrossRef\]](#)
57. Shalchy, F.; Rahbar, N. Nanostructural Characteristics and Interfacial Properties of Polymer Fibers in Cement Matrix. *ACS Appl. Mater. Interfaces* **2015**, *7*, 17278–17286. [\[CrossRef\]](#)
58. Lilli, M.; Jurko, M.; Sirjovova, V.; Zvonek, M.; Cech, V.; Scheffler, C.; Rogero, C.; Ilyn, M.; Tirillò, J.; Sarasini, F. Basalt fibre surface modification via plasma polymerization of tetravinylsilane/oxygen mixtures for improved interfacial adhesion with unsaturated polyester matrix. *Mater. Chem. Phys.* **2021**, *274*, 125106. [\[CrossRef\]](#)
59. Zhang, W.; Zou, X.; Wei, F.; Wang, H.; Zhang, G.; Huang, Y.; Zhang, Y. Grafting SiO₂ nanoparticles on polyvinyl alcohol fibers to enhance the interfacial bonding strength with cement. *Compos. Part B Eng.* **2019**, *162*, 500–507. [\[CrossRef\]](#)
60. Ferreira, S.R.; Pepe, M.; Martinelli, E.; Silva, F.d.A.; Filho, R.D.T. Influence of natural fibers characteristics on the interface mechanics with cement based matrices. *Compos. Part B Eng.* **2018**, *140*, 183–196. [\[CrossRef\]](#)
61. Lin, C.; Kanstad, T.; Jacobsen, S.; Ji, G. Bonding property between fiber and cementitious matrix: A critical review. *Constr. Build. Mater.* **2023**, *378*, 131169. [\[CrossRef\]](#)

62. Mohamed, O.A.; Al Hawat, W.; Keshawarz, M. Durability and Mechanical Properties of Concrete Reinforced with Basalt Fiber-Reinforced Polymer (BFRP) Bars: Towards Sustainable Infrastructure. *Polymers* **2021**, *13*, 1402. [[CrossRef](#)]
63. Cui, S.; Xu, X.; Yan, X.; Chen, Z.; Hu, C.; Liu, Z. Experimental study on the interfacial bond between short cut basalt fiber bundles and cement matrix. *Constr. Build. Mater.* **2020**, *256*, 119353. [[CrossRef](#)]
64. Zhao, D.; Zhou, Y.; Xing, F.; Sui, L.; Ye, Z.; Fu, H. Bond behavior and failure mechanism of fiber-reinforced polymer bar-engineered cementitious composite interface. *Eng. Struct.* **2021**, *243*, 112520. [[CrossRef](#)]
65. Wei, W.; Liu, F.; Xiong, Z.; Yang, F.; Li, L.; Luo, H. Effect of loading rates on bond behaviour between basalt fibre-reinforced polymer bars and concrete. *Constr. Build. Mater.* **2020**, *231*, 117138. [[CrossRef](#)]
66. Zhang, R.; Jin, L.; Liu, M.; Du, X.; Liu, J. Refined modeling of the interfacial behavior between FRP bars and concrete under different loading rates. *Compos. Struct.* **2022**, *291*, 115676. [[CrossRef](#)]
67. Bakar, M.B.C.; Rashid, R.S.M.; Amran, M.; Jaafar, M.S. Evaluation of the bond-dependent factors for CFRP bars used as structural reinforcement: A critical review. *Case Stud. Constr. Mater.* **2023**, *18*, e02064. [[CrossRef](#)]

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