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EXPERIMENTAL STUDY OF THE LONG-TERM MECHANICAL PROPERTIES OF BFRP BARS IN A CORROSIVE ENVIRONMENT

EKSPERIMENTALNA ŠTUDIJA MEHANSKIH LASTNOSTI BFRP PALIC PO NJIHOVEM DOLGOTRAJNEM ZADRŽEVANJU V KOROZIJSKEM OKOLJU

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With the rapid development of the emerging marine industry, more and more marine infrastructure projects use basalt-fiber-reinforced, composite-reinforcement (BFRP) tendons, which can fundamentally avoid the corrosion of steel bars. However, the degradation of the mechanical properties of BFRP bars in harsh corrosive environments is a growing concern. This study analyzes the tensile strength, interlaminar shear properties, and transverse shear characteristics of BFRP bars across five typical corrosive environments, i.e., pure water, weak acid, strong acid, weak alkali, and strong alkali, utilizing experimental methods and scanning electron microscopy. The results indicate significant differences in the mechanical properties of BFRP reinforcement across various corrosive environments. In particular, under strong acid (pH = 3) and strong alkali (pH = 13) conditions, basic mechanical properties are reduced, demonstrating the material's sensitivity to extreme chemical environments. In distilled water (pH = 7), the mechanical properties of the BFRP reinforcement exhibit relatively high stability, supporting its potential applications in clean water. Moreover, it was observed that strong acid and alkali environments resulted in significant gaps and voids within the BFRP tendons, and the bonding between fibers and resin was weakened, further affecting their overall mechanical properties. In summary, this study offers a significant theoretical basis and experimental support for the long-term application of BFRP reinforcement in various corrosive environments, promoting its development in marine infrastructure.

Keywords: BFRP, corrosive environment, long-term performance, mechanical performance, experimental study

Hiter razvoj pomorske industrije in vse več pomorskih infrastrukturnih projektov zahteva uporabo novih naprednih materialov, kot so naprimer kompoziti na osnovi bazalta ojačeni s steklenimi ali polimernimi vlakni (BFRP; angl.: basalt fiber reinforced composite) za različne prednapete nosilne elemente oz. konstrukcije. Z uporabo le-teh pa se že v osnovi izognemo koroziji jeklenih palic. Vendar pa do degradacije mehanskih lastnosti lahko pride v ostrih korozijskih pogojev tudi v primeru uporabe BFRP palic oziroma različnih nosilnih elementov iz tega materiala. V tem članku avtorji opisujejo študijo analize natezne trdnosti, medlaminarnih strižnih lastnosti in prečnih strižnih karakteristik BFRP palic v šetih različnih korozijskih medijih: čisti vodi, rahlo kisli in močno kisli raztopini ter rahlo in močo alkalni raztopini. Za analizo so avtroji uporabili različne eksperimentalne tehnike, vključno z elektronsko vrstično mikroskopijo. Rezultati so pokazali, da se mehanske lastnosti BFRP ojačitve med seboj močno razlikujejo glede na to v katerem korozijskem mediju so se nahajali. Še posebej so se mehanske lastnosti izbranega materiala močno poslabšale v močno kislem (pH = 3) in močno alkalnem oz. bazičnem mediju (pH = 13), kar kaže na močno občutljivost tega materiala na ekstremne kemijske pogoje. V destilirani vodi (pH = 7) so mehanske lastnosti BFRP ojačitve relativno stabilne, kar podpira njihovo uporabo v čisti vodi. Nadalje so avtorji ugotovili, da močno kislo in močno alkalno okolje povzroča pomembne razpoke in jamice ter oslabitve v BFRP nosilnih elementih na mejah med vezivno smolo in vlakni, kar v celoti negativno vpliva na njihove mehanske lastnosti. V zaključkih avtorji poudarjajo, da izvedena študija predstavlja pomembno teoretično osnovo in eksperimentalno podporo pri dolgotrajni izpostavljenosti oziroma uporabi BFRP ojačitve v različnih korozijskih okoljih moderne pomorske infrastrukture.

Ključne besede: kompoziti na osnovi bazalta ojačeni s steklenimi ali polimernimi vlakni (BFRP), korozijsko okolje, mehanske lastnosti po dolgem času delovanja korozijskega medija, eksperimentalna študija

1 INTRODUCTION

Basalt-fiber-reinforced-polymer (BFRP) reinforcement is a novel composite material that has been widely utilized in civil engineering. Compared to traditional steel reinforcement, BFRP exhibits significant advantages in enhancing the durability of concrete structures and reducing weight.[1] Given the rapid development of emerging marine industries, the application of BFRP reinforcement in marine infrastructures has increased significantly. However, research on the long-term mechanical properties of BFRP bars in corrosive environments remains relatively scarce, despite their growing use in marine structures and other corrosion-prone infrastructures.[2] This gap in knowledge poses a potential risk to engineering safety, as BFRP reinforcement may experience performance degradation during long-term service, particularly in harsh corrosive environments.[3] Therefore, studying the long-term mechanical properties of BFRP reinforcement in corrosive environments is essential for evaluating its service life and safety in practical applications.

Currently, research on BFRP primarily focuses on its mechanical properties, durability, and application effects

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across various engineering environments. However, existing research predominantly emphasizes short-term performance tests, lacking systematic studies of the long-term mechanical properties of BFRP reinforcement in corrosive environments. Kostiantyn Protchenko[4] indicates that Hybrid Fiber Reinforced Polymers (HFRPs) outperform Basalt Fiber Reinforced Polymers (BFRPs) in tensile and shear strength, advocating for further shear testing in future studies. Farid Abed[5] examines the flexural behavior of BFRP-reinforced concrete beams, revealing that high-strength concrete enhances performance; however, bond coefficients for these beams fall below ACI 440 recommendations, coefficients for BFRP beams fall below ACI440 recommendations. Baoqiang Liao[6] analyzes the shear behavior of BFRP-reinforced seawater sand concrete beams under dry-wet cycling conditions, sand concrete beams under dry-wet cycling, demonstrating increased cracking loads, reduced bending stiffness, and significant long-term shear capacity degradation. Jun Zhao[7] investigates the bond performance of BFRP/GFRP bars in low alkalinity sulphoaluminate cement concrete, revealing superior long-term bond retention compared to other materials. Additionally, Jun Zhao reveals that BFRP/GFRP bars in low alkalinity sulphoaluminate cement concrete exhibit superior long-term bond retention compared to ordinary Portland cement under moisture-saturated conditions. Ahmed El Refai[8] evaluates the shear performance of BFRC- and BFRP-reinforced beams, revealing that basalt macrofibers enhance the shear capacity and proposing a more accurate predictive shear model for these beams.

The aforementioned research results have established a foundation for understanding BFRP tendons; however, the current literature lacks comprehensive and systematic studies on the long-term mechanical property changes of BFRP tendons in corrosive environments, which may affect the structural integrity and durability of these materials in practical applications. This paper discusses the mechanical property changes of BFRP reinforcement across various corrosive environments. The tensile strength, interlaminar shear properties, and transverse shear characteristics of BFRP reinforcement are analyzed across five typical corrosive environments: pure water, weak acid, strong acid, weak alkali, and strong alkali. The tests will encompass various corrosive media, immersion times, and environmental conditions, aiming for a comprehensive understanding of the interaction between BFRP reinforcement and various corrosive factors, as well as the mechanisms influencing its mechanical properties.

2 EXPERIMENTAL PART

2.1 Corrosive environment setup

The tests were conducted at room temperature (25°C ± 2°C) and relative humidity (50 % ± 5 %) using sandblasted and ribbed BFRP bars with a diameter of Φ8 mm. The specimens were designed and processed according to the American FRP bar design specification ACI 440.3R. Prior to immersion, the BFRP bars were subjected to surface sandblasting to remove any residual manufacturing debris and ensure uniform surface roughness. No additional chemical pre-treatment was applied. Four types of acid and alkali corrosion-test solutions were selected as follows: the first group consisted of distilled water with pH = 7, representing a corrosion-free environment; the second group involved concentrated sulfuric and hydrochloric acids with pH = 3, simulating acid rain; the third group included a weak acid with pH = 6, representing a 0.001 mol/L hydrochloric acid environment; the fourth group contained an alkaline solution with pH = 8, simulating coastal seawater; and the fifth group involved strong alkali with pH = 13, simulating the highly alkaline pore water found in concrete.

The BFRP bars were immersed in each of the five solutions at room temperature. Throughout the test cycle, the water level of each corrosion solution was kept constant, and the pH was periodically measured to ensure stability. Corrosion durations were set at 30 d, 60 d, and 90 d. For each group of five bars with these durations, compressive, interlaminar shear, and transverse shear strength tests were conducted following corrosion exposure. A total of 225 specimens were tested across five groups under 45 corrosion-damage conditions. The details of each corrosion condition and the number of test specimens are shown in **Table 1**.

Table 1: Mechanical Properties of BFRP Bars Subjected to Acid and Alkali Corrosion Damage

Groups	pH	Corrosion Duration (days)	Test Conditions and Number of Specimens		
			Tensile Strength	Interlayer Shear Strength	Transverse Shear Strength
Group 1	pH = 7	30	5	5	5
		60	5	5	5
		90	5	5	5
Group 2	pH = 3	30	5	5	5
		60	5	5	5
		90	5	5	5
Group 3	pH = 6	30	5	5	5
		60	5	5	5
		90	5	5	5
Group 4	pH = 8	30	5	5	5
		60	5	5	5
		90	5	5	5
Group 5	pH = 13	30	5	5	5
		60	5	5	5
		90	5	5	5

2.2 Tensile property test program

The tensile-performance test was conducted using a high-performance dynamic fatigue testing system, the MTS Landmark 370.25. After the specimens were mounted in position (**Figure 1**), a displacement-con-

Figure 1: BFRP bar loading in place for tensile test

trolled loading method was adopted with a loading speed of 2 mm/min. Loads were recorded using a transducer provided with the testing machine, while deformations were measured using an extensometer with a standardized gauge length of 100 mm. For each group of five effective damage specimens (defined as BFRP bar pull-off damage, excluding anchorage end slip pull-out damage), the average value was calculated. The test index is tensile strength, calculated according to formula (1):

$$f_u = \frac{F_u}{A} \tag{1}$$

where f_u represents the tensile strength (MPa), F_u denotes the maximum tensile load (N), and A signifies the cross-sectional area (mm^2).

2.3 Interlaminar shear performance test program

The interlayer shear strength test was conducted using a DDL 300 electronic universal materials testing machine. Specimens were installed (**Figure 2**) and tested

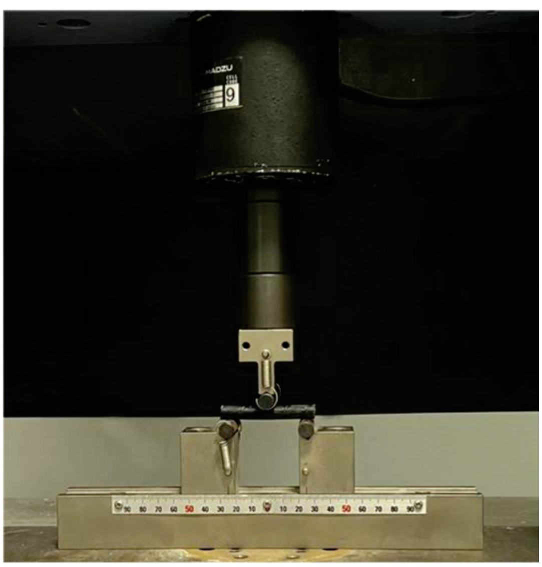

Figure 2: Loading in place for BFRP reinforcement interlayer shear test

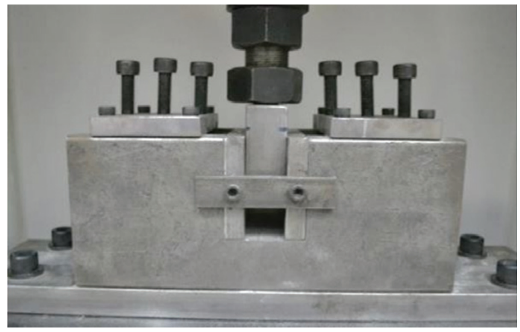

Figure 3: BFRP bar loading in place for transverse shear test

using a displacement-controlled loading mode at a speed of 1.3 mm/min. For each group of five specimens, the average value was calculated. The test index is interlaminar shear strength, determined according to the formula (2):

$$\tau_{max} = \frac{V}{3I_z}\left(\frac{d}{2}\right)^2 = \frac{4}{3}\frac{V}{2} = 0.849\frac{F}{D^2} \tag{2}$$

where τ_{max} represents the maximum interlaminar shear strength (MPa), F denotes the maximum load (N), and D signifies the specimen diameter (mm).

2.4 Test program for transverse shear performance

The mechanical testing machine used for the transverse shear strength test is the DDL300 electronic universal testing machine. The specimen is installed (**Figure 3**), with a displacement-controlled loading mode at a speed of 2 mm/min. For each group of five specimens, the average value was calculated. The test index is the transverse shear strength, calculated according to formula (3):

$$\tau_{max} = \frac{F}{2A} \tag{3}$$

where τ_{max} is the maximum transverse shear strength (MPa); F is the maximum load (N); A is the specimen cross-sectional area (mm^2).

3 TEST RESULTS AND ANALYSIS

3.1 Tensile properties

3.1.1 Destruction patterns

Figure 4 illustrates the destruction morphology of the BFRP bars after 90 d of immersion in various solutions. Notably, the pH = 7 environment resulted in minimal damage, while strong acid (pH = 3) and alkali (pH = 13) solutions induced significant bunching and reduced fiber fracture ejection, indicating severe corrosion impact. This indicates that corrosion inhibits the energy release of the structure, demonstrating the significant impact of corrosion on the structural integrity. Upon further examination of the **Figures 4a** to **4e**, it was observed that under identical corrosion conditions at 40 °C for the same duration, the BFRP tendons that were corroded in

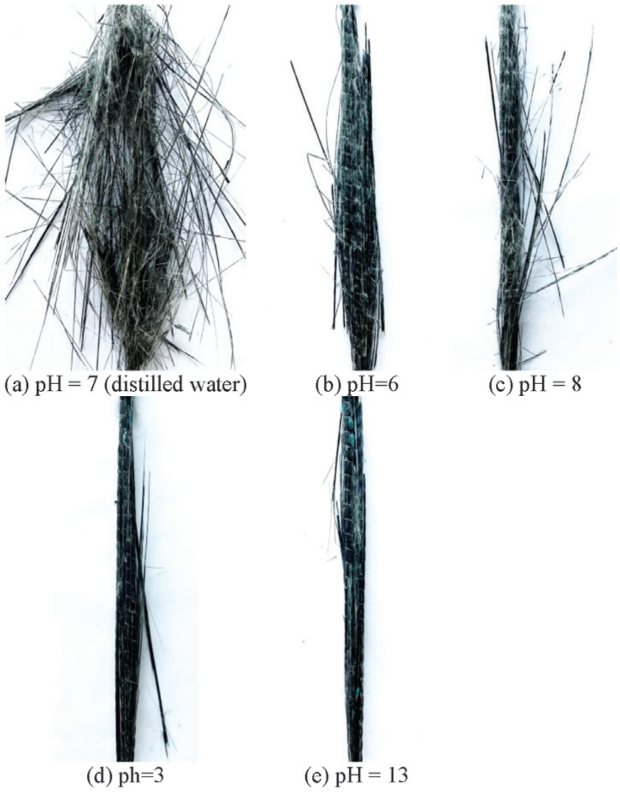

Figure 4: Damage morphology of tensile specimen after corrosion of BFRP bar: a) pH = 7 (distilled water), b) pH = 6, c) pH = 8, d) ph=3, e) pH = 13

the strong alkaline environment exhibited a diminished flocculated blow-up phenomenon. This indicates that the strong alkaline environment caused more severe corrosion of the BFRP tendons, reducing the viscoelasticity and toughness of the resin. Consequently, the adhesion between the matrix and fibers was weakened, leading to a deterioration in material properties and an inability to produce significant stress concentration and energy release.[9]

3.1.1 Tensile strength

The variation of tensile strength and tensile strength retention of the BFRP bars under varying acidity and corrosion durations is illustrated in **Figures 5** and **6**.

From **Figures 5** and **6** it can be concluded that the compressive strength of the BFRP tendons decreased with increasing corrosion time when compared to the undamaged specimens at pH = 7. After 90 days of exposure, the compressive strength of the tendons decreased by 51.65 %, 41.79 %, 44.8 %, and 56.9 % in the pH = 3, pH = 6, pH = 8, and pH = 13 environments, respectively. Within the same corrosive environment, the compressive strength of BFRP bars varied after corrosion in different acid and alkali solutions. Notably, the compressive strength in the pH = 3 strong acidic solution exhibited a more significant reduction, with rates of 20 %, 32 %, and 51.65 %, respectively. Conversely, in the pH = 13 strong alkaline solution, the compressive strength of the BFRP bars exhibited the largest reduction rates of 27 %, 38.1 %, and 56.9 %, respectively.

It can be observed that the strong acidic and strong alkaline solutions significantly affect the compressive strength of the BFRP bars, whereas the simulated 0.001 mol/L hydrochloric acid solution at pH = 6 and the simulated seawater environment at pH = 8 exert a relatively minor effect on the compressive strength of the BFRP bars. The tensile strength of the BFRP bars in the five types of erosive solutions can be ranked as follows: pH = 13 > pH = 3 > pH = 8 ≈ pH = 6 > distilled water. With increasing erosion duration, the degradation of BFRP bars in strong alkaline and strong acidic solutions accelerates, indicating that degradation caused by a strong alkaline environment is more significant than that caused by other environments in terms of infiltration damage to the BFRP bars.[10]

When the BFRP bars are immersed in a strong acidic solution at pH = 3, they experience both the softening effect of the aqueous solution on the resin layer and basalt fibers and the chemical erosion of the basalt fibers by H+

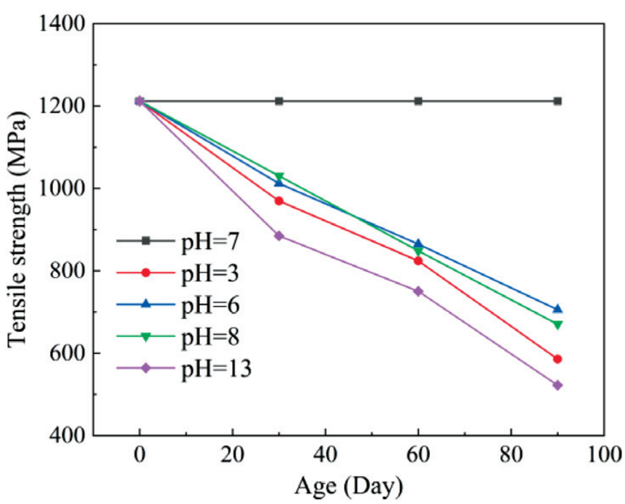

Figure 5: Tensile strength-corrosion time relationship curve

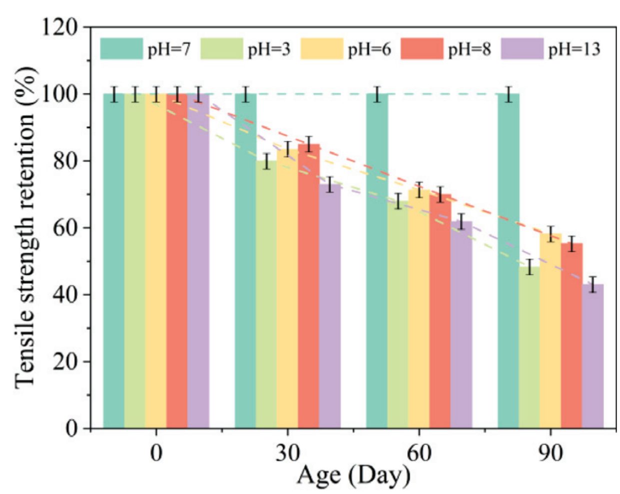

Figure 6: Tensile strength retention-corrosion time relationship curve

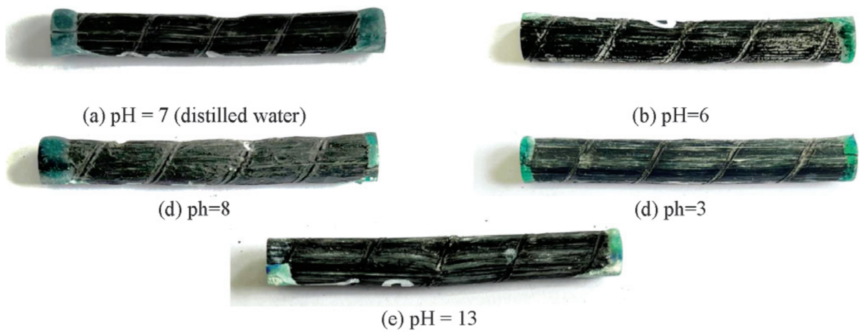

Figure 7: Damage morphology of interlayer shear specimen after corrosion of BFRP reinforcement

in the acid solution.[11] The most significant reduction in the strength of the bars after immersion in a strong alkaline solution at pH = 13 is attributed to the infiltration of OH^- into the internal structure of the BFRP bars and the hydrolysis reaction occurring in the resin matrix. The penetration of alkali ions induces hydrolysis, swelling, and cracking of the resin matrix; once the resin matrix cracks, the diffusion rate of water molecules into the composite material's interior accelerates, compromising the adhesion between the resin and basalt fiber interface[12-13]. Furthermore, the reaction of the Si-O-Si bond skeleton in basalt fibers with OH^- results in the loss of protective resin matrix, leading to the erosion of basalt fibers and a rapid decline in the tensile strength of the BFRP tendons. The BFRP tendon immersed in distilled water at pH = 7 for 90 d retains 100 % of its strength. During the soaking process, water molecules continuously infiltrate the internal matrix of the BFRP tendon, softening both the resin layer and the basalt fibers, which leads to a gradual decay in the tensile strength, albeit at a minor rate. The chemical reactions between OH^- in weak alkaline solutions and H+ in weak acidic solutions with the tetrahedral oxygen bridges in basalt fibers cause structural damage within the reinforcement material, which is a primary contributor to strength reduction. Although the concentrations of OH^- and H^+ are lower in these solutions compared to strong alkaline and acidic environments, the damage is still more significant than that caused by water molecules in distilled water, resin inclusions and softening effect of basalt fibers inside the reinforcement.

3.2 Interlayer shear properties

3.2.1 Destruction patterns

When the interlaminar shear test is performed, **Figure 7** reveals the changes in the damage morphology of the BFRP reinforcement under different corrosive environments. In the distilled water environment at pH = 7, the corroded BFRP reinforcement exhibited minimal changes in damage morphology, indicating that this environment provides a degree of protection for the material's stability. However, as the corrosion environment deteriorated, the damage to the specimens significantly increased in the stress-concentration regions. Particularly under strong acid and alkaline conditions, the material not only exhibited significant depression but also developed severe damage phenomena, such as deep penetration and material spalling. These changes indicate that the corrosive environment impacts the BFRP reinforcement, accelerating material deterioration, reducing its bearing capacity, and exacerbating localized stress concentrations. Consequently, this leads to a marked reduction in structural stability and service life.

3.2.2 Interlaminar shear strength

The variation rules of interlayer shear strength and retention under varying acidity and corrosion time are illustrated in **Figures 8** and **9**.

The results indicate that the interlayer shear strength of BFRP bars exhibited a gradual decreasing trend with prolonged corrosion time. The retention of interlayer shear strength for BFRP bars immersed in pH = 3, pH = 6, pH = 8, and pH = 13 solutions for 90 d was 87.40 %, 90.00 %, 90.02 %, and 85.24 %. In pure water, the interlayer shear performance of BFRP bars was more stable, decreasing from 45.81 MPa to 44.01 MPa, resulting in a strength retention of 96.07% after 90 d of immersion. The strong alkali solution with pH = 13 exhib-

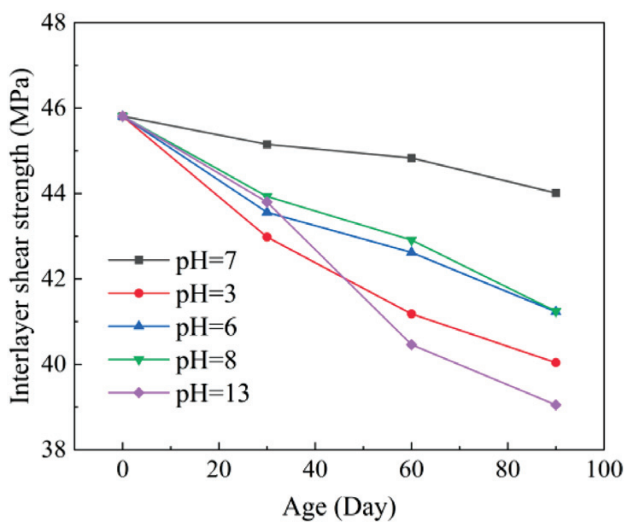

Figure 8: Interlayer shear strength-corrosion time relationship curve

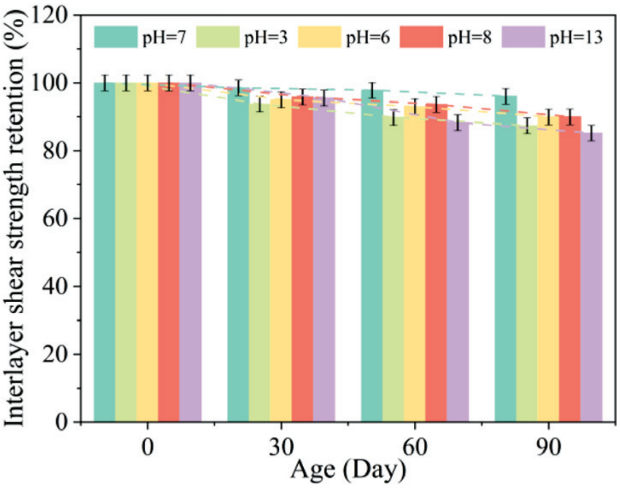

Figure 9: Interlayer shear strength retention-corrosion time relationship curve

ited the most significant reduction in interlayer shear strength of the BFRP tendons, decreasing from 45.81 MPa to 39.05 MPa. The retention rates were 95.61 %, 88.32 %, and 85.24 % after (30, 60 and 90) d, respectively, indicating that the strong alkali environment has a substantial effect on the interlayer shear strength of the BFRP tendons.

The five environments exerted varying effects on the corrosion of the tendons. An analysis of the effects of erosion solutions on the interlaminar shear strength of BFRP bare reinforcement over time revealed two distinct patterns: 1) BFRP reinforcement exhibited the least decay in interlaminar shear strength in the sterile environment of distilled water, while a significant degradation in interlaminar shear strength was observed in the other four environments. 2) The degradation rate of the BFRP reinforcement in a strong alkali solution was significantly higher than that of the other four solutions, particularly after 50 d. The interlayer shear strength retention rate after 90 d of corrosion in the strong alkali solution was only 85.24 %. This indicates that the hydrolysis and etching reactions of the BFRP tendon were accelerated by high concentrations of OH^- ions, leading to the debonding of numerous fibers from the resin and ultimately to the accelerated reduction of interlaminar shear strength.

3.3 Transverse shear performance

3.3.1 Destruction patterns

Through the observation and comparative analysis of the damage morphology of the transverse shear specimens shown in **Figure 10**. The differences in damage forms of the transverse shear specimens after corrosion are not significant, indicating a relatively consistent damage pattern and fracture characteristics. In the transverse shear performance test, the BFRP bars did not produce significant sound; however, their damage forms exhibited two characteristics: first, the number of shear damage surfaces of the bars varied between one and two, which may be attributed to the non-uniformity of the bars, particularly in the ribbing, resulting in differences in the force distribution and bearing capacity. Second, the shear damage surface of the rib material exhibited a 45° oblique section. This occurred due to the shear process of the rib material and the presence of localized extrusion from the loading device, causing the longitudinal fibers to bend and subsequently bear tensile stresses, ultimately leading to fiber pull-out damage.

3.3.2 Transverse Shear Strength

The variation patterns of the transverse shear strength and retention of the BFRP bars under different acidity levels and corrosion durations are illustrated in **Figures 11** and **12**.

The results indicate that the transverse shear strength of the BFRP bars demonstrates a decreasing trend with increased corrosion duration. The transverse shear strength retention of BFRP bars immersed in solutions with pH levels of 3, 6, 8 and 13 for 90d was 79.46 %, 82.04 %, 83.57 % and 77.55 %, respectively. In contrast, the transverse shear performance of the BFRP bars in pure water remained relatively stable, decreasing from 305.50 MPa to 275.20 MPa after 90 d of immersion, resulting in a strength retention of 90.08 %. In contrast, the

(a) pH=7 (distilled water) (b) pH=6 (d) ph=8 (d) ph=3 (e) pH = 13

Figure 10: Damage morphology of interlayer shear specimen after corrosion of BFRP reinforcement

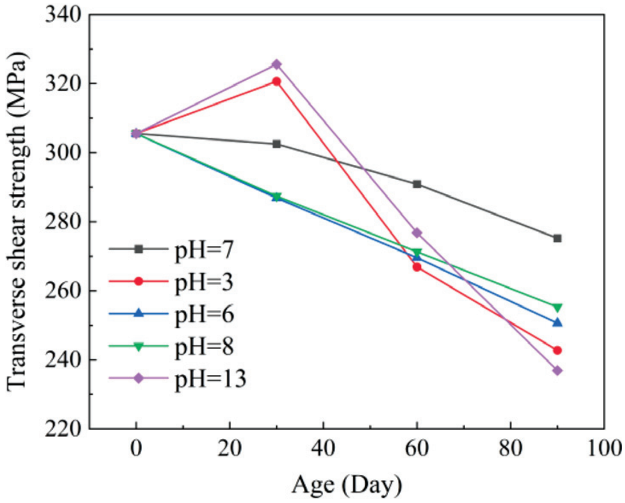

Figure 11: Transverse shear strength-corrosion time relationship curve

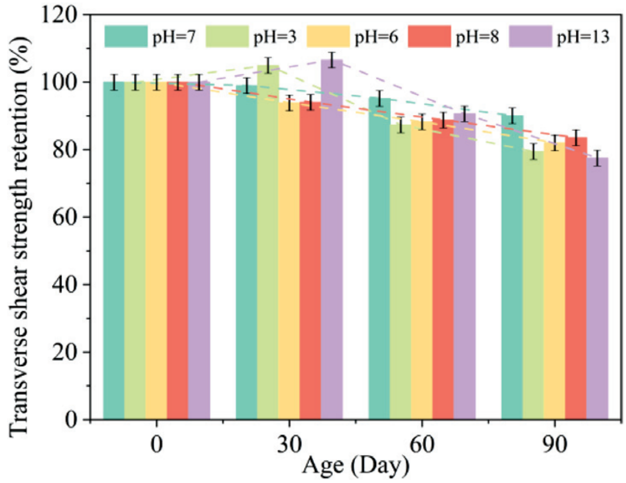

Figure 12: Transverse shear strength retention-corrosion time relationship curve

reduction rate of the transverse shear strength for BFRP bars in a strong alkaline solution with a pH of 13 was the most pronounced, decreasing from 305.50 MPa to 236.90 MPa. The transverse shear strength retention rates were 106.58 %, 90.60 %, and 77.55 % at (30, 60 and 90) days, respectively.

The degradation curve of the transverse shear strength of the BFRP exhibits fluctuations and a general decrease over the 90-day immersion period in the erosion solution, with no discernible linear pattern. The retention of strength after 90 d, in order of severity, is as follows: pH 13 solution > pH 3 solution > pH 8 solution ≈ pH 6 solution > distilled water. This indicates that the strong alkaline environment exerts a more significant effect on the transverse shear strength of the BFRP bars. This is attributed to the presence of more alkaline substances in the erosion solution, which exacerbates the degradation of the BFRP bars. Degradation and post-curing processes occur in the resin matrix of BFRP bars during immersion; when the post-curing effect is less significant than the erosive effects of the external corrosive medium, the transverse shear strength of BFRP bars exhibits a decreasing trend. Compared to acidic solutions and distilled water, the strength of basalt fibers decreased most significantly due to the violent chemical reactions between the alkaline solution and the silica-oxygen tetra-

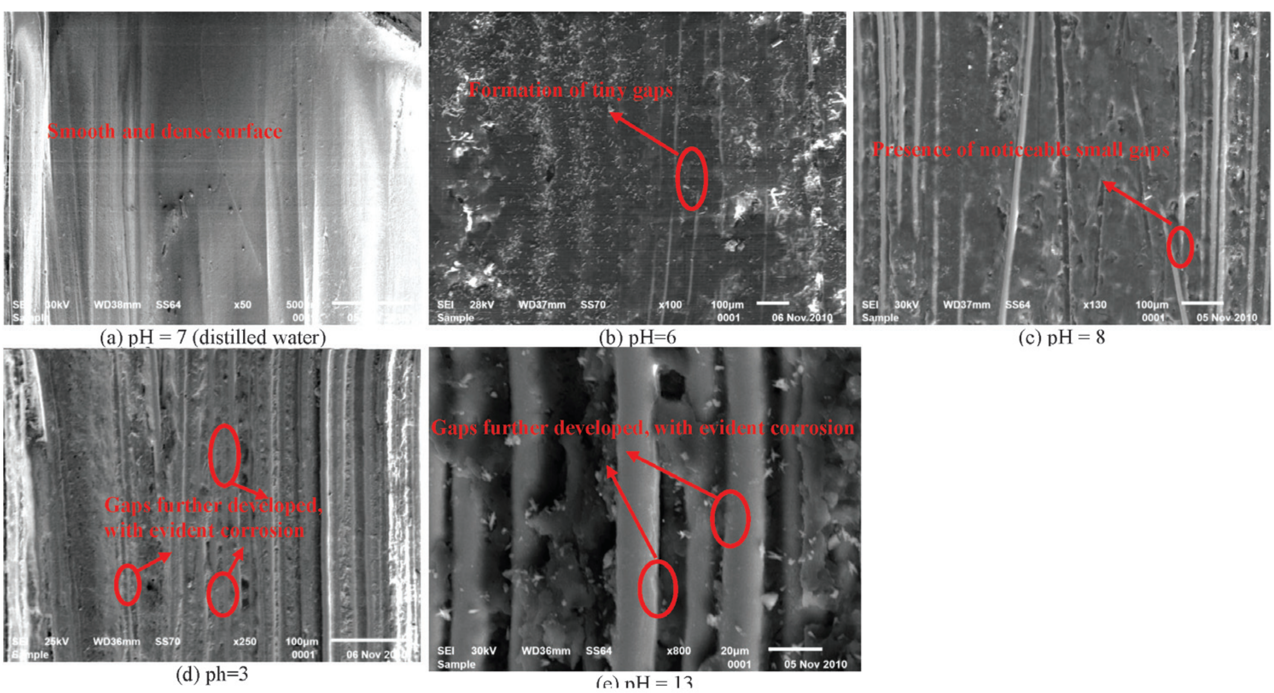

Figure 13: SEM observations of longitudinal section of BFRP bar

hedral bridging oxygens in the basalt fibers, resulting in the destruction of their internal structure.

4 SEM MICROANALYSIS

This section focuses on the observation and analysis of the micro-morphological changes of the BFRP tendons in various corrosive environments using scanning electron microscopy (SEM). In the experiment, the BFRP tendons were immersed and aged in five distinct corrosive solutions for 90 d. The results indicated that significant physical and chemical changes occurred within the tendons during the corrosion process, including resin hydrolysis and debonding at the fiber-resin interface, which reflect the weakening of interfacial interactions in the material during prolonged immersion. As illustrated in **Figures 13a** to **13e**, the SEM images obtained under various corrosive environments reveal the specific effects of different corrosive conditions on the microscopic morphology of the BFRP reinforcement.

As shown in **Figure 13**, in distilled water at pH 7, the fibers are bonded by resin, maintaining good integrity, and no depressions or holes have yet formed on the fibers and tendons. In the corrosion solutions at pH 6 and pH 8, tiny gaps between the fibers have begun to form. In the pH 8 corrosion solution, an obvious small gap is present between the fibers. In contrast, in the corrosion solutions at pH 3 and pH 13, gaps within the BFRP tendon have developed further, indicating significant corrosion phenomena. **Figure 13e** indicates that the originally smooth glass fibers exhibit localized etching. After 90 d in a pH 13 corrosive environment, the resin and fiber wrapping of the tendon are significantly weakened, consistent with the long-term tensile performance test data. This indicates that the tendon exhibits weaker alkali resistance, severely affected by the alkaline environment. This also explains why the mechanical properties of all the BFRP bars in the pH 13 corrosive solution are significantly lower than those in other solutions.

The corrosive environments differ, resulting in the gradual appearance of voids and defects of varying sizes within the BFRP bars. The formation of these voids can likely be attributed to the invasion of water molecules or solution ions into the bars, as well as reactions between the fibers and substrate or physical erosion.[14] Simultaneously, the bonding state between the fibers and resin is significantly weakened as environmental alkalinity increases. This indicates that the corrosion process alters not only the surface state of the reinforcement, but also severely affects the integrity and continuity of the interface, thereby significantly reducing interface performance.

A comparison of the BFRP bar structure following immersion for SEM observation leads to the derivation of the following two principles: 1) The degradation of the mechanical properties of the BFRP bar is attributed to the bonding of the fibers by the resin matrix, which collectively withstands the external forces and governs the properties of the BFRP bar, including strength and stiffness[15]. The corrosive environment, along with chemical or physical reactions in the BFRP reinforcement, results in debonding between the fibers and resin, which is the primary cause of the degradation of the mechanical properties of the BFRP reinforcement. 2) Fiber-resin debonding and resin hydrolysis, resulting from varying acidity and alkalinity of the solutions, lead to differing degrees of debonding and hydrolysis. This variation explains why the BFRP reinforcement exhibits different tensile strength, interlaminar shear strength, and transverse shear strength in various corrosive environments.

5 CONCLUSIONS

This paper investigates the tensile strength, interlaminar shear performance, and transverse shear characteristics of BFRP tendons in five typical corrosive environments: pure water, weak acid, strong acid, weak alkali, and strong alkali. The main conclusions are as follows:

(1) This study investigates the tensile strength, interlaminar shear performance, and transverse shear characteristics of BFRP tendons in five corrosive environments. The results show significant mechanical property degradation in extreme acid (pH = 3) and alkali (pH = 13) conditions. The SEM analysis reveals that the corrosion induces gaps and weakens the fiber-resin bonding, directly affecting the mechanical performance. These findings highlight the importance of considering corrosive environments in BFRP applications.

(2) Over the 90-day immersion period, the strongly acidic environment caused a 51.65 % reduction in compressive strength, while the strongly alkaline environment displayed the highest strength decay rate of 56.9 %. These data clearly indicate that the corrosion resistance of BFRP tendons is significantly compromised under extreme acidic and alkaline conditions, thereby affecting their reliability and safety in practical applications.

(3) The interlayer shear strength of the BFRP reinforcement exhibited relatively high stability, with a retention rate of 96.07 % in a distilled water environment at pH = 7. This indicates that the BFRP reinforcement is capable of maintaining its performance in a non-corrosive environment, thus supporting its application in clean environments.

(4) The SEM analysis results revealed the significant effects of various corrosive environments on the microstructure of the BFRP tendons. In strong acid and alkali environments, notable gaps and voids developed within the reinforcement, and the bond between the fibers and the resin was significantly weakened. This hydrolysis and debonding phenomenon directly caused the degradation of mechanical properties, indicating that microstructural changes are the root cause of performance degradation. Therefore, in practical applications, attention

must be given to the micro-morphology of BFRP tendons to more accurately predict changes in their mechanical properties.

6 REFERENCES

[1] Z. Dong, Y. Sun, G. Wu, et al. Flexural behavior of seawater sea-sand concrete beams reinforced with BFRP bars/grids and BFRP-wrapped steel tubesJ. Composite Structures, 268 (**2021**), 113956, doi:10.1016/j.compstruct.2021.113956

[2] B. Zhang, H. Zhu, J. Chen. Bond durability between BFRP bars and seawater coral aggregate concrete under seawater corrosion environmentsJ. Construction and Building Materials, 379 (**2023**), 131274, doi:10.1016/j.conbuildmat.2023.131274

[3] X. Liu, P. Tang, W. Chen. Alkalinity optimization and long-term life prediction for BFRP bars serving in simulated marine concrete environmentsJ. Journal of Building Engineering, 86 (**2024**), 108919, doi:10.1016/j.jobe.2024.108919

[4] K. Protchenko, F. Zayoud, M. Urbański, et al. Tensile and shear testing of basalt fiber reinforced polymer (BFRP) and hybrid basalt/carbon fiber reinforced polymer (HFRP) barsJ. Materials, 13 (**2020**), 24: 5839, doi:10.3390/ma13245839

[5] F. Abed, M. Al-Mimar, S. Ahmed. Performance of BFRP RC beams using high strength concreteJ. Composites Part C: Open Access, 4 (**2021**), 100107, doi:10.1016/j.jcomc.2021.100107

[6] B. Liao, Y. Du, G. Ma, et al. Shear behavior of seawater sea-sand concrete beams reinforced with BFRP bars after seawater dry-wet cyclingJ. Engineering Structures, 316 (**2024**), 118573, doi:10.1016/j.engstruct.2024.118573

[7] J. Zhao, H. Pan, Z. Wang, et al. Bond durability of BFRP and GFRP bars in sulphoaluminate cement concrete under water immersion environmentJ. Construction and Building Materials, 432 (**2024**), 136521, doi:10.1016/j.conbuildmat.2024.136521

[8] A. El Refai, W. Alnahhal, A. Al-Hamrani, et al. Shear performance of basalt fiber-reinforced concrete beams reinforced with BFRP barsJ. Composite Structures, 288 (**2022**), 115443, doi:10.1016/j.compstruct.2022.115443

[9] S. Li, S. Guo, Y. Yi, et al. Transverse low-velocity impact performance of BFRP bars after exposure to the saline-alkaline environmentJ. Construction and Building Materials, 307 (**2021**), 124650

[10] G. Feng, D. Zhu, S. Guo, et al. A review on mechanical properties and deterioration mechanisms of FRP bars under severe environmental and loading conditionsJ. Cement and Concrete Composites, 134 (**2022**), 104758

[11] G. Feng, D. Zhu, S. Guo, et al. A review on mechanical properties and deterioration mechanisms of FRP bars under severe environmental and loading conditionsJ. Cement and Concrete Composites, 134 (**2022**), 104758

[12] Y. Yi, S. Guo, S. Li, et al. Effect of alkalinity on the shear performance degradation of basalt fiber-reinforced polymer bars in simulated seawater sea sand concrete environmentJ. Construction and Building Materials, 299 (**2021**), 123957, doi.:10.1016/j.conbuildmat.2021.123957

[13] X. Guo, C. Xiong, Z. Jin, et al. Deterioration of basalt/carbon-based hybrid-FRP bars in a simulated pore solution of seawater sea-sand concreteJ. Journal of Building Engineering, 54 (**2022**), 104634, doi:10.1016/j.jobe.2022.104634

[14] M. Rafieizonooz, J. H. J. Kim, H. Varaee, et al. Testing methods and design specifications for FRP-prestressed concrete members: a review of current practices and case studiesJ. Journal of Building Engineering, 73 (**2023**), 106723, doi:10.1016/j.jobe.2023.106723

[15] S. M. Harle, Durability and long-term performance of fiber reinforced polymer (FRP) composites: A reviewC//Structures. Elsevier, 60 (**2024**), 105881