Environmental impact on the durability of FRP reinforcing bars

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Abstract:

Fiber reinforced polymer (FRP) bars are being widely used in civil engineering applications to replace steel bars due to their excellent durability. Existing research on the durability of FRP bars mainly focuses on glass fiber reinforced polymer (GFRP) and basalt fiber reinforced polymer (BFRP) bars. Different conclusions have been drawn due to differences in fibers, resins, fiber volume fractions, solution concentrations, and aging temperatures adopted by researchers. Some results are even contradictory, especially between relatively recent and previous studies. In this paper, data of 557 experiments on tensile strength and elastic modulus of GFRP and BFRP bars exposed to different harsh environments are collected from existing literature, and the durability of GFRP and BFRP bars in the water, acid, salt, and alkali solutions are investigated. Different influence factors are considered including the matrix type, fiber volume fraction and exposure temperature, etc. Furthermore, a new prediction model for the long-term performance of FRP bars is developed based on an existing model and the data collected in this paper. The tensile strength of GFRP and BFRP bars degenerates faster in alkali, and water environments, followed by acid solution, and has the best durability in salt solutions. Except the water solution, GFRP bars show better corrosion resistance than BFRP bars in alkali, salt, and acid solution. The new prediction is simple in form and clear in the physical meaning and can be considered for both GFRP and BFRP bars.

Keywords: GFRP bars; BFRP bars; durability; harsh environment; tensile strength; elastic modulus; prediction model.

1. Introduction

Traditional reinforced concrete structures have the problem of premature degradation due to the corrosion of steel bars, especially where deicing salts are routinely used, or the structures are in the marine environment. The corrosion of steel bars results in the volume expansion of the bars and spalling of the concrete covers, thus reducing the durability of structures and consequently causing safety hazards [1, 2].

To improve the durability, the corrosion of steel bars has been prevented by using several methods including surface coating, rust inhibitor, and cathodic protection [3-6]. Although these measures can slow down the corrosion rate, however, they cannot solve this problem fundamentally. The steel bars will still corrode in a harsh environment after a period of time. Fiber reinforced polymers (FRPs) are a type of advanced composite materials composed of the polymer matrix (epoxy, vinyl-ester, or polyester thermosetting plastic) reinforced with high-performance fibers (glass, carbon, basalt, or hybrid). Due to their excellent corrosion resistance, FRPs are superior to traditional steel reinforcements to enhance the durability of reinforced concrete structures [7-9]. In addition to excellent corrosion resistance [10, 11], high strength to weight ratio, good fatigue performance, and electric insulation of FRPs make them an ideal replacement of steel reinforcement [12-20]. Due to these advantages, FRP bars are being successfully used in engineering practice, including concrete parking garages [12], concrete pavements [13], and concrete bridges [14, 15]. From amongst the four common types of FRPs, i.e., aramid fiber-reinforced polymer (AFRP), basalt fiber-reinforced polymer (BFRP), carbon fiber-reinforced polymer (CFRP), and glass fiber-

reinforced polymer (GFRP), GFRP is the most widely used because of their high performance to price ratio, high strength, lightweight, good corrosion resistance to chloride ion and chemical environment, high fatigue endurance, thermally and electrically non-conductive, and transparent to magnetic fields [16, 21, 22]. Despite being relatively new, BFRPs have recently attracted a lot of attention owing to high resistance against low and high temperatures affect, excellent environmental friendliness, fire resistance, and durability, as well as the lower potential cost [23, 24]. The durability performance of FRPs has been assessed in a range of environmental and exposure conditions. Although GFRP and BFRP bars have outstanding salt corrosion resistance compared to steel bars [25-28], studies have indicated that their mechanical performance gradually degenerates in other conditions, such as alkali, moisture, and extreme temperature [25-27, 29-32].

Commonly used GFRP bars are mainly formed by E-glass fibers impregnating the resin matrix. The SiO_2 in the E-glass may hydrate with the hydroxide ion (OH^-) in the alkali environment [26, 33-35]. This hydration deteriorates the Si-O-Si bond of GFRPs, causing micro-cracks and accelerating the corrosion of the fibers and resins in the presence of the alkali solution, thus weakening the protection of matrix to fiber and ultimately resulting in the deterioration of GFRP bars [25, 26, 29, 33, 34]. For boron-free glass fibers (E-CR), the contents of SiO_2 are more than the E-glass, and the price is slightly more expensive than the E-glass. Moreover, the alkali resistance of E-glass and E-CR glass fibers may not differ significantly [36], whereas the E-CR glass bars show better strength retention ratios than E-glass bars with the same diameter and sizing

agent. According to Benmokrane et al. [37], the reduced tensile strengths of E-glass and E-CR glass bars are 15%-30% and 8%-18% with 15mm diameter and the same sizing agent after the same exposure time in alkali condition, respectively. For the BFRP bars, the damage resulting from the alkali presence mainly exists at the fiber-resin interface rather than the fiber itself. The diffusion of water molecules and OH^- into the resin and fiber-resin interface erodes and damages the fiber-resin interface and causes the interface debonding [28, 30, 38]. Furthermore, the silane coupling agent containing SiO_2 used for the basalt fiber reacts with OH^- in the alkali environment and breaks the bond between the resin and fibers [38]. Since the interface plays an important role in the load transfer from matrix to fibers, the mechanical performance of BFRP bars is highly affected by the deterioration of the interface. There are many different types of proprietary fiber sizing, which usually affect the mechanical performance of FRP composites [39]. For instance, E-CR glass bars with sizing PS and BFRP bars with PS3 exhibited the highest tensile strength and transverse shear strength after 3 months of exposure in the 60°C alkali solution [37]. The silane coupling agent is the most commonly used sizing for basalt fiber, which can change the interfacial hydrogen bonds to stronger covalent ones and then improve the bonding between the fiber and resin [40]. However, there are not widely recognized test methods or metrics for investigating the long-term effectiveness of these coupling agents under different exposure conditions.

Furthermore, moisture diffusion into composite materials in the humid environment varies in extent and rate. The moisture causes a mass uptake, followed by the

plasticization of matrix and a decrease in the glass transition temperature (T_g). Also, the moisture leads to the swelling of the fiber and resin, resulting in initial stress, which weakens the bonding of the fiber-resin interface and degrades the mechanical properties of FRP bars [29, 33, 34, 41].

Moreover, FRP bars have a relatively low glass transition temperature. As the external temperature approaches or exceeds the glass transition temperature, the resin softens and the molecular bonds break, and thus reducing the force transfer capacity between the fibers and resin. As a result, the tensile strength and the elastic modulus of FRP bars decrease [31, 42].

In recent years, the durability of FRPs has been assessed in many studies by accelerating the aging of FRP bars through raising temperature [25-30, 35, 38, 43-57]. Different conclusions have been drawn due to varying fibers, resins, fiber volume ratios, solution concentration, and aging temperatures adopted. Among these studies, there is sometimes a large contradiction in results even for the same conditions. For example, the strength retention ratio of GFRP bars is 70.4% after 1440 hours in the 40°C simulated alkali solution [29], while that of 95.2% reported by Won et al. [47] with the same fiber, resin, diameter, exposure time, temperature, and pH value. D'Antino et al. [2, 58] collected the data from different literature and investigated the effect of environment and sustained stress on the durability of GFRP bars. However, the durability of BFRP bars and the environmental impact on the elastic modulus of FRP bars is still lacking rigorous research. Moreover, different prediction models for the long-term performance of FRP bars have been developed for varying conditions [28,

45, 59-62]. But all of these prediction models were based on the researcher's own test results.

In this paper, long-term performance of GFRP and BFRP bars is assessed in terms of both the tensile strength as well as elastic modulus. A total of 557 experimental results of long-term tensile strength and elastic modulus of GFRP and BFRP bars conditioned in different environments are collected from studies of 23 research groups and presented. These conditions include variation in the exposure to salt, acid, water, and alkali environments. Different parameters affecting the tensile strength and elastic modulus are investigated including exposure temperature, fiber volume, matrix, and bar diameters. Furthermore, a new prediction model for the long-term performance of FRP bars is also developed. The developed prediction model is simple in form and clear in the physical meaning and considers both the GFRP and BFRP bars.

2. Experimental database

As fiber volume fraction is an important factor determining the mechanical properties of FRP bars; therefore, the database is collected from the studies which have mentioned the fiber volume fraction. In total, results of 557 experiments are obtained from 23 different groups including 352 experimental results of GFRP bars (247 specimens of the tensile strength and 105 specimens of the elastic modulus) and 205 experimental results of BFRP bars (123 specimens of the tensile strength and 82 specimens of the elastic modulus) [25-30, 35, 38, 43-57]. Except for two specimens, all specimens have different parameters. The parameters include physical parameters of FRP bars (including fiber type, resin type, fiber volume fraction, diameter, and surface treating)

and experimental parameters (including aging time, temperature, and solution type). The two specimens of GFRP bars have the same physical and experimental parameters [26, 45], while the strength retention ratios are 92.48% and 95% after 2880 hours exposure time in the 20°C alkali solution, respectively. This difference is within the measurement error range.

The GFRP bars are mainly processed by E-glass impregnating vinyl ester resin matrix and then manufactured with the pultrusion process (63.97% of total specimens). In comparison, the BFRP bars are mainly composed of the basalt fiber and epoxy resin matrix (61.79% of total specimens). Furthermore, the specimens investigated in this paper have different parameters of fiber volume fraction (v_f), diameter (ϕ), tensile strength (σ_{fu}) and elastic modulus (E_{fu}) of the unconditioned specimen, and surface treatment.

For GFRP bars, different fibers (including E-glass, AR-glass, and E-CR glass) with different matrices (including polyester (PE), unsaturated polyester (U-PE), vinyl ester (VE), modified vinyl ester (M-VE), epoxy (E), and polyethylene (PT)) have been used. The fiber volume fraction ranges from 56% to 72% and the diameter (ϕ) from 6 mm to 25.4 mm. The tensile strength (σ_{fu}) of the unconditioned specimens ranges from 453 MPa to 1542 MPa and the elastic modulus (E_{fu}) from 39.9 GPa to 60.4 GPa. The frequency distribution of the above parameters is depicted in Figure 1 a, b, c, d, and e, respectively.

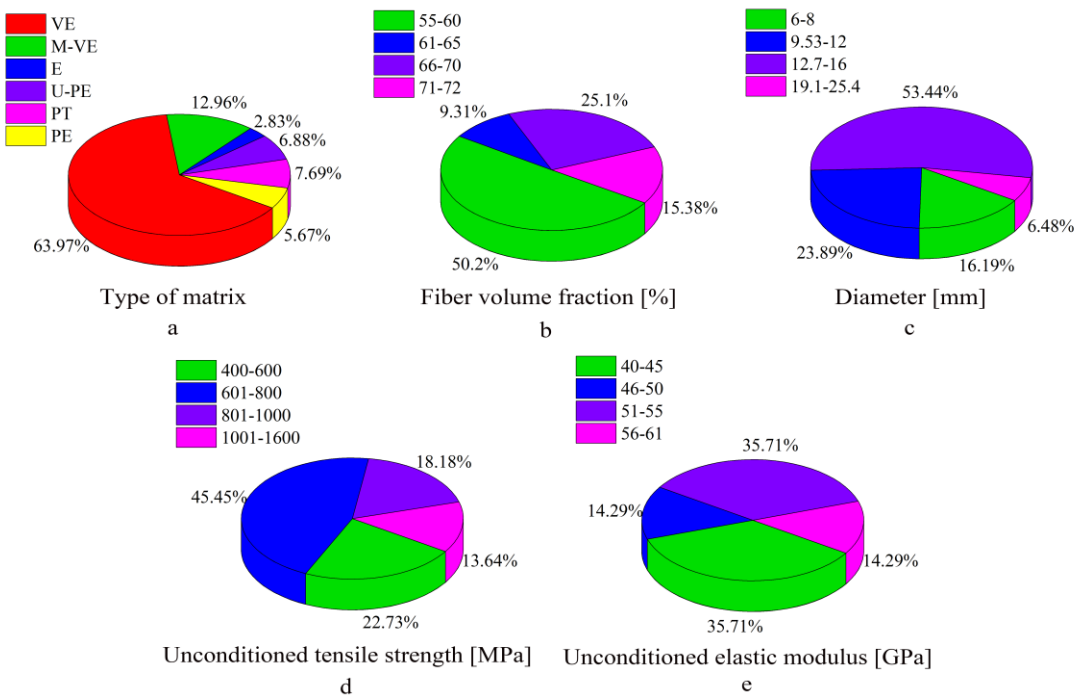

Figure 1 Frequency distribution of GFRP bars: (a) matrix type, (b) fiber volume fraction, (c) diameter, (d) unconditioned tensile strength, (e) unconditioned elastic modulus

For BFRP bars, different matrices are used, including polyester (U-PE), vinyl ester (VE), epoxy (E). The fiber volume fraction ranges from 60% to 72% and the diameter from 6 mm to 12 mm. The tensile strength of the unconditioned specimens ranges from 899.1 MPa to 1680 MPa and the elastic modulus from 35.4 GPa to 69 GPa. The frequency distribution of these parameters is depicted in Figure 2 a, b, c, d, and e, respectively.

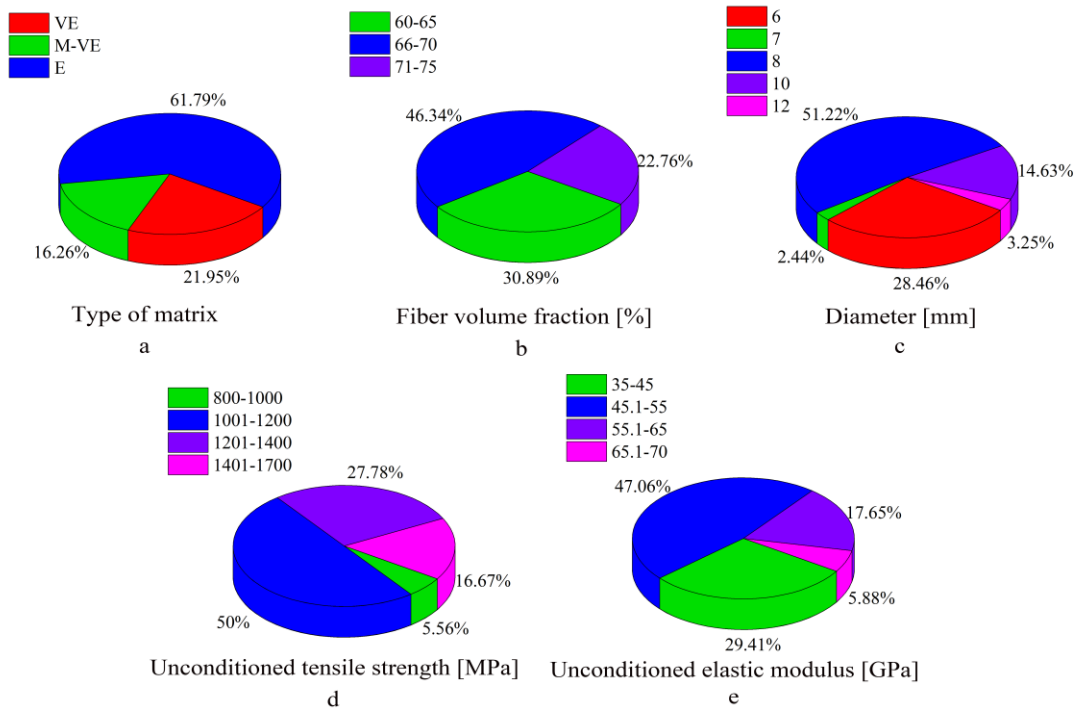

Figure 2 Frequency distribution of BFRP bars: (a) matrix type, (b) fiber volume fraction, (c) diameter, (d) unconditioned tensile strength, (e) unconditioned elastic modulus

The aging of the specimens is accelerated by immersing them in the water, salt, acid, or alkali environment for a certain period. The details are presented in Tables A1-A8 and can be found in supplementary data. Furthermore, to enhance the bonding performance between FRP bars and concrete, the surface is treated with different methods, namely sand coating (Sa), ribbing (R), grooving (G), helically wrapping (W) or a combination of them. According to D'Antino et al. [2], the surface treatment does not influence the tensile strength and elastic modulus significantly. Therefore, this parameter is not considered in the analysis.

3. Data analysis

The FRP bars were investigated by immersing in different solutions based on ACI

440.3R-15 [21] and CSA S807-19 [63], including water, acid solution, salt solution, and alkaline solution. The water, salt, acid, and alkaline solutions are usually used to simulate high humidity, seawater & deicing salt ambient, acid rain, and pore solution of concrete, respectively. Furthermore, the tensile strength retention ratio (σ_f/σ_{fu}) and the elastic modulus retention ratio (E_f/E_{fu}) are adopted in this paper to evaluate the durability of the FRP bars. The retention ratios are defined as the value of the conditioned FRP bars (σ_f, E_f) as a percentage of its original value (σ_{fu}, E_{fu}).

3.1. FRP bars immersed in the water solution

Test results of 51 specimens are collected from 6 groups, including 32 GFRP bars and 19 BFRP bars, which are immersed in the tap or deionized water for different exposure times [26-29, 53, 56]. FRP bars differ in diameters, matrices, and fiber volume fractions and are listed in Table A1 and Table A2. As the corrosion is accelerated by increasing the temperature [26-29, 53, 56], four temperature ranges are used i.e., 20°C, 40°C, 60°C and 80°C.

Strength retention ratios of FRP bars at 20°C, 40°C, 60°C, and 80°C for different exposure time are shown in Figure 3. Time starts at 0 for each temperature, GFRP and BFRP are distinguished with different colors, and various symbols are adopted to distinguish the different diameters, matrix types, and fiber volume fractions from the same literature, which is the same for all figures in this section.

In general, the strength retention ratios of both GFRP and BFRP bars gradually decrease with the increase of exposure time (Figure 3). For GFRP bars, the minimum strength

retention ratio is 43.9% after 3168 hours of exposure time reported by Kim et al. [29], while the minimum strength retention ratio for BFRP bars is 53.92% after 2160 hours reported by Wu et al. [56].

Furthermore, the temperature has a significant impact on the durability of FRP bars. In the water solution with 20℃, the strength retention ratios of GFRP and BFRP bars decrease slowly over time. With the increase in temperature, the trend of the reduction of strength retention ratios of FRPs becomes more and more obvious over time. In the 80℃ water temperature, there is a clear degradation of the tensile strength for both GFRP and BFRP bars. As reported by Manalo et al. [64], increasing the temperature can accelerate the moisture uptake rate. In addition, the composites take up more moisture in water than saline solution, second only to alkali solution. The moisture and water penetrate the matrix and cause the debonding between the fiber and resin. Therefore, FRP bars have lower durability in water. The average strength retention ratio and coefficient of variation (CV) of bars in water solution for different temperatures are listed in Table 1. It can be found that BFRP bars have higher average strength retention ratios than GFRP bars in water solutions with different temperatures.

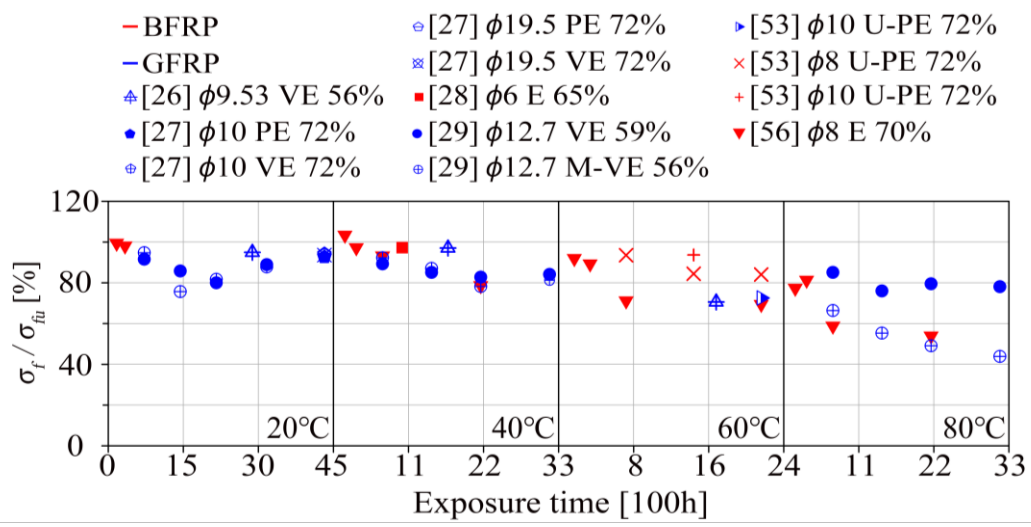

Figure 3 Strength retention ratios of bars exposed to the water solution

Table 1 Average strength retention ratios and coefficient of variation of bars immersed in the water solution for different temperatures

Temperature [°C]	FRP bars	Average σ_f/σ_{fu} [%]	CV
20	GFRP	90.38	0.067
	BFRP	101.54	0.035
40	GFRP	86.35	0.064
	BFRP	93.95	0.088
60	GFRP	71.57	0.014
	BFRP	84.68	0.106
80	GFRP	66.68	0.217
	BFRP	67.84	0.173

The GFRP and BFRP bars in terms of different matrix types subjected to water environment with different exposure time are shown in Figure 4 and Figure 5, respectively. For GFRP bars, vinyl ester and polyester matrix do not affect the residual strength. Specimens with vinyl ester [26] show better durability than unsaturated polyester [53] in the 60°C water solution, which is consistent with other reports [33, 34]. The specimens with the modified vinyl ester (v_f=56%) have a faster degradation

ratio than vinyl ester (v_f=59%) in the 80°C, whereas, they have a similar degradation ratio in 20°C and 40°C. This difference depends not only on matrix type but also on the fiber volume fraction. As the matrix starts to degenerate when the temperature approaches the glass transition temperature, this degeneration significantly affects the strength retention ratio with a low fiber volume fraction. For BFRP bars with the matrix mainly adopting the epoxy and unsaturated polyester, the specimens with unsaturated polyester show better durability than the ones with epoxy in the 60°C water solution [53, 56]. However, this phenomenon is in contrast with general knowledge. The molecular chain of polyester is formed by the polymerization of unsaturated organic compounds. The bond between the carbon and oxygen atoms of the molecular chains can be broken when the FRPs long-term exposure to OH^- and Cl^- environments. This cracking causes micro-cracks in the matrix structure and leads to loss of strength, and moisture diffusion increases rapidly. However, the epoxy resin does not contain ester groups, and it generally does not undergo hydrolysis reactions in water solution [33, 34]. Therefore, the specimens with epoxy have higher durability than unsaturated polyester. This contrast may be attributed to the different tensile test set-ups and FRP bar failure modes in different literature.

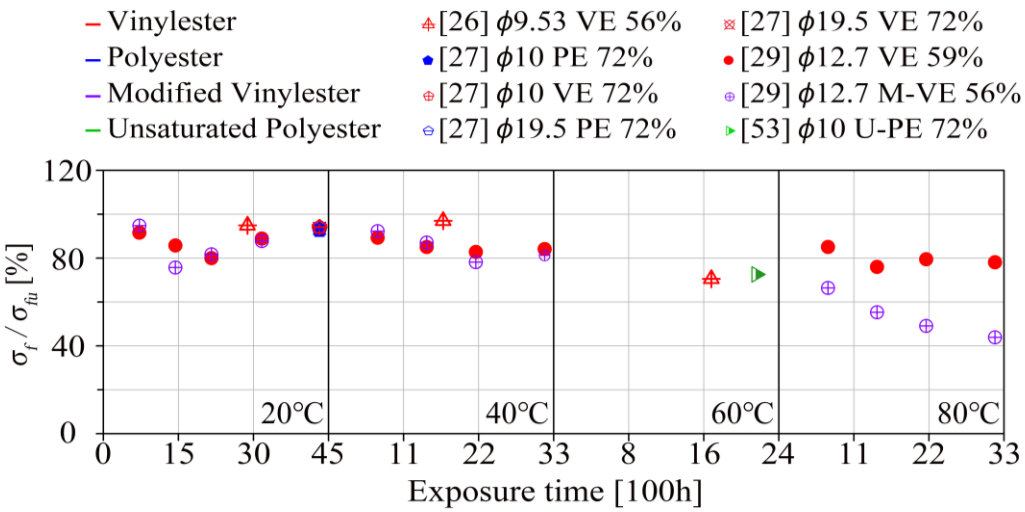

Figure 4 Strength retention ratios of GFRP bars with different matrix types exposed to water solution

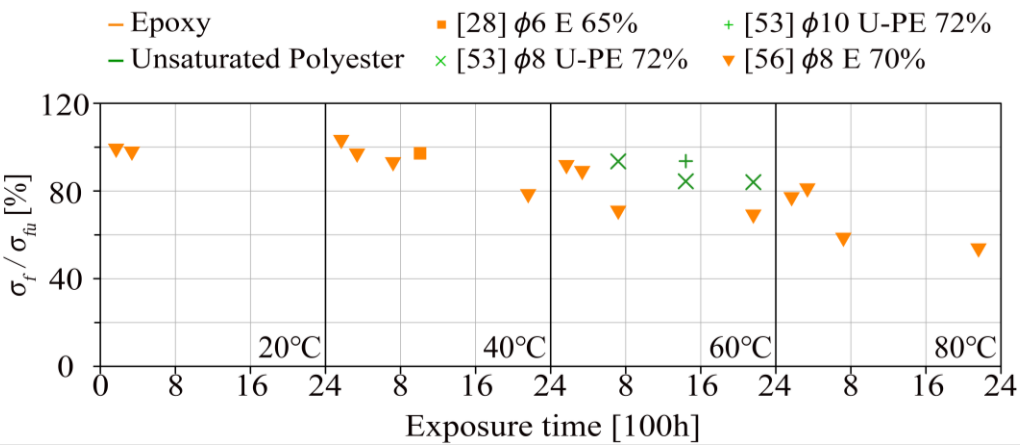

Figure 5 Strength retention ratios of BFRP bars with different matrix types exposed to water solution

Results of specimens comprised of different fiber volume fractions conditioned in the water solution with different temperatures and exposure time are shown in Figure 6. The strength retention ratios of GFRP bars increases slightly with increasing v_f in the 20°C environment, while this changing trend becomes evident in the 80°C condition. It can be noticed that this phenomenon is also related to the matrix types, as discussed above. For BFRP bars, an evident influence of fiber volume fraction on the strength

retention ratio cannot be observed. The data from Wu et al. [56] with the same v_f in the 20°C, 60°C, and 80°C water solutions indicates that v_f rarely influence the strength retention ratio in the 40°C water solution. The reason of the fiber volume fractions does not have an evident effect on the strength retention ratios of FRP bars at a lower temperature is that the fiber, matrix, and interface between the fiber and matrix of FRP bars hardly degenerate. It is reversed when the temperature is closer to the glass transition temperature, the combination between the moisture uptake and higher temperature causes the faster degradation rate for FRP bars with lower fiber volume fractions.

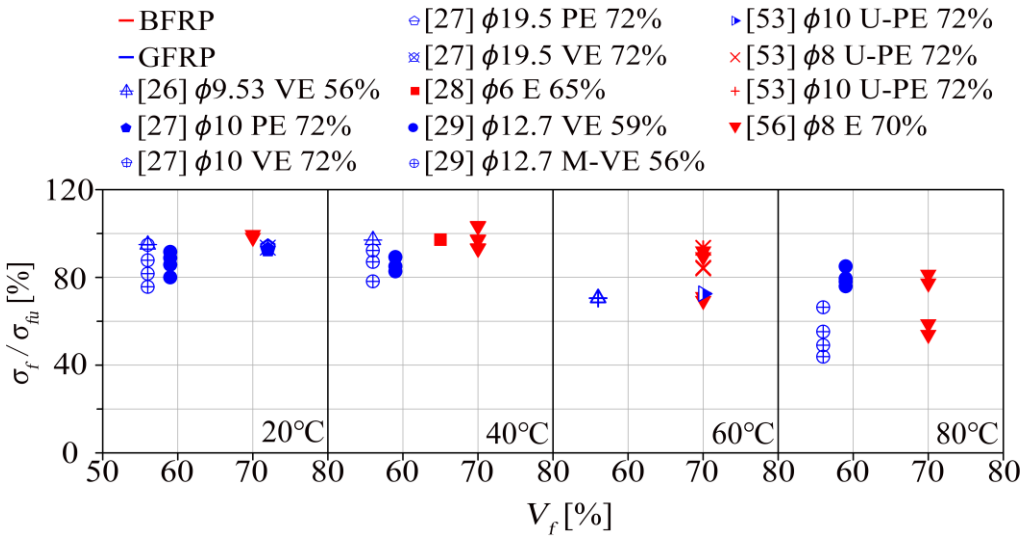

Figure 6 Strength retention ratios of FRP bars with different fiber volume fraction exposed to water solution

3.2. FRP bars immersed in acid solution

Data of 60 specimens including 33 GFRP bars and 27 BFRP bars, and their tensile strengths and elastic modulus are taken from 6 groups of research [27, 28, 44, 51, 53, 55]. FRP bars with varying diameters, matrices, and fiber volume fractions are listed in

Table A3 and Table A4 of the supplementary data. H_2SO_4 solution or HCl solution with pH=3 is used to simulate the acid environment. The bars are immersed in the acid solution heated to accelerate degradation. Three different temperatures are adopted, i.e. 20°C, 40°C, 60°C.

The strength retention ratios of GFRP and BFRP bars, immersed in the acid solution at 20°C, 40°C, and 60°C for different exposure times, are shown in Figure 7. It can be seen that the data mainly concentrates on 60°C and have less data at 20°C or 40°C. The strength retention ratios of both GFRP and BFRP bars gradually decrease with increasing the exposure time in the 60°C acid solution. The acid solution has a relatively smaller effect on GFRP bars, while a relatively greater effect on BFRP bars. As reported by Yu [53], the strength retention ratio of GFRP bars is 93.44% after an exposure time of 2160 hours, while that of BFRP bars is 63.09% after the same time in the same acid and temperature condition. But it should be noticed that the damage was localized for the BFRP bars, which may cause the lower tensile strength of BFRP bars [53]. As reported in Table 2, the average strength retention ratio of GFRP bars is higher than that of BFRP bars.

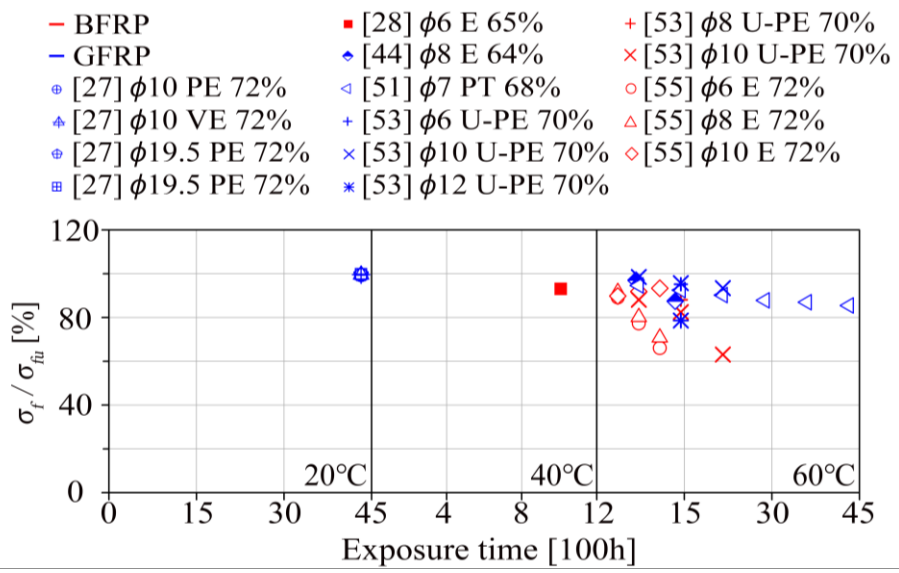

Figure 7 Strength retention ratios of FRP bars exposed to the acid solution

Table 2 Average strength and elastic modulus retention ratios of bars immersed in the acid solution for different temperatures

Temperature [°C]	FRP bars	Average σ_f/σ_{fu} [%]	CV	Average E_f/E_{fu} [%]	CV
60	GFRP	91.05	0.059	97.06	0.067
	BFRP	82.46	0.120	100.15	0.007

The elastic modulus retention ratios of GFRP and BFRP bars, in the acid solution at 20°C, 40°C, 60°C for different exposure times, are shown in Figure 8. The elastic modulus of GFRP bars hardly decreases after a long exposure time, and some of them even increase, while that of BFRP bars degenerate obviously over the exposure time. The elastic modulus retention ratios of GFRP bars with unsaturated polyester and vinyl ester increase when the temperature elevates, this can be attributed to further polymerization of the resin matrix. While this mechanical mechanism seems not significant for GFRP and BFRP bars with typical epoxy resin. Results from Yu [53] show that the elastic modulus retention ratio of GFRP bars is 111.07% after an exposure

time of 2160 hours, and that of BFRP bars is 85.8% after the same exposure time. The average elastic modulus retention ratios of GFRP and BFRP bars are shown in Table 2.

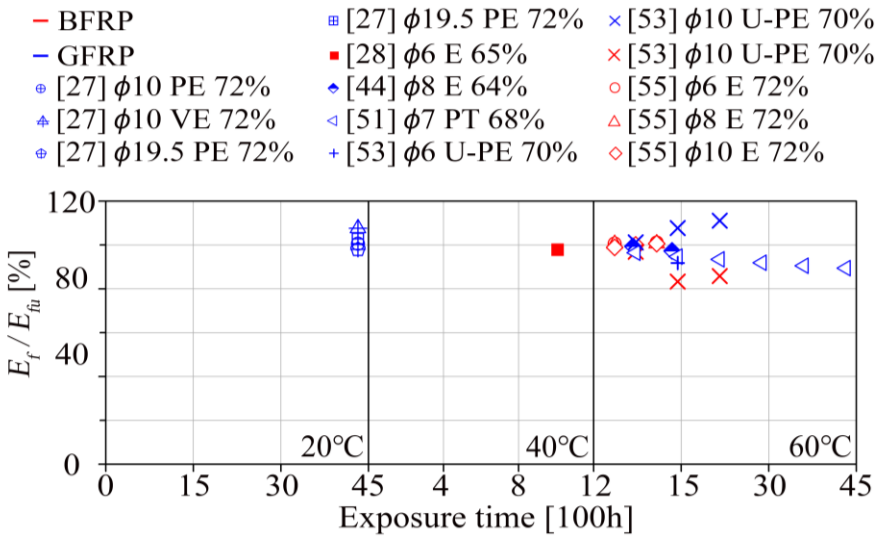

Figure 8 Elastic modulus retention ratios of FRP bars exposed to acid solution

3.3. FRP bars immersed in the salt solution

The data consists of 60 specimens of tensile strength including 40 GFRP bars and 20 BFRP bars tested by eight groups [25-29, 44, 53, 57] and 33 specimens of the elastic modulus with 13 GFRP bars and 20 BFRP bars [25, 27, 28, 44, 53, 57]. FRP bars vary in diameters, matrices, and fiber volume fractions and are listed in Table A5 and Table A6 of supplementary data. Among them, there are 8 BFRP bars embedded in moist concrete and then immersed in the seawater [57]. The accelerated corrosion method is adopted by increasing the temperature and concentration of the solution. Four temperatures are used in the literature, i.e. 20°C, 40°C, 60°C, and 80°C. In addition, different concentrations are adopted to simulate the effect of seawater and deicing salt condition, including 3%, 3.5%, and 7% by weight as well as a saturated solution.

The strength retention ratios of GFRP and BFRP bars, in the salt solution with 20°C,

40℃, 60℃, and 80℃ for different exposure time, are shown in Figure 9. Results of BFRP bars wrapped by cement mortar [57] are also considered and represented by the first symbol (×). In [27], the first four symbols denote the GFRP bars immersed in the simulating seawater, and others represent the bars immersed in the deicing salt solution.

In the 20℃ environment, GFRP bars gave little degradation with the increase of the time, and the minimum strength retention ratio is 88%. However, Lv [57] reported a severe degradation of the BFRP bars wrapped by cement mortar at the same temperature, where the minimum strength retention ratio was 58.04%. This phenomenon may be caused by the coupling action of the salt and alkali environment, which can exacerbate the degeneration ratio of BFRP bars. In the 40℃ salt solution, both GFRP and BFRP bars tend to degenerate at the beginning, and the degree of degradation gradually decreased with time. The GFRP bars degenerated slowly in the 60℃ salt environment, while the BFRP bars degenerated more quickly. The maximum degradation ratio of the tensile strength of GFRP bars occurred in the 80℃ salt solution. Except 80℃, both GFRP and BFRP bars show better durability. Because the salt ions are larger than the water ions, the moisture uptake is lowest compare with other corrosion environments [65]. Moreover, the salt ions can form a thin layer of salt on the surface of FRP bars, which will decrease the diffusion rate of the solution into the bars. [25].The average strength retention ratios of bars are shown in Table 3. The reason for the average strength retention ratio of BFRP bars in 40℃ higher than which in 20℃ is that the specimens wrapped by mortar are considered in the 20℃. If these specimens are not considered, the average strength retention ratio of BFRP bars is 93.08% in 20℃

salt solution. It can be found that GFRP bars have a higher average strength retention ratio than BFRP bars in the 20℃ and 60℃ salt solutions.

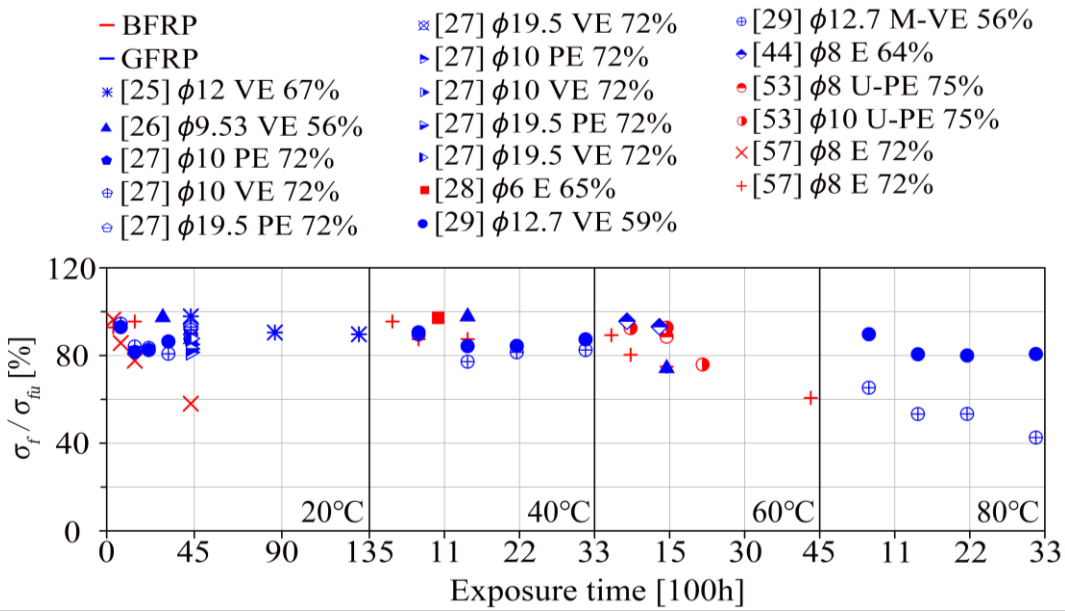

Figure 9 Strength retention ratios of bars exposed to the salt solution

Table 3 Average strength and elastic modulus retention ratios of bars immersed in the salt solution for different temperatures

Temperature [℃]	FRP bars	Average σ_f/σ_{fu} [%]	CV	Average E_f/E_{fu} [%]	CV
20	GFRP	87.98	0.059	101.9	0.041
	BFRP	86.27	0.141	93.5	0.032
40	GFRP	86.14	0.066	—	—
	BFRP	89.26	0.075	95.02	0.028
60	GFRP	87.67	0.109	98.52	0.005
	BFRP	81.88	0.123	91.27	0.119
80	GFRP	68.2	0.233	—	—
	BFRP	—	—	—	—

The strength retention ratios of FRP bars, with different matrix types exposed to the salt solution, are shown in Figure 10 and Figure 11. The GFRP bars with various matrix

types show relatively excellent resistance against salt corrosion. It should be noted that the specimens with modified vinyl ester degenerate faster than that with vinyl ester in the 80°C salt solution with the same exposure time [29]. This is similar to the GFRP bars immersed in the water solution (see Section 3.1). For BFRP bars, the matrix mainly adopts the epoxy resin. The specimens with unsaturated polyester (v_f =75%) show slightly better durability than the ones with epoxy (v_f=72%) in 60°C salt solution. This phenomenon is not only related to the matrix type but also related to the fiber volume fraction.

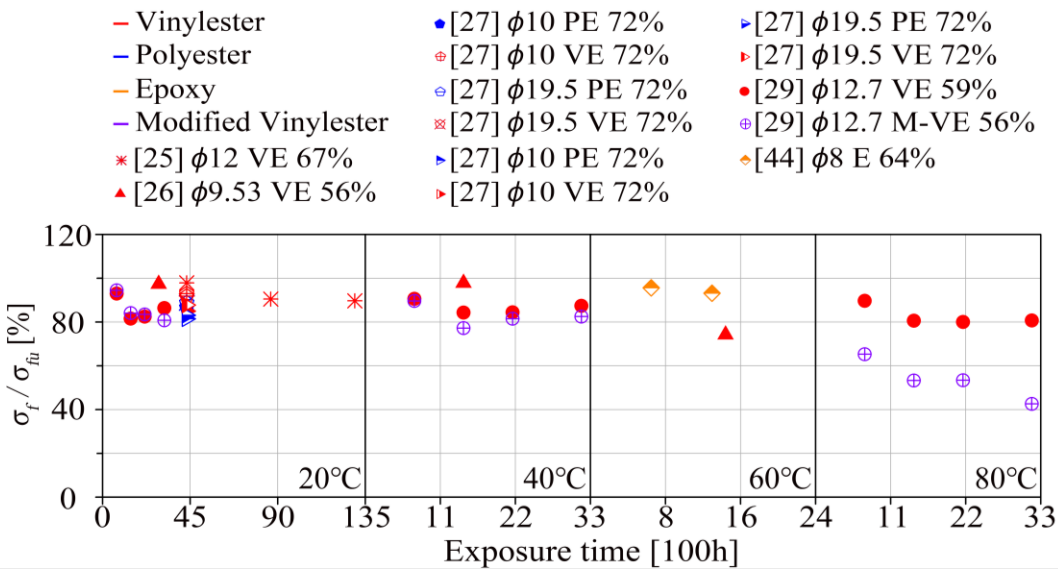

Figure 10 Strength retention ratios of GFRP bars with different matrix types exposed to the salt solution

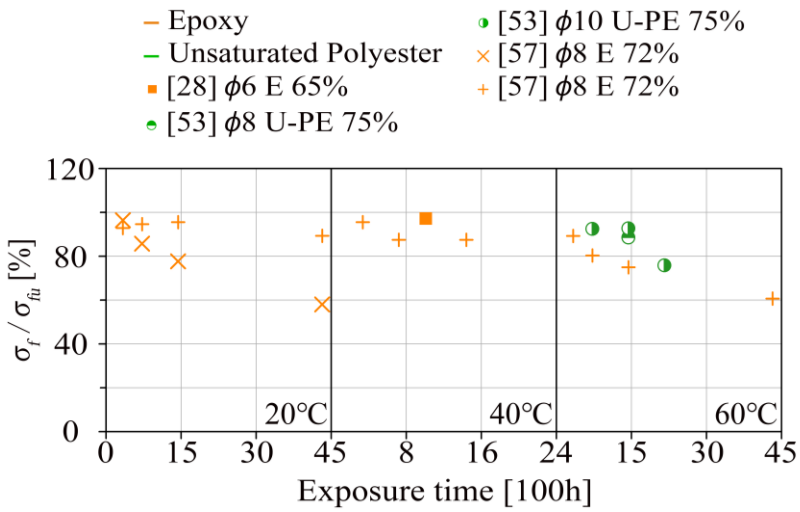

Figure 11 Strength retention ratios of BFRP bars with different matrix types exposed to the salt solution

FRP bars with different fiber volume fractions exposed to the salt solution are shown in Figure 12. In the 20°C condition, the fiber volume fraction has little impact on the strength retention ratio, which is consistent with D'Antino's report [2]. In the 40°C condition, the strength retention ratios of GFRP bars have a little increase with increasing v_f. The strength retention ratios of the GFRP bars increase obviously with the increase of v_f in the 60°C and 80°C salt solutions. The reason for this phenomenon is probably the gradually softening of the resin with the temperature rise, which can have a more significant effect on the bars with lower fiber volume fraction. The influence of v_f on the strength retention ratio of BFRP bars in the 20°C and 40°C salt environments cannot be observed, while that of the BFRP bars shows a slight decrease with the increase in v_f in the 60°C salt environment.

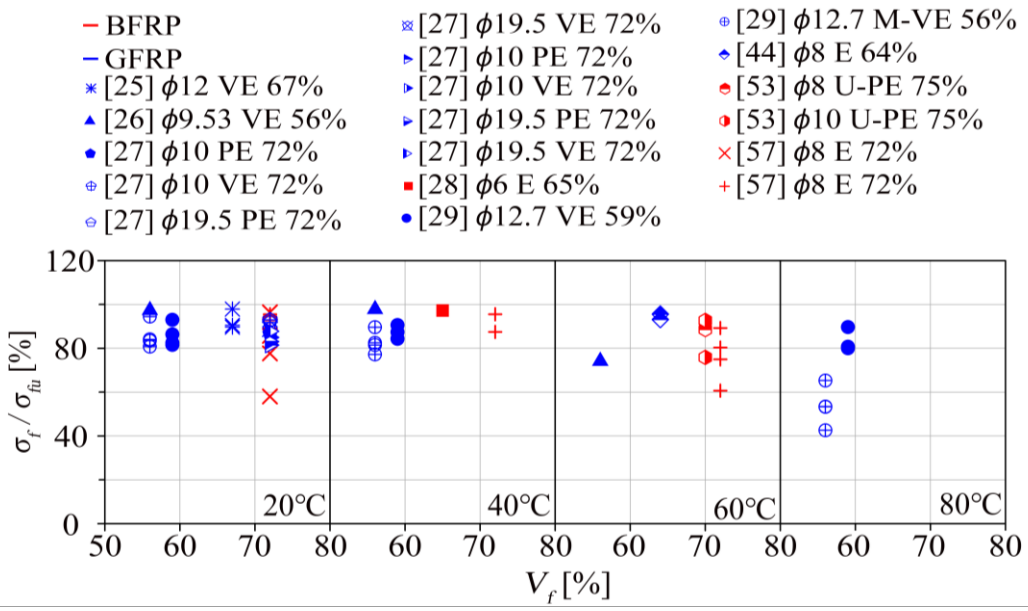

Figure 12 Strength retention ratios of FRP bars with different fiber volume fractions exposed to the salt solution

The elastic modulus retention ratios of GFRP and BFRP bars, immersed in the salt solution at 20°C, 40°C, 60°C for different exposure time, are shown in Figure 13. It can be found that the salt environment has little impact on the elastic modulus. The average elastic modulus retention ratios of bars are listed in Table 3. In general, the GFRP bars have a higher average elastic modulus retention ratio than BFRP bars in the salt solution.

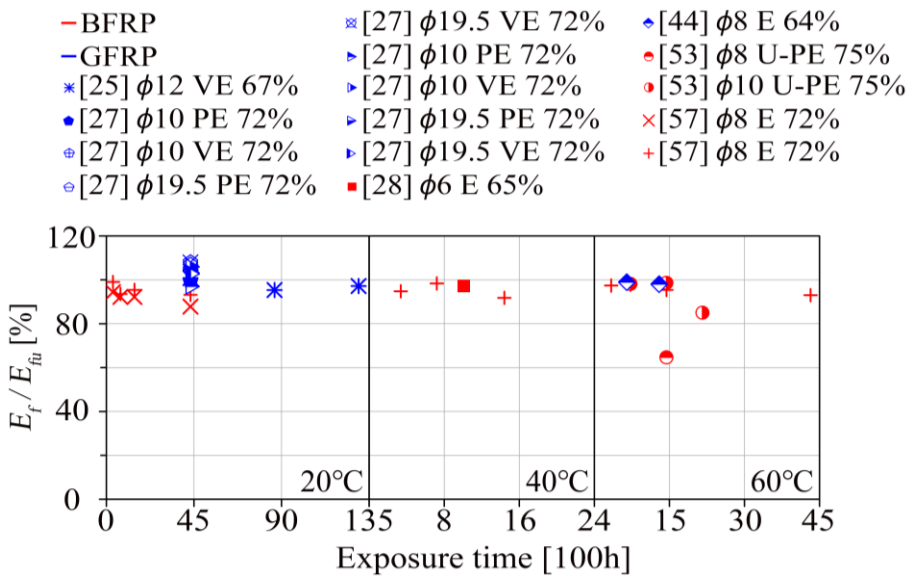

Figure 13 Elastic modulus retention ratios of bars exposed to the salt solution

3.4. FRP bars immersed in the alkali solution

The residual tensile strength and elastic modulus of FRP bars exposed to the alkali environment are investigated by 20 groups [26-30, 35, 38, 43-52, 54, 56]. The tensile strengths of 188 specimens were tested, including 136 GFRP bars and 52 BFRP bars. Furthermore, the elastic modulus of 94 specimens are tested [27, 28, 30, 35, 38, 43, 44, 46, 48, 49, 51, 52, 54], including 62 GFRP bars and 32 BFRP bars. The GFRP bars are mainly comprised of E-glass fibers impregnated in a vinyl ester matrix. However, other fibers i.e., AR-glass, and E-CR glass fibers, and other matrices i.e., modified vinyl ester, epoxy, polyester, polyethylene are also used. Among them, AR-glass fiber has excellent alkali resistance, which can potentially improve the durability of GFRP bars [27], and E-CR glass fiber is a boron-free and modified E-glass fiber with good water and acid resistance [36]. Furthermore, these FRP bars have different diameters and fiber volume fractions. The details of the GFRP bars are summarized in Table A7 of the supplementary data. The BFRP bars are mainly made of basalt fibers and epoxy matrix. Other matrices, such as vinyl ester and unsaturated polyester, are also adopted. More details of these BFRP bars are provided in Table A8 of the supplementary data. The FRP bars are immersed in the alkali solution with different concentrations for different times, and heating is used to accelerate degradation progress. The concrete alkali environment is simulated by three pH ranges, namely pH=12, pH=12.5-13, and pH=13.5-13.6. Four temperatures are considered i.e., 20℃, 40℃, 60℃, and 80℃. Results from Robert et al. [43] on the GFRP bars firstly embedded in moist concrete then immersed in tap water to simulate the aggressive environment as well. Furthermore,

Robert et al. [49] firstly apply 80% of ultimate tensile strength to create micro-cracks in the GFRP bars and then embed them in a moist mortar with increased temperature, which is also included in this section. However, GFRP bars subjected to hot-dry cycles reported by Chen et al. [26] are not considered because the temperature is not clear.

The strength retention ratios of FRP bars subjected to different alkali environments at 20°C, 40°C, 60°C, and 80°C for different exposure time are depicted in Figure 14. In the study by Chen et al. [26], the first symbol (▲) denotes the GFRP bars with E-glass fiber immersed the solution of normal concrete, the second symbol (⊕) means the GFRP bars with E-glass fiber immersed the solution of high-performance concrete, and the third symbol (⊗) represents the GFRP bars with E2-glass fiber immersed the solution of normal concrete. For the results by Dong [38], the first (△) and fourth (◭) symbol denote the BFRP bars with epoxy resin treated with different exposure time, the second symbol (◭) means the BFRP bars with vinyl ester resin and the third symbol (△) represents the BFRP bars with epoxy resin wrapped by cement mortar then immersed the simulating alkali solution. As seen from Figure 14, the strength retention ratios of both GFRP and BFRP bars gradually decrease with the increase of exposure time. Temperature significantly exacerbates the degradation ratio of FRP bars. The minimum strength retention ratio of GFRP bars is 31.7% in 80°C alkali solution obtained by Wang et al. [50], and the minimum for BFRP bars is 30.4% in 60°C reported by Dong [38].

In the 20°C alkali solution, namely at room temperature, the degradation ratio is slow with the increase of exposure time. As presented by Chen et al. [26], GFRP bars made

of E2-glass fibers show the lowest strength retention ratio of 54.87% after an exposure time of 2880 hours, while the bars using E-glass fibers have a better corrosion resistance after the same exposure time and pH solution. The GFRP bars with pH=12.6 (simulating the pore solution of the high-performance concrete environment) have a higher residual strength ratio than with pH=13.6 (simulating the pore solution of normal concrete) [26]. This phenomenon attributes to the alkalinity of the solution decreased with the decrease of the pH, which causes the hydration reaction to decrease gradually. Similar results are reported by Chen et al. [45] and Fergani et al. [35] with pH=12.6. The BFRP bars with a smaller diameter have lower corrosion resistance than the bars with a larger diameter in the same condition of pH and exposure time [54]. In the 40℃ alkali environment, the degradation ratio of BFRP bars is similar to the 20°C condition. In the 60°C alkali environment, more data are collected, and both GFRP and BFRP bars have a faster degradation ratio. As concluded by Sawpan et al. [46], the strength retention ratio of GFRP bars is 75.17% after 17280 hours of exposure in 60°C condition. However, the strength retention ratio of BFRP bars is 30.4% after an exposure time of 1080 hours [38]. The degradation rate is significantly accelerated in the 80°C condition. The minimum strength retention ratio of GFRP bars is 31.74% in this case, while that of BFRP bars is 48.4%. As reported by Wu et al. [56], the strength retention ratios of BFRP bars reduce from 99.5% to 48.4% when the temperature increased from 20°C to 80°C. At the same time, the strength retention ratios of GFRP bars decrease from 84.27% to 31.7% for the same temperature range. The average strength retention ratios of FRP bars are listed in Table 4. As can be seen, the average strength retention ratios of BFRP

and GFRP bars do not have a significant difference in 20℃, 40℃ and 80℃ alkali conditions, while GFRP bars have better performance in the 60℃. Similarly, Benmokrane et al. [37] found that the reduced tensile strength of GFRP (E-glass and E-CR glass) and BFRP bars are 8%-31% and 14%-43% after 3 months exposure in 60℃ alkali solution, respectively.

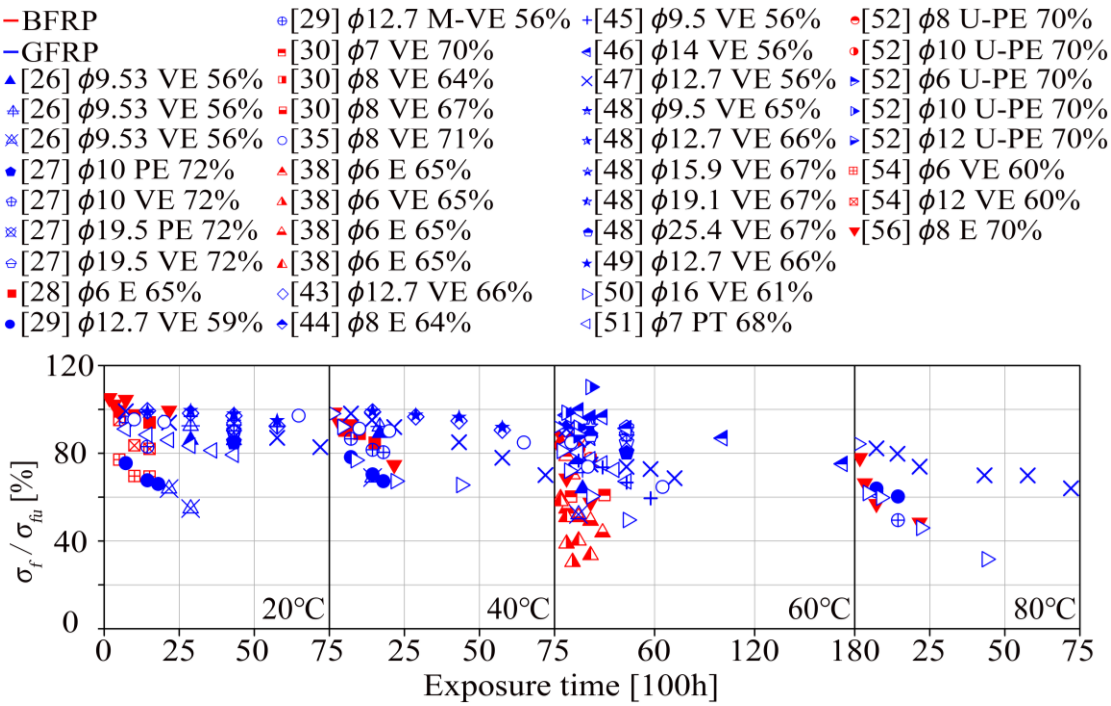

Figure 14 Strength retention ratios of FRP bars exposed to the alkali solution

Table 4 Average strength and elastic modulus retention ratios of FRP bars immersed in the alkali solution for different temperatures

Temperature [℃]	FRP bars	Average σ_f/σ_{fu} [%]	CV	Average E_f/E_{fu} [%]	CV
20	GFRP	88.65	0.119	96.72	0.067
	BFRP	90.65	0.136	99.89	0.027
40	GFRP	85.99	0.124	101.68	0.027
	BFRP	89.21	0.08	96.38	0.011
60	GFRP	81.04	0.157	96.73	0.095

80	BFRP	65.17	0.277	89.67	0.185
	GFRP	63.98	0.213	—	—
	BFRP	62.41	0.176	—	—

The change in strength retention ratios of FRP bars with v_f is shown in Figure 15. In the 20°C alkali solution, the strength retention ratios of BFRP bars appear to increase with increasing v_f, and the same trend is observed for GFRP bars when the fiber volume fraction is higher than 59%. An apparent effect of v_f on the strength retention ratio cannot be observed for GFRP and BFRP bars in the 40°C and 60°C alkali solutions. In the 80°C alkali solution, the strength retention ratio of GFRP bars increases with the increase of v_f [29]. This phenomenon is contrary to the results of GFRP bars in the 20°C alkali condition. It is mainly because the degradation ratio of matrix resin increases when the temperature is closer to or higher than the glass transition temperature, which in turn affects the tensile strength of the bars with relatively low fiber volume fraction [2].

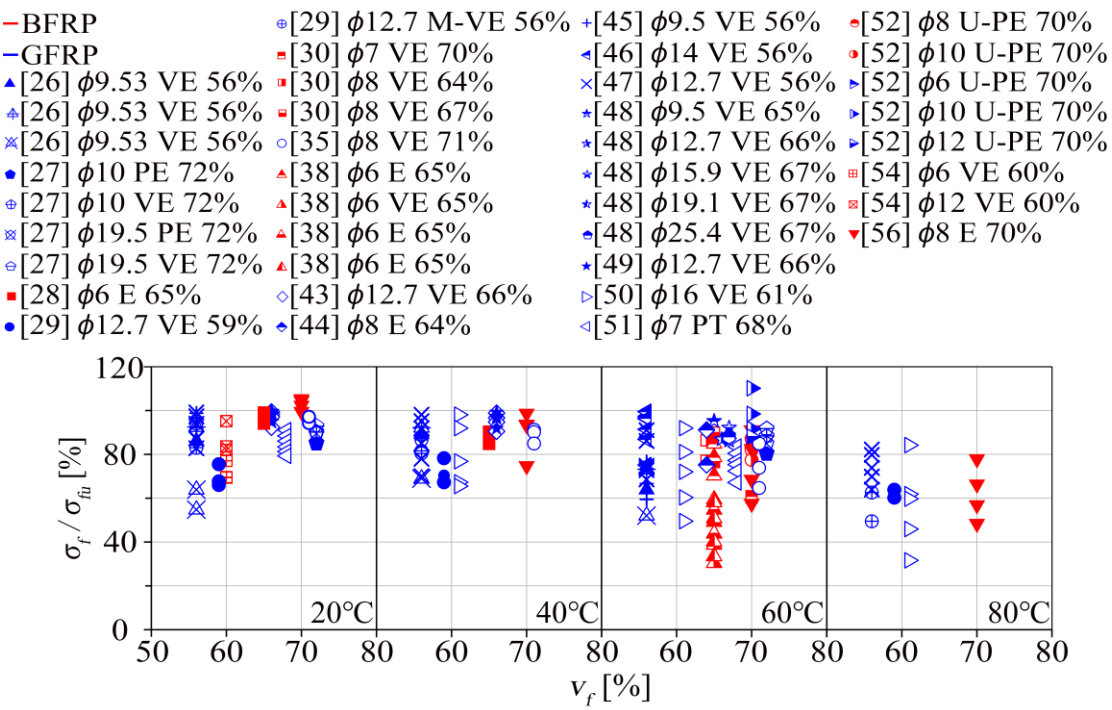

Figure 15 Strength retention ratios of bars exposed to the alkali solution for the different fiber volume fractions

Strength retention ratios of bars exposed to different alkali solutions for different diameters are plotted in Figure 16. Unlike the steel bars, whose properties can be assumed as the same for different diameters, GFRP bars are size-dependent in terms of longitudinal strength due to the shear-lag effect [66]. To illustrate this phenomenon, Hollaway [67] measured a reduction in the tensile strength of up to 40% when the bar diameter increases from 9.5 to 20 mm. However, the effect of each diameter on the strength retention ratio of FRP bars cannot be identified from the scatter results (see Figure 16 Strength retention ratios of bars exposed to the alkali solution for different diameters). Benmokrane et al. [48] tested the durability of 9.5 mm, 12.7 mm, 15.9 mm, 19.1 mm and 25.4 mm GFRP bars in the 60°C alkaline solution, for which the strength retention ratios are 95.2%, 86.9%, 92.2%, 86.3%, and 88.1%, respectively. The results show that the bars with larger diameters have a lower strength retention ratio than the bars with smaller diameters in the alkaline solution. Although all fibers bear the tensile load together, the outer fibers have higher stress than the inner fibers due to shear leg effect. In the alkali solution, the outer surface of the GFRP bars is affected and degenerates faster. The outer surface is subjected to higher stresses when the bars are loaded, the failure and breakage transfer instantly to the inner fibers, causing the failure of GFRP bars. However, the strength retention ratio increases from 90.23% to 92.9% for GFRP bars with 10 mm and 19.5 mm diameters with the same fiber and resin type, fiber volume fraction, and exposure time [27].

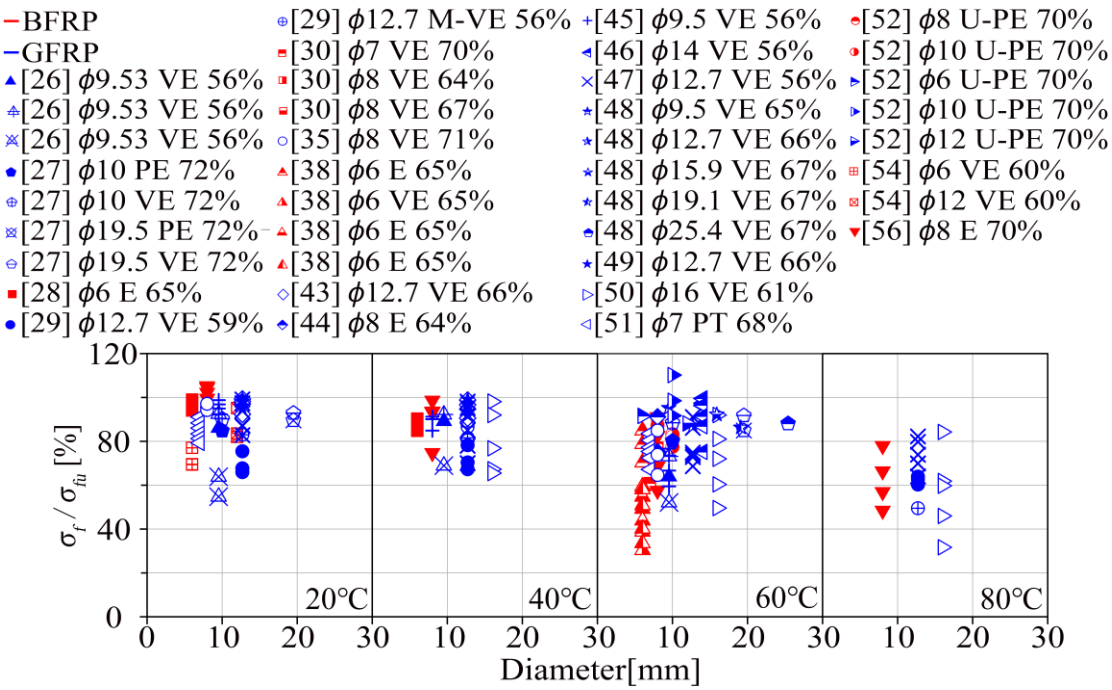

Figure 16 Strength retention ratios of bars exposed to the alkali solution for different diameters

Figure 17 and Figure 18 show the effect of different matrix types on the strength retention ratio of FRP bars. Since the dispersion of the experimental results is relatively large, it is difficult to see the effect of matrix types on the strength retention ratios of GFRP bars. Results by Kim et al. [29] show that the bars with modified vinyl ester have a better corrosion resistance than the bars with vinyl ester in the 20°C and 40°C alkali environments, while the strength retention ratios are 49.5% and 60.3% for the bars with modified vinyl ester and vinyl ester after 1440 hours of exposure time in the 80°C condition. The results of GFRP bars with AR-glass and polyester or vinyl ester show that the bars with vinyl ester have a better performance in both 20°C and 60°C conditions. It can also be noticed that most GFRP bars are made of vinyl ester resin. For BFRP bars, most of them are made of epoxy. The specimens with epoxy show better

durability than the specimens with vinyl ester in the 20℃and 60℃ alkali solutions. Furthermore, the unsaturated polyester specimens show a better corrosion resistance than the epoxy ones in the 60℃ condition.

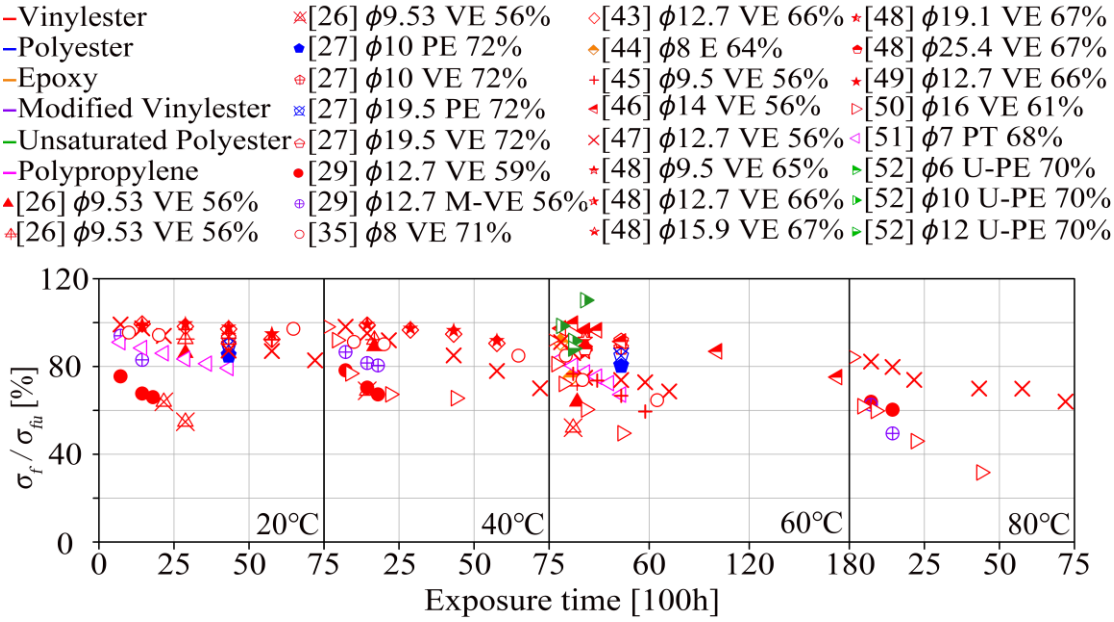

Figure 17 Strength retention ratios of GFRP bars with different matrix types exposed to the alkali solution

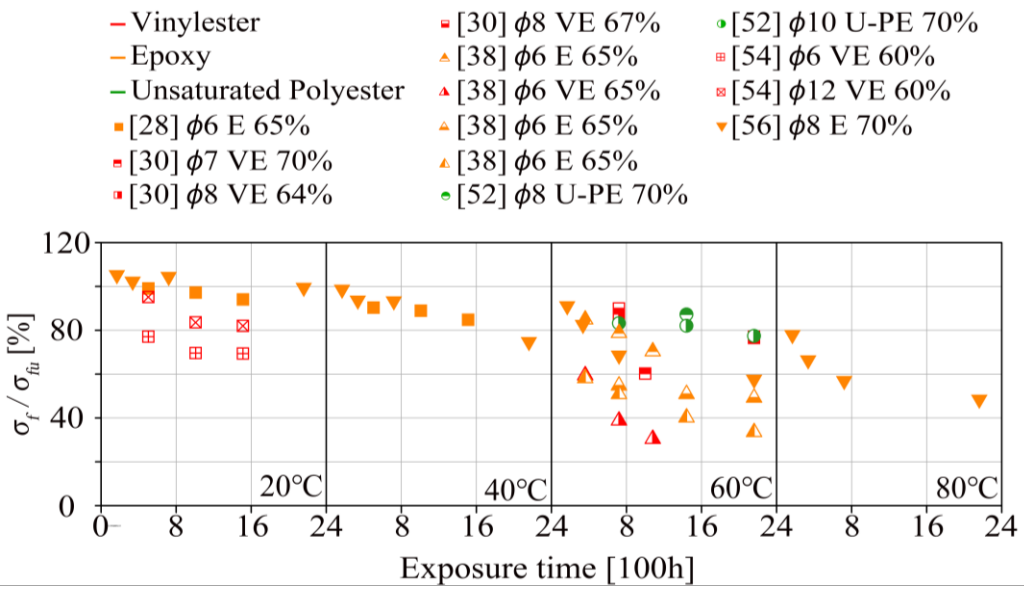

Figure 18 Strength retention ratios of BFRP bars with different matrix types exposed to the alkali solution

Figure 19 shows the elastic modulus retention ratios of FRP bars exposed to the alkali solution. Except for the 60℃ solution, the alkali environment has almost no obvious influence on the elastic modulus of both GFRP and BFRP bars. There is a large scatter in the 60℃ alkaline environment, and the maximum elastic modulus retention ratio of GFRP bars is 118.36% after 6480 hours of exposure time as tested by Fergani et al. [35], while the elastic modulus retention ratio degenerates fast in the experiments from Wang et al. [51]. The elastic modulus retention ratio decreases from 89.57% to 73.03% when exposure time increases from 720 to 4320 hours. The use of polypropylene resin may cause these results. BFRP bars also have a faster degradation than GFRP bars in the tests of Li et al. [52]. The average elastic modulus retention ratios are listed in Table 4. The post-curing reaction of the resin is promoted when the temperature increase, causing the elevation of elastic modulus. Therefore, the elastic modulus of GFRP bars at 40℃ higher than which at 20℃.

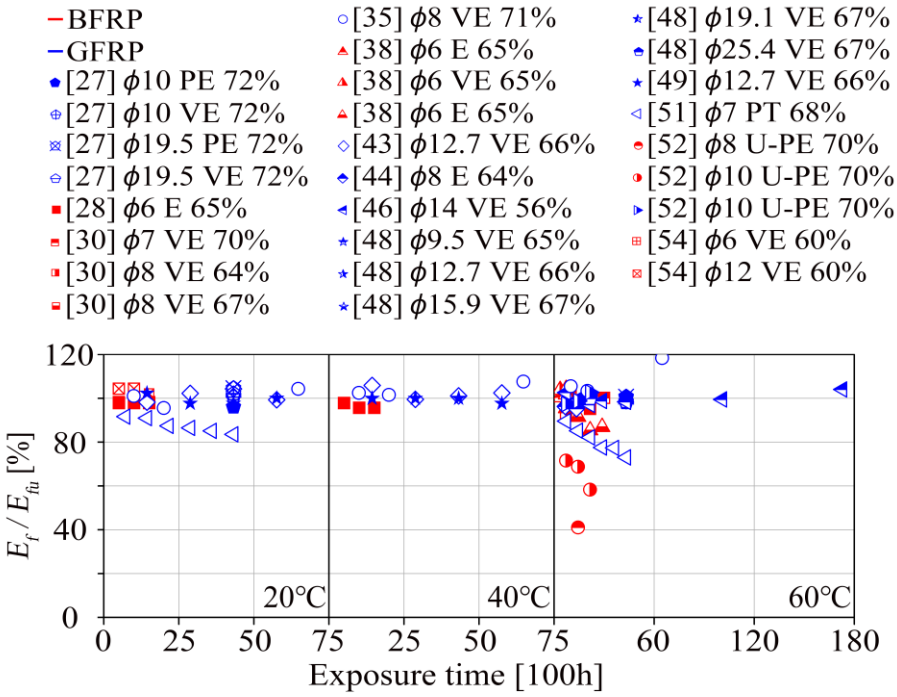

Figure 19 Elastic modulus retention ratios of FRP bars exposed to the alkali solution

3.5. Discussion

Both the strength retention ratio and elastic modulus retention ratio of GFRP and BFRP bars are analyzed in this study, but there are some differences and contradictions due to data collected from different groups. This discrepancy is probably caused by different parameters of FRP bars, different methods of accelerating corrosion, different anchoring ways, and etc.

The most commonly used method of accelerating corrosion is to increase the temperature in severe environmental conditions, for which temperatures of 40°C, 60°C, and 80°C are usually adopted in research studies. Temperature generally plays a vital role in accelerating the corrosion rate and assumes that the reaction process is not changed. While the FRP bars have a lower glass transition temperature, the mechanical properties of the FRP bars are affected once the temperature approaches or exceeds the glass transition temperature. Additionally, moisture absorbed by the composites combined with the temperature of exposure induces stresses in the material, which consequently damages fibers, matrix, and their interface, thus decreases the tensile strength of FRP bars [25]. Robert et al. [68] also found that the use of relatively high temperature will induce uncontrolled degradation mechanisms, amplify the loss of mechanical properties. The maximum temperature of aging should be limited to 60°C in the alkali solution. Moreover, the temperature of the real environment is much less than 60°C, these experiment results should be combined with the real environmental temperature.

From the results section, it can be found that the alkaline environment has the worst effect on GFRP and BFRP bars, even in lower temperatures. But it can be noticed that almost all the bars are directly immersed in the simulated alkali solution, while the bars in reinforced concrete structures are usually used in conditions different from the simulated alkali conditions. Bars wrapped by concrete or mortar have a small contact area with concrete, which is more representative of the real-life situation. As found by Robert et al. [43], the GFRP bars embedded in moist concrete exposed to tap water at 20ºC and 40ºC show less degradation than bars immersed in alkali solution at the same conditions. Although GFRP bars are preloaded at 80% of ultimate tensile strength to create cracks and micro-cracks before being wrapped by saturated cement mortar, the bars also show excellent corrosion resistance in the 20ºC and 40ºC tap water after different exposure times [49]. Manalo et al. [64] compared the durability of bare GFRP bars and cement-wrapped GFRP bars in different solutions. The author found that the alkali solution had a greater impact on the GFRP bars than tap water and saline solution. The retention interlaminar shear strength of cement-wrapped GFRP bars was 68% after 112 days of conditioning at 80℃, while that of bare GFRP bars only 23% at the same condition. For bare FRP bars in a simulating solution, the solution concentrations hardly change, causing the concentration gradients between the solution and the fiber higher during the overall experimental process. However, the replenishment rates are relatively low for the FRP bar reinforced concrete structures. The concrete pore solution is unsaturated except for the submerged piers and hydro dams, and the concrete has a low porosity (approximately 35%). Moreover, the pH decreases with the increase of time in

the FRP-reinforced concrete structures [69]. Therefore, the bare FRP bars directly immersed in the simulated solution should be replaced by mortar or cement wrapped bars in the accelerated experiment. This method will be closer to the real field environment and apparently improve the accuracy of the prediction model of long-term performance.

Some researchers also studied the effect of real field conditions on the GFRP bars. Al-Salloum et al. [25] investigated two typical field conditions for GFRP bars i.e., hot-dry field conditions (RF) of Riyadh and a combination of hot-dry arid land and hot-humid environment of the Middle East represented by Eastern coast of the Kingdom in the Gulf area (Jubail city) (JF). Both the strength retention ratios are 99.6%, and the residual moduli are 99.9% and 100.5% after 18 months of exposure time in RF and JF environments, respectively. Mufti et al. [69] studied the durability of GFRP in concrete in several field structures across Canada. Five field environments, namely Hall's Harbor Wharf, Joffre Bridge, four-span Chatham Bridge, Crowchild Trail Bridge, and Waterloo Creek Bridge which have been in service for the last 5 to 8 years are chosen to remove cores of GFRP-reinforced concrete. Analytical methods including optical microscopy, scanning electron microscopy, energy dispersive x-ray, differential scanning calorimetry, and infrared spectroscopy are used to analyze the change of composite of GFRP bras after being suffered the alkali environment concrete for 5-8 years exposure. Results demonstrated that GFRP bars show good alkali corrosion resistance and no any chemical degradation processes of GFRP bars in all of the field structures. Benmokrane et al. [70] assessed the durability of GFRP bars which embedded in the bridge wall on

the southeast side of the Val-Alain Bridge. The physical and mechanical properties of straight and bent GFRP bars were tested, such as water absorption, interlaminar shear strength, etc. The results show that there was no chemical degradation or physical contamination of resin, fiber, and interface of GFRP bars in the concrete structure exposure to freeze-thaw cycles, wet-dry cycles, and deicing salts conditions after 11 years. Benzecry et al. [71, 72] investigated the durability of GFRP bars extracted from 11 bridges which suffered the wet-dry cycles, freezing-thawing cycles, and deicing salt conditions for 15-20 years. Physical, chemical, and mechanical properties were tested to value the durability of GFRP bars under that conditions. The results demonstrated that the reduced tensile strength of GFRP bars is 2.13% after 17 years of exposure, the shear strength of part specimen has a higher value than the original bars due to the post-curing of the resin, and the physical damage and elemental distribution just have a slight change. From the field durability study, it can be concluded that the GFRP bars are durable in concrete. But it can be found that there is a larger degradation of tensile strength of GFRP bars from section 3 of this paper, even in the lower temperature. Therefore, it is important to build the corresponding relationship between the experiment and the field durability of FRP bars.

Most researchers reported that all harsh environmental conditions have little effect on the elastic modulus. However, from section 3 of this paper, it can be found the elastic modulus has a significant fluctuation with increasing exposure time. The elastic modulus hardly degenerates when the temperature is low, but there is an obvious decrease in elastic modulus when the temperature increases. In addition, the elastic

modulus of BFRP bars has a faster degradation than GFRP bars when the temperature reaches 60℃ in all solutions. Although increasing the temperature accelerates the degradation of the fiber, resin, and fiber-resin interface, which also can promote the post-curing reaction of the resin, thus improving the elastic modulus of the FRP bars [52, 73]. It is generally believed that the elastic modulus of FRP bars mainly depends on the fiber. In various harsh environments, the damage occurs primarily in the matrix and the interface between the fiber and the resin. The fiber hardly breaks, so the elastic modulus is rarely affected. Indeed, glass fibers will degrade in the presence of heavy moisture, acids, or alkaline solution, causing losses in elastic modulus and tensile strength [34]. Considering FRPs have small degeneration that mainly occur in the higher temperature environment, the elastic modulus is not discounted in ACI 440.3R [21]. Unlike the tensile strength and rupture strain, which must consider the environmental reduction factors.

Research and applications of newly developed material BFRP bars are becoming more and more extensive. Different from GFRP bars, corrosion mainly occurs in the silane coupling agents. It causes the debonding between the basalt fiber and resin matrix and then causes the degradation of the mechanical properties of BFRP bars. Besides, it should be noticed that basalt fibers are produced directly from volcanic rocks, this production process will not strictly control the composition unlike the glass fiber. However, the chemical compositions of volcanic rocks change with different districts, which will cause the property of basalt fibers to inconsistent [74]. Eventually, it may affect the durability of BFRP bars in different corrosion environments. Different

environments have different effects on the mechanical properties of GFRP and BFRP bars. As can be seen from Figure 20, the BFRP bars have a slightly higher average strength retention ratio than the GFRP bars in the 20°C and 40°C alkali solutions. However, the GFRP bars have better alkali resistance than BFRP bars overall. In the water solution, the BFRP bars have higher average strength retention ratios than GFRP bars in the 20℃, 40℃, 60℃ and 80℃, and the BFRP bars show better corrosion resistance than the GFRP bars as well. In the acid solution, the GFRP bars have better acid resistance than BFRP bars in the 60°C temperature. In the salt solution, the GFRP bars have a higher average strength retention ratio than BFRP bars in the 20°C and 60°C. Generally, BFRP bars show better corrosion resistance than GFRP bars in water solution, while the GFRP bars show better durability in salt, acid, and alkali environment. However, the FRP bars are often in a coupling environment, which has a more complex effect than a single environment. More investigation is essential to explore the effect of the coupling environment on FRP bars in the future.

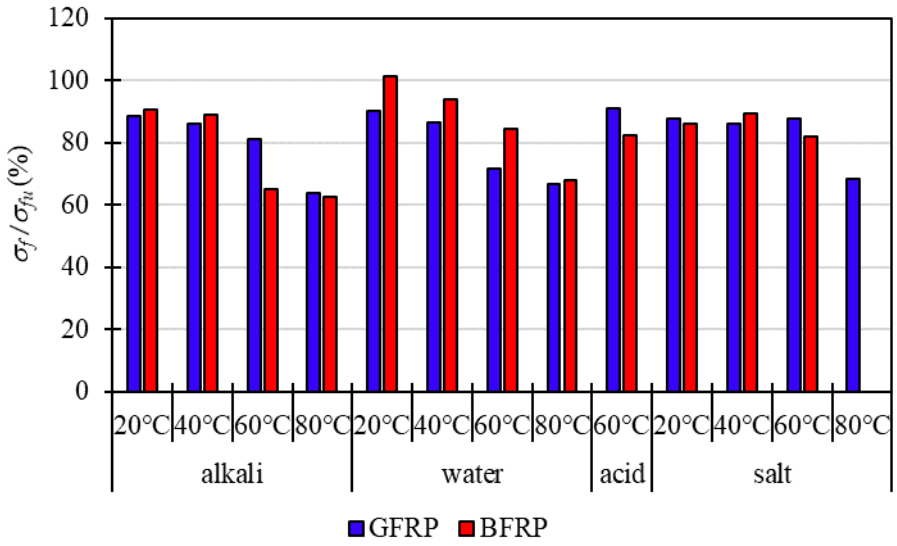

Figure 20 Average strength retention ratios of GFRP and BFRP bars in different

solutions

Moreover, it can be found that the matrix has an important effect on FRP bars and different fibers should match with the suitable matrix. For GFRP bars, the specimens with vinyl ester and epoxy show better durability, while the specimens with epoxy have better corrosion resistance for BFRP bars. As found by Benmokrane et al. [75], the glass/vinyl ester bars have the best physical and mechanical properties in the alkali environment, while the basalt/epoxy bars have better compatibility than basalt/vinyl ester bars. In addition, the glass /polyester bars have the weakest interface between the fiber and resin, and they have a higher moisture uptake than glass /vinyl ester bars and glass /epoxy bars [16].

The clear effect of fiber volume fractions on the strength retention ratio is not observed from section 3. The degeneration of FRPs is induced by the degeneration of fiber, resin, and fiber-resin interface. In general, the interface is damaged by moisture uptake, which appears to manifest faster than the degeneration of fiber and resin. The resin will soften with higher temperatures, especially as it approaches the glass transition temperature. Comparing with the resin and fiber-resin interface, the degeneration of fiber is not easy to damage. Therefore, the fiber volume fractions have little impact at the lower temperature. The interface and resin will degenerate when the temperature close to the glass transition temperature, which has an evident effect on the FRP bars with lower fiber volume fractions, just as found in Section 3. The influence of different factors on the durability of GFRP and BFRP bars are discussed in this part and section 3, which can be summarized in Table 5.

Table 5 Influence of different factors on the durability of FRP bars

Effect factors	Durability of GFRP and BFRP bars
Temperature	The degradation ratio increases rapidly when the temperature exceeds 60℃. It is suggested that the experimental temperature should not exceed 60℃ because the uncontrol degradation mechanisms will be induced by high temperatures
Exposed time	The degradation will be exacerbated with increasing time, especially the coupling action of temperature and high concentration solution
Matrix type	Glass/vinyl ester and basalt/epoxy bars have excellent durability
Fiber fraction volume	The strength retention ratio of bars increases with increasing v_f when the $T > T_g$
Diameter	No obvious relationship between the diameter and strength retention ratio of GFRP bars
Solution types	Alkali>water>acid>salt (the order of degradation rate is from large to small)

In this paper, the retention ratios of strength and elastic modulus are adopted to reflect the durability of FRP bars in water, acid, saline, and alkali environments. Other mechanical properties, such as interlaminar shear strength, transverse shear strength, flexural strength, and flexural modulus of elasticity also have been studied by some researchers [16, 48, 75, 76]. Although the higher tensile strength of FRPs is the most basic and important mechanical characteristic, the other properties also play important roles. The change of the interlaminar shear strength can reflect the degradation of the fiber-resin interface. The matrix can protect fibers and transfer the load to fibers, while

the interface is the most important part for load transfer. Therefore, considering the other mechanical properties attribute to understand comprehensively the durability of FRPs. Moreover, besides the mechanical properties are used to assess the durability of the FRPs, differential scanning calorimetry (DSC), scanning electron microscopy (SEM) and fourier transform infrared spectroscopy (FTIR) are also adopted to analyze the degeneration mechanism. DSC can obtain the thermal behavior, such as the glass transition temperature and cure ratio. DSC is used to observe the microstructure before and after aging. FTIR is used to identify the chemical change or degradation. Therefore, durability research should combine more mechanical properties and methods of analysis.

FRPs are typical anisotropic material with weak and brittle transverse compressive and shear strengths. Therefore, to prevent FRP bars from being pinched off, which must be anchored in the gripped head when the tensile strength is tested by a testing machine. Several anchorages are developed, such as bonded-type and split-wedge anchors, and the different failure models can be occurred by different anchor methods [77, 78]. If the damage occurs in the anchor, the lower tensile strength will be obtained. Tensile rupture is the ideal mode of failure, while the slippage between the bars and anchor can cause lower strength. D'Antino et al. [2] reckon some discrepancy of residual tensile strength at the similar corrosion environment caused by the failure mode of bars. The effective anchor is the prerequisite for obtaining the correct tensile strength of FRP bars. Only when the FRP bars are properly anchored, their durability in different environments can be assessed reasonably. Recently, Arczewska et al. [79] investigated the relationship

between the flexural test and the direct tensile test. The results indicated that the flexural test is a faster, cheaper, and simpler method, and this method has a good potential to determine the tensile strength and stiffness of GFRP bars through implementing the Weibull weakest link flaws distribution model.

Recently, some different methods are used to improve the durability of FRP bars. For GFRP bars, AR-glass and E-CR glass are used in the alkaline corrosion environment, and the new manufacturing process as well to enhance the performance of FRP bars. Newly developed GFRP bars were researched by Al-Salloum et al. [25], which showed better durability than old generation GFRP bars in salt, water, alkali, and two field conditions. As reported by Banibayat et al. [80], BFRP bars manufactured by the wet-layup method showed a better performance. The PVA (polyvinyl alcohol) is used as filler when manufacturing the GFRP bars. The optimized GFRP rebar shows better tensile strength and bond performance levels than the GFRP rebar currently in the market [1]. Benmokrane et al. [37] researched the effect of different fibers, fiber sizing, resin, and manufacturers on the durability of FRP bars, and given a criterion for optimizing the manufacture parameters to achieve different mechanical properties. For example, the E-CR glass/vinyl ester bars have a higher unconditional interlaminar shears strength, while the E-glass/vinyl ester bars have better interlaminar shears strength after the corrosion of alkali solution. Hybrid fiber is also an efficient method to improve the durability of FRP bars, especially for GFRP and BFRP bars in the alkali environment. For instance, the hybrid FRP bars can be composited with carbon fiber out layer and glass or basalt fiber core with an appropriate ratio. Although hybrid FRP

bars can enhance the durability by the excellent corrosion resistance of carbon fiber coat, the cost will higher than GFRP and BFRP bars.

4. Prediction of long-term performance

Based on the accelerated corrosion test results, the long-term performance of FRP bars in various corrosive environments can be predicted. As the environment has little effect on elastic modulus, the long-term performance prediction mainly concentrates on the tensile strength of FRP bars. Currently, there are four famous prediction models:

The first model is proposed by Tannous et al. [59], assuming that the peripheral areas of FRP bars that are penetrated by ion erosion completely withdraw from work and can no longer bear any load. The strength retention ratio value can be calculated by Eq. 1.

$$Y = 100(1 - \frac{\sqrt{2DCt}}{r_0})^2 \tag{1}$$

Where Y is tensile strength retention value, D is the diffusion coefficient, C is the solution ion concentration, t is the time and r_o is the diameter of FRP bars. When using the above formula, it is necessary to determine the values of parameters D and C in advance through a moisture absorption test, which makes the application process of the above formula cumbersome. Also, since the ion concentration value of the pure water environment is zero, formula (1) does not apply to the aqueous solution immersion environment.

The second model is first proposed by Litherland et al. [60] in 1998 and is successfully used to predict the residual strength of fiber-glass concrete. However, this model does

not use assumptions based on any degradation mechanism. The strength retention ratio value in this model can be calculated by Eq. 2.

$$Y = a\log(t) + b \tag{2}$$

Where a and b are fitting constants. A new approach was proposed by Huang and Benmokrane et al. [81, 82], which is based on the parallel relationship of curves fitted by Eq. 2 between the different temperatures. However, some researchers [45, 83, 84] find that the fitting curves at different temperatures are not parallel to each other when using the proposed Eq. 2 to fit their test data, which makes it impossible to predict long-term performance.

The third model assumes that in a double logarithmic coordinate system, the strength retention rate (Y) and the environmental action time (t) have a linear relationship [61]. The strength retention ratio value can thus be calculated by Eq. 3.

$$\log(Y) = a\log(t) + b \tag{3}$$

The fourth model assumes that the intensity retention rate (Y) has an exponential relationship with the environmental action time (t) [45]. Model 4 is based on the cognition that fiber-resin interface debonding is the main internal mechanism of FRP bar mechanical performance degradation. Eq. 4 is used to calculate the strength retention ratio value in this model.

$$Y = 100\exp(\frac{-t}{\tau}) \tag{4}$$

Where τ is a fitted parameter. This model is originally used to predict the flexural

strength retention rate of composite plates after environmental effects, and it is often used by researchers [28, 45, 62] in the long-term performance prediction of FRP bars. Therefore, model 4 is adopted to predict the long-term performance of FRP bars. Based on Eq. 4, the fitted parameter τ is listed in Table 6-Table 7. The temperature adopts the Kelvin and can be converted by Eq.5.

$$T = C + 273 \tag{5}$$

Where T is the temperature in Kelvin, C is the temperature in Celsius.

Table 6 τ of the GFRP bars

Type of solution	Temperature (K)			
	293	313	333	353
water	31183	13372	5806	4824
acid	—	—	21725	—
salt	43092	13591	7951	5109
alkali	33940	23166	17421	6015

Table 7 τ of the BFRP bars

Type of solution	Temperature (K)			
	293	313	333	353
water	19211	10969	7969	2362
acid	—	—	5038	—
salt	12757	11234	8166	—
alkali	10137	7955	3141	1823

The parameter τ change with the temperatures and solution types are shown in Figure 21and Figure 22. As can be found, the τ of both GFRP and BFRP bars gradually decrease with the increase of temperature in the different solutions.

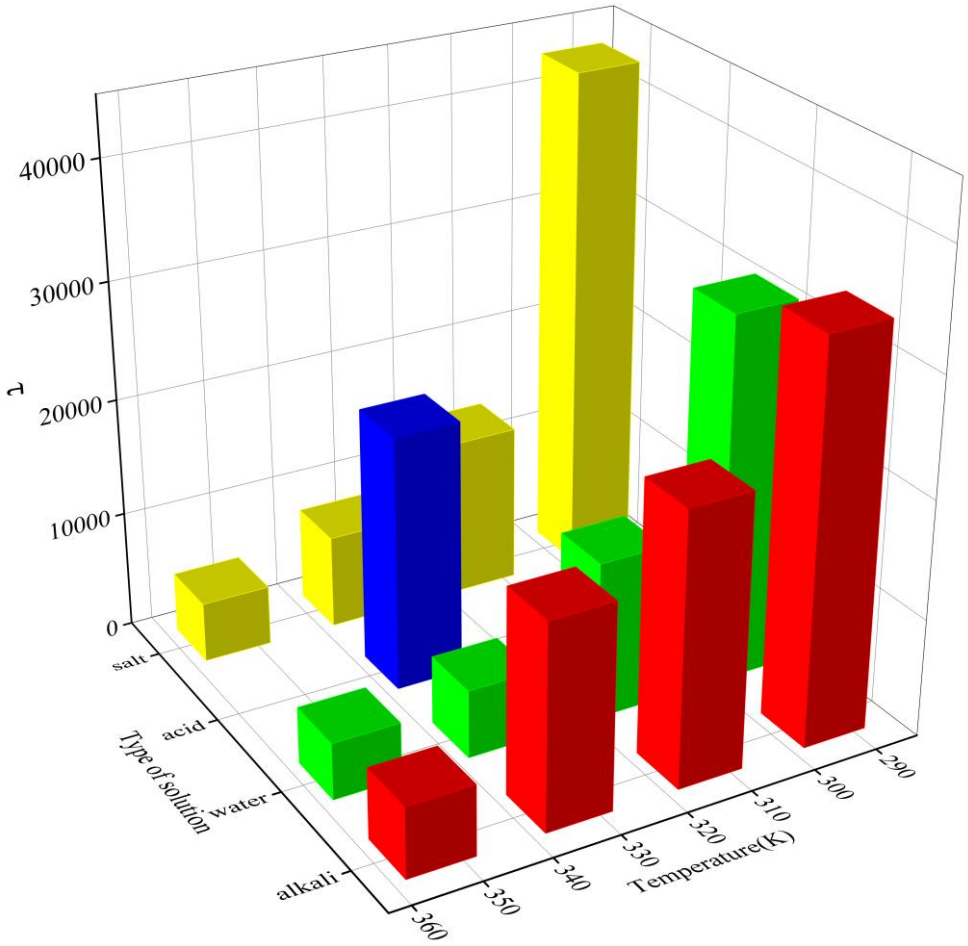

Figure 21 τ of the GFRP bars in different temperatures and solution types

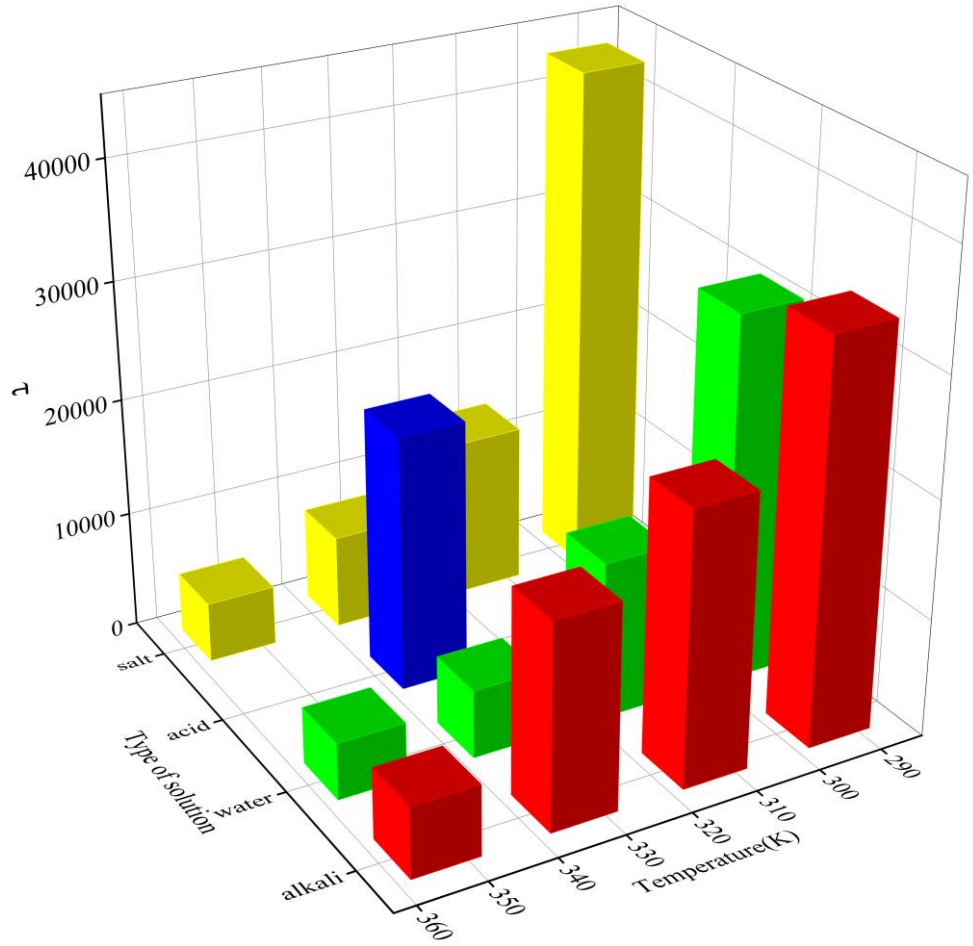

Figure 22 τ of the GFRP bars in different temperatures and solution types

However, the physical meaning of the parameter τ is not clear, and the parameter τ in each corrosion environment needs to be fitted according to the experimental results. In this paper, data of FRP bars in different harsh environments are collected, and model 4 is modified by making the physical meaning of the parameter clearer. The τ related to the temperature, solution types, and the types of FRP bars as analyzed above. The modified formulation can be presented as Eq. 6.

$$Y = 100\exp(\frac{-t}{T^{\phi}}) \tag{6}$$

Where T is the kelvin temperature, ϕ is the coefficient about the temperature and solution types. The ϕ value can be calculated based on the τ, therefore, the relationship between the ϕ and T in different solutions can be drawn in Figure 23 and Figure 24. In the acid solution, because the data of GFRP and BFRP bars is mostly limited to 60℃, the relationship between the ϕ and T can be neglected in this solution. Furthermore, 95% confidence intervals, which can demonstrate the confidence level of the parameters, are drawn with pink shades in Figure 23 and Figure 24.

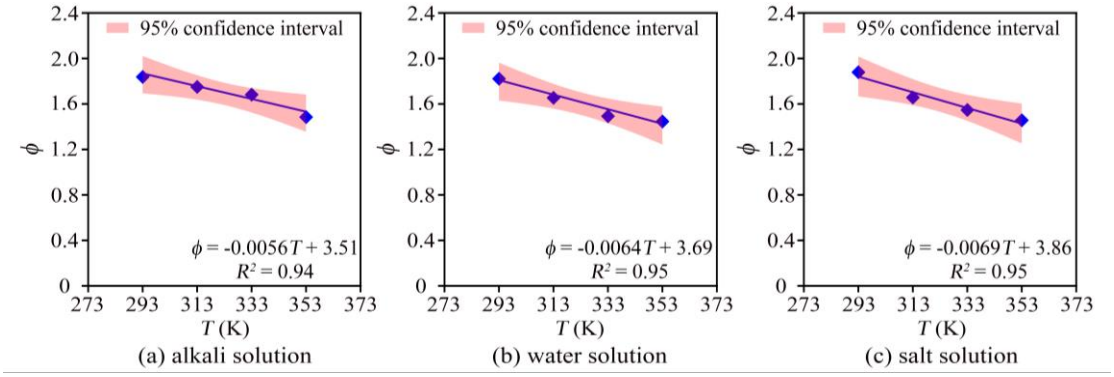

Figure 23 The relationship between ϕ and T for GFRP bars

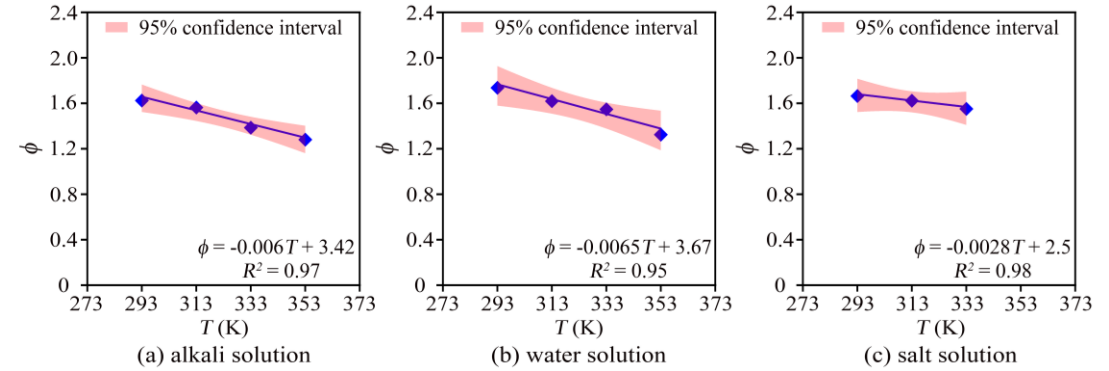

Figure 24 The relationship between ϕ and T for BFRP bars

As seen in Figure 23 and Figure 24, the ϕ and T show a linear relationship in different solutions. Therefore, the relationship between the ϕ and T is presented as Eq. 7.

$$\phi = aT + b \tag{7}$$

Where a and b are fitting parameters, T is the kelvin temperature. The value of a and b

in different solutions and FRP bars are shown in Table 8 and Table 9. Based on the *a* and *b*, the prediction curves are shown in Figure 25-Figure 27. Although the prediction model can predict the strength retention ratio well, deviation at longer time periods can be seen between the predicted strength retention ratio and the collected test data. This might be due to the large dispersion of collected available data especially in the alkali solution (can be seen from Figure 27). Moreover, Eq. (6) and (7) have been developed based on the effect of different solution types, temperatures, and aging time. However, many factors are affecting the durability of FRP bars, including matrix type, fiber volume ratio, diameter, temperature, solution type, and fiber type etc. If all these parameters are considered in the modified formulation, the accuracy of the prediction curve can be enhanced. However, it is difficult to consider all factors based on the collected available data which has a large dispersion. Hence, this limitation can be improved by generating more testing results with exact classification in future study.

Table 8 Fitting parameters of GFRP bars

Type of solution	a	b	R^2
water	-0.0064	3.69	0.95
salt	-0.0069	3.86	0.95
alkali	-0.0056	3.51	0.94

Table 9 Fitting parameters of BFRP bars

Type of solution	a	b	R^2
water	-0.0065	3.67	0.95
salt	-0.0028	2.50	0.98
alkali	-0.006	3.42	0.97

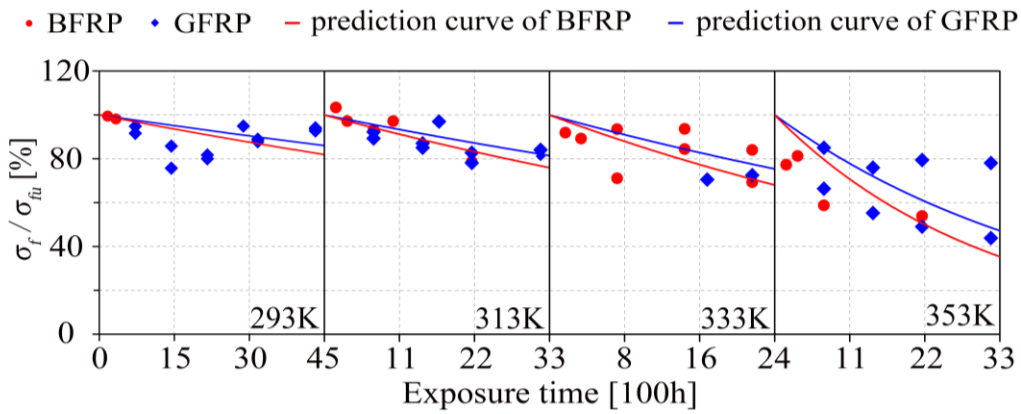

Figure 25 Prediction curves for strength retention ratios versus time in water solution

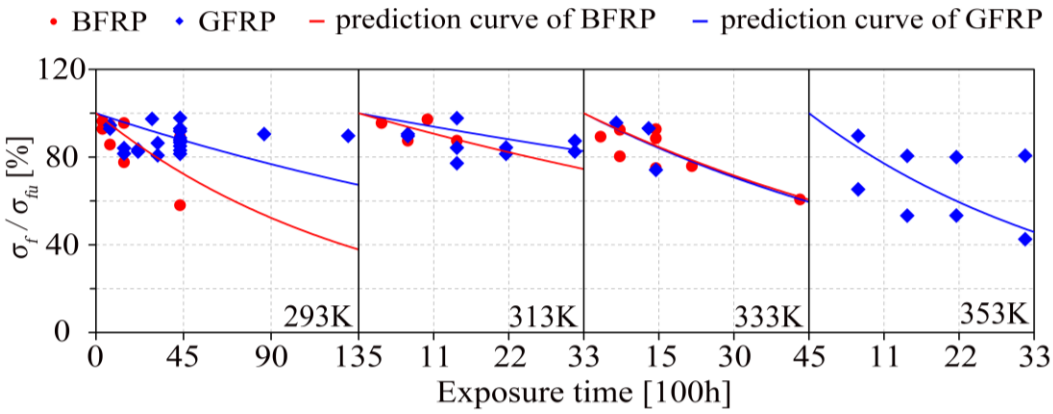

Figure 26 Prediction curves for strength retention ratios versus time in salt solution

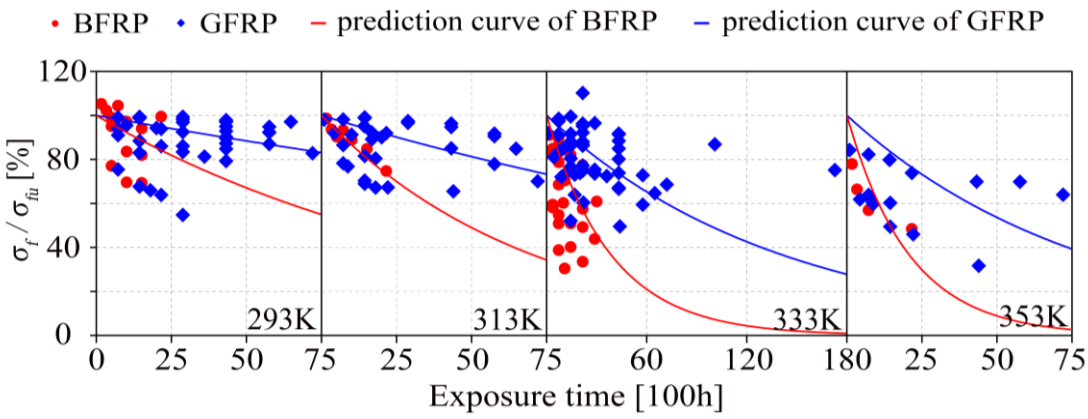

Figure 27 Prediction curves for strength retention ratios versus time in alkali solution

5. Conclusions and recommendations

In this paper, data of 557 experiments on tensile strength and elastic modulus of GFRP and BFRP bars exposed in different harsh environments are collected from existing

literature, and the durability of GFRP and BFRP bars in different solutions is investigated. Different parameters are considered, including matrix types, fiber volume fraction, exposed temperature, etc. Then, a new prediction model for the long-term performance of FRP bars has been developed based on an existing model and the collected data. The following conclusions can be drawn:

1. Both the GFRP and BFRP bars degenerate fastest in the alkali solution, followed by the water environment, the acid solution, and the lowest in salt solutions. Moreover, GFRP bars show a better corrosion resistance than BFRP bars in the alkali, acid, and salt solution, while the opposite in the water solution.

2. To achieve good durability, different fibers should match with the corresponding matrix. For example, glass/vinyl ester and basalt/epoxy bars showed excellent durability. The fiber volume fractions had an apparent impact on the durability of FRP bars at a higher temperature, while the influence of diameter on the durability of GFRP bars fluctuated greatly, without obvious relationships.

3. There is a large difference between the experimental tests and the field environment, and the cement or mortar wrapped FRP bars should be adopted to replace the bare bars in the accelerating experiments of aging.

4. The parameters of the prediction model proposed in this paper have clear physical meanings. The prediction results show that the degradation rate of BFRP bars is faster than GFRP bars in the same environment.

Although a large amount of test data is collected, the data is mainly concentrated in

GFRP bars in an alkaline environment. Fewer data is available in acid, water, and salt solutions, resulting in large differences in conclusions and even some contradictions. In the future, more tests should be conducted to verify, especially the durability of BFRP bars in various environments. Also, more field tests are needed to verify the durability of FRP bars and establish the conversion relationship between accelerated corrosion and field tests.

Acknowledgments

The authors gratefully appreciate the financial support provided by the National Natural Science Foundation of China (NSFC 51708566, NSFC 51890903, NSFC 51908012) and Strategic Consulting Project of Chinese Academy of Engineering (2019-XY-22).

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