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BOND STRENGTH OF GFRP BARS IN FIBER CONCRETE IN COASTAL ENVIRONMENT CHARACTERISTIC OF THE MEKONG DELTA

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ABSTRACT: Glass fiber-reinforced polymer (GFRP) is considered an alternative to steel reinforcement in concrete structures in highly corrosive environments. The bond characteristics of GFRP bars in concrete is an important parameter that determines the feasibility of using this material with non-corrosive concrete. Thus, the paper presents the experimental results of the bond strength of GFRP bars in fiber concrete in a coastal environment characteristic of the Mekong Delta in the south of Vietnam. Research results within 2 years showed that the bond strength of GFRP bars in fiber concrete increased over time and gave a maximum value corresponding to 5.0% silica fume content. In this study, the correlation between the bond strength of control specimens that were cured in the laboratory and specimens that were cured in actual conditions was established. In addition, the experimental results also showed that the impacts of salty water and alum (pH, salinity, temperature, wet-dry cycle) had almost no effect on the bond strength of GFRP bars in fiber concrete. These environmental influences need to be investigated further.

Keywords: Bond strength, GFRP bars, Fiber concrete, Coastal environment characteristics

1. INTRODUCTION

The corrosion of steel reinforcement in reinforced concrete structures is a serious problem, especially when the structures exist in highly corrosive environments, such as coastal environments. The coastal environment can be divided into 3 zones: flooding, water up and down, and atmospheric. Most reinforced concrete structures are damaged due to the corrosion of the reinforcement. The corrosion process and its products damage the interface between the steel bar and the concrete, thus degrading bond strength and ultimately shortening the service life of the concrete structure. This increases the cost of periodic maintenance, repairs, and rehabilitation of reinforced concrete structures not only in Vietnam but also around the world. Thus, there are many solutions involving alternate materials and techniques for reinforcement in reinforced concrete structures [1-11]. These include coating techniques (fusion bonded epoxy and galvanized coatings) on steel or non-metallic reinforcements (carbon fiber-reinforced polymer, glass fiber-reinforced polymer, and aramid fiber-reinforced polymer). Among these alternatives, the GFRP bar has received increasing attention due to its high chemical resistance, high strength-weight ratio, and high cost efficiency, as well as its superior corrosion resistance [4].

The bond characteristics of GFRP bars in concrete are the most critical parameter for the implementation of the material in concrete structures. Unlike steel reinforcement materials, GFRP materials have anisotropic, non-homogeneous, and linear elastic properties, which results in different force transfer mechanisms between the reinforcement and concrete. The primary factors affecting bond behavior, such as the concrete strength, concrete cover, and concrete confinement provided by transverse reinforcement, have been investigated based on either the beam test or direct pullout test [5-11].

The bond strength of GFRP bars in concrete has been studied by the authors under different conditions, including in concrete and fiber concrete specimens [4-11]. However, in Vietnam, there is no research on the bond strength of GFRP bars in dispersed fiber concrete over time in actual conditions that can be used to evaluate the bond degradation. Therefore, this paper focuses on the bond strength of GFRP bars in dispersed fiber concrete over time and the impacts of some factors, such as the silica fume content and environmental conditions (coastal water characteristic of the Mekong Delta and tap water in the laboratory), on the bond strength of the GFRP bars.

2. RESEARCH SIGNIFICANCE

This paper presents experimental results on the bond strength of GFRP bars in dispersed fiber concrete in a coastal environment characteristic of the Mekong Delta in the south of Vietnam. Research results within 2 years showed that the bond strength of GFRP bars in fiber concrete increased over time and gave a maximum value corresponding to 5.0% silica fume content. The experimental results also showed that the impacts of salty water and alum (pH, salinity, temperature, wet-dry cycle) had almost no effect on the bond strength of GFRP bars in fiber concrete.

3. EXPERIMENTAL PROGRAM

An experimental program was designed to investigate the bond strength of GFRP bars in fiber concrete in a coastal environment characteristic of the Mekong Delta in the south of Vietnam (Fig.1). Eighteen sets of bond specimens and 9 sets of compression specimens were prepared. At least 3 specimens were prepared per set. These specimens had different silica fume contents, with curing times of 90, 360, and 630 days in tap water (in the laboratory) and seawater (coastal water characteristic of the Mekong Delta). In the notation of the test sets, as shown in Fig.1, the first letter designates the type of specimen ("B" for bond and "M" for compression); the next two characters represent the silica fume content ("2.6" indicates silica fume/cement = 2.6%). The next two characters represent the environmental conditions ("DC" for control specimens that were cured in the laboratory and "BT" for specimens that were cured in actual conditions). The last characters represent the curing time ("90" indicates that the age of the specimens was 90 days).

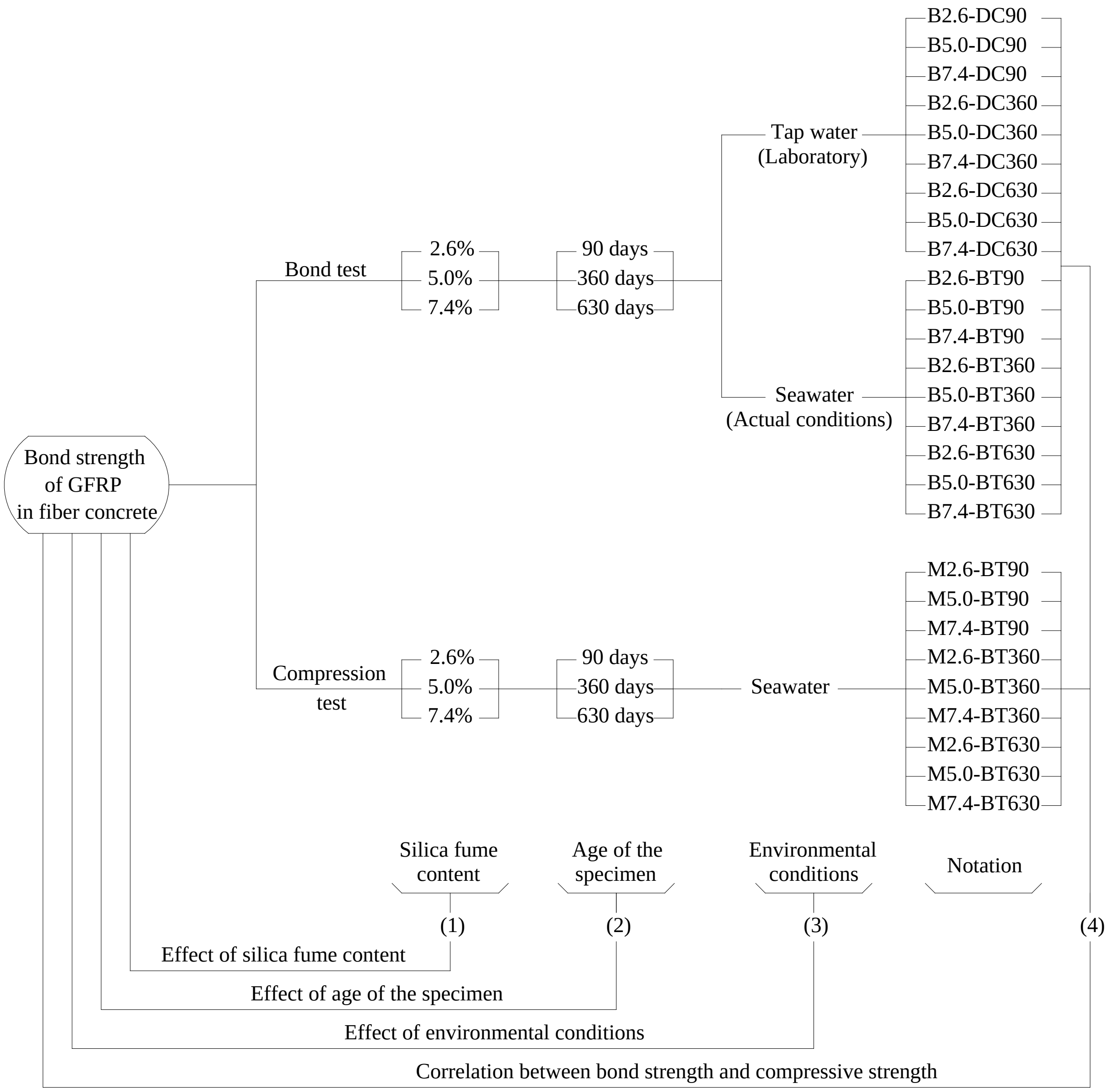

Fig.1 Experimental program

3.1 Materials and Mix Proportioning

Available materials popular in the Mekong Delta were used. In particular, there are new materials that have been applied in practice, such as polypropylene (PP) fiber and GFRP bars. The cement used (C) is cement PCB 40 created by following TCVN 6260:2009 [12]. The fine aggregate is river sand with a fineness modulus of 2.2, and the coarse aggregate is crushed stone with Dmax = 20 mm, conforming to TCVN 7570:2006 [13]. The active mineral additive is silica fume (Si) created by following TCVN 8827:2011 [14]; the third generation superplastic chemical additive carbonylate is used, based on TCVN 8826:2011 [15]. Polypropylene (PP) fiber reinforcement of the 54 mm fiber type conforms to TCVN 12392-2:2018 [16]/ASTM C1116 [17]/BS EN 14889-2 [18]. The GFRP bars have a nominal diameter D = 8 mm, complying with TCVN 11109:2015 [19]. The mechanical properties of the PP fiber and GFRP bars are shown in Table 1.

Table 1 Properties of PP and GFRP

Properties	PP	GFRP
Nominal diameter, mm	2.20	8.0
Actual diameter, mm	2.18	7.5
Tensile strength, MPa	570	960
Elongation, %	16.5	1.7
Modulus of elasticity, GPa	6.5	58

Experimental methods were used to study the effects of the environment on the compressive strength and the bond strength of the GFRP bars in fiber concrete. According to the research statistics on corrosion prevention for concrete and reinforced concrete used in a marine environment, it is necessary to use a water/cement ratio (W/C) < 0.45, where the minimum cement content is 350 kg/m^3 of concrete. The mineral additive silica fume is used, with contents of 2.6%, 5.0%, and 7.4%, respectively. The fixed superplasticizer content is 0.8 per 100 kg of cement and the PP fiber content of the concrete is 6 kg/m^3. Fiber-reinforced concrete has a slump of 4 ± 2 cm. Details of the fiber concrete mix are shown in Table 2.

Table 2 Mix proportions of fiber concrete mixes (kg/m^3)

Mix	Cement	Fine aggregate	Coarse aggregate	Water	Silica fume
2.6%	350	840	1040	144	9.1
5.0%	350	840	1040	144	17.5
7.4%	350	840	1040	144	25.9

The degree of corrosion in seawater depends on the salt content of chlorine ions (Cl^-) and sulfate ions (SO_4^{2-}), the pH, and the temperature of seawater. In addition, there is also the impact of mechanical corrosion due to tides, waves, or dry-wet cycles. There are four main factors: alkaline solutions (pH concentration), dry-wet cycles, salinity, and temperature. The project selected Binh Dai district, Ben Tre province, as the type locality, with a relatively large stretch of the coastal area, to study the erosion environment. The test results of seawater specimens collected in this area during times of ebbing water (July 2018) and rising water (July 2020) are shown in Table 3.

Table 3 Characteristics and chemical composition of seawater

Composition	7/2018	7/2020
pH at 25ºC	8.50	6.90
Salinity, g/kg	12.20	15.40
Magnesium, g/L	0.14	0.09
Sodium, g/L	1.16	0.72
Chloride, g/L	2.04	6.37
Sulfate, g/L	0.27	0.82

3.2 Casting and Testing Specimens

A compressive strength test was conducted with 150 x 150 x 150 mm cube specimens, as shown in Fig.2. The GFRP bars were waxed to ensure a working depth of the bond in the concrete of about 50 mm [20,21], as shown in Fig.3. Cylinders measuring 100 mm x 100 mm were prepared for testing the bond strength, shown in Fig.4. PP fiber concrete was used.

Fig.2 Preparation of compression test specimens

Fig.3 GFRP bars were waxed

Fig.4 Preparation of bond test specimens

The test specimens, after being cast and cured for 28 days in the laboratory, continued to be cured in the coastal seawater environment in Binh Dai district, Ben Tre province, as shown in Fig.5. After that, the specimens were taken and transferred to the laboratory for testing, as shown in Fig. 6. The control specimens were immersed in the laboratory from July 2018 to July 2020.

Fig.5 Curing of test specimens in actual conditions

Fig.6 Collection of a specimen after two years under actual conditions

The equipment used for concrete compression testing has a maximum testing capacity of 3000 kN and an accuracy of 1% (Fig.7). The bond tester has a maximum capacity of 100 kN and an accuracy of 1%, and a jig for the bond test is shown in Fig.8.

Fig.7 Compressive strength testing equipment

Fig.8 Bond strength testing equipment

4. RESULTS AND DISCUSSION

4.1 Compressive Strength of Concrete

Concrete specimens before and after the compression test are shown in Fig.9 and Fig.10. The results of the compression test are shown in Table 4 and Fig.11.

Fig.9 Concrete specimens before compression

Fig.10 Concrete specimens after compression test

Table 4. Average compressive strength results (MPa)

Mix	90-day	360-day	630-day
2.6%	76.60	84.40	84.50
5.0%	76.67	86.20	86.55
7.4%	76.50	79.70	84.45

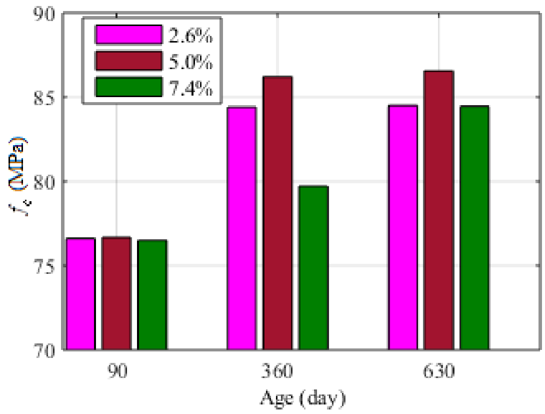

Fig.11 Average compressive strength according to different silica fume contents and curing times

The results in Table 4 and Fig.11 show that the compressive strength in specimens with a silica fume content of 5.0% was higher than that of mixes with silica fume contents of 2.6% and 7.4%. In addition, the compressive strength of concrete increases with increasing curing time. Specifically, the compressive strength increases rapidly (from 4.2% to 12.4%) when the curing time increases from 90 to 360 days and increases slowly (from 0.1% to 6%) when the curing time increases from 360 to 630 days.

4.2 Bond Strength of GFRP Bars in Fiber Concrete

4.2.1 Test results

Typical specimens from after the bond between GFRP bars and fiber concrete was tested are shown in Fig.12. It can be seen that the failure mode of all specimens is due to pullout.

Fig.12 Failure mode

The average bond strength is calculated according to Eq. (1) [21]:

$$\tau = \frac{F}{\pi d_b l_e} \tag{1}$$

where F is the tensile failure load (N); d_b is the bar diameter; and l_e is the embedded length in concrete (bonded length, mm).

The bond strength of GFRP bars in fiber concrete is specified in ACI 440.1R-06 [22]:

$$\frac{\tau}{0.083\sqrt{f_c^{'}}} = 4.0 + 0.3\frac{C}{d_b} + 100\frac{d_b}{l_e} \tag{2}$$

where $f_c^{'}$ is the concrete compressive strength (MPa) after 28 days (convert the cubic concrete strength to the cylindrical strength); c is the lesser of the cover to the center of the bar or one-half of the center-on center spacing of the bars being developed.

The results of the bond strength test and according to ACI 440.1R-06 are shown in Table 5, Fig.13, and Fig.14. It can be observed that the bond strengths obtained from the tests are higher than those predicted by ACI 440.1R-06. Similar to the compressive strength, the bond strength in specimens with a silica fume content of 5.0% was higher than that of mixes with fume contents of 2.6% and 7.4%. The bond strength of GFRP bars in fiber concrete increases with the curing time for the specimens cured in actual conditions and the control specimens. Specifically, the bond strength increases from 1.5% to 8.8% when the curing time increases from 90 to 360 days and increases rapidly (from 8.4% to 16.0%) when the curing time increases from 360 to 630 days.

Table 5 Bond strength results (MPa)

Mix	Actual conditions			Control specimens			ACI 440.1R-06
	90-day	360-day	630-day	90-day	360-day	630-day	
2.6%	16.82	17.08	19.81	17.23	17.66	20.16	14.34
5.0%	17.07	18.21	20.37	17.51	19.05	20.76	14.30
7.4%	16.51	17.42	19.31	17.19	18.19	19.72	14.43

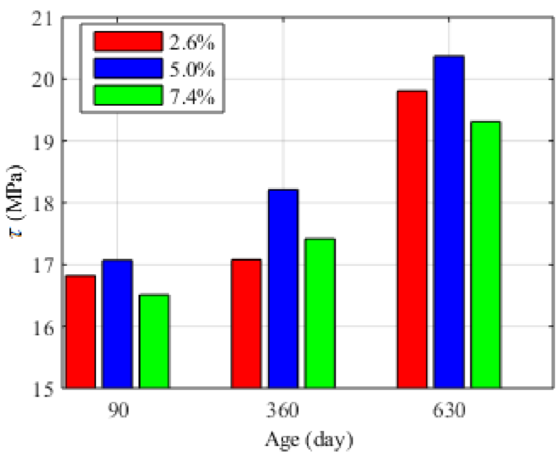

Fig.13 Bond strength in actual conditions

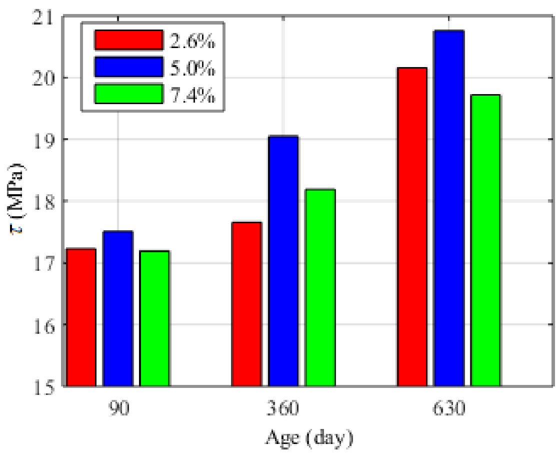

Fig.14 Bond strength of control specimens

4.2.2 Impacts of environmental conditions

The correlation between the bond strength of control specimens that were cured in the laboratory and specimens that were cured in actual conditions is shown in Fig.15. As seen in Fig.15, the bond degradations of the specimens that were cured in actual conditions are not that different than those of the control specimens (about 1.7–4.4%). These environmental influences need to be investigated further.

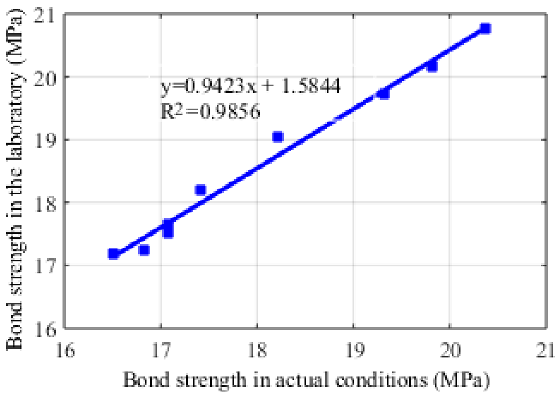

Fig.15 Bond degradations

4.2.3 Correlation between bond strength and compressive strength

Fig.16 was created to describe the relationship between the bond strength and the concrete compressive strength. Clearly, the large scatter data still display an increasing trendline with the increase of the concrete compressive strength, by a certain proportionality to f_c .

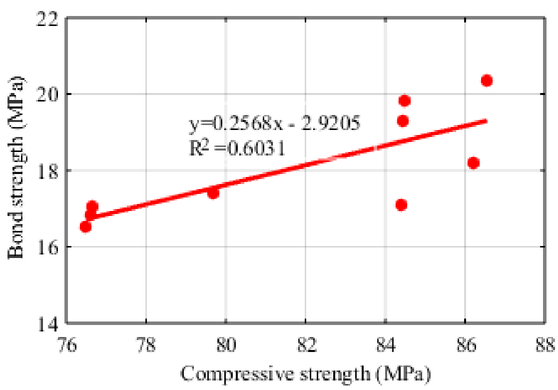

Fig.16 Bond strength versus concrete strength

5. CONCLUSION

This paper presented the experimental results over the study period of 2 years in a coastal environment characteristic of the Mekong Delta and for the control specimens. Some conclusions and recommendations can be made as follows:

1. Using a silica fume content of 5.0% will give the compressive strength and bond strength of GFRP bars in fiber concrete higher than that of mixes with silica fume contents of 2.6% and 7.4%.

2. The bond strength of GFRP bars in fiber concrete increases with the curing time for both specimens cured in actual conditions and the control specimens. The bond strength increases from 1.5% to 8.8% when the curing time increases from 90 to 360 days and increases rapidly (from 8.4% to 16.0%) when the curing time increases from 360 to 630 days.

3. The impacts of the salty, alum water environment (pH, salinity, temperature, dry-wet cycle) on the bond strength of GFRP bars in fiber concrete are not much according to this research. The bond degradations of the specimens that were cured in actual conditions are not that different than those of the control specimens (about 1.7–4.4%). These environmental influences need to be investigated further.

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