Hindawi
Advances in Materials Science and Engineering
Volume 2017, Article ID 6327848, 13 pages
https://doi.org/10.1155/2017/6327848

Research Article

Experimental Investigation of the Effects of Concrete Alkalinity on Tensile Properties of Preheated Structural GFRP Rebar

Hwasung Roh,[1] Cheolwoo Park,[2] and Do Young Moon[3]

[1]*Department of Civil Engineering, Chonbuk National University, Jeonju 561-756, Republic of Korea*
[2]*Department of Civil Engineering, Kangwon National University, Samcheok 245-711, Republic of Korea*
[3]*Department of Civil Engineering, Kyungsung University, Busan 608-736, Republic of Korea*

Correspondence should be addressed to Do Young Moon; dymoon@ks.ac.kr

Received 6 July 2017; Revised 15 September 2017; Accepted 24 September 2017; Published 29 October 2017

Academic Editor: Jun Liu

The combined effects of preexposure to high temperature and alkalinity on the tensile performance of structural GFRP reinforcing bars are experimentally investigated. A total of 105 GFRP bar specimens are preexposed to high temperature between 120°C and 200°C and then immersed into pH of 12.6 alkaline solution for 100, 300, and 660 days. From the test results, the elastic modulus obtained at 300 immersion days is almost the same as those of 660 immersion days. For all alkali immersion days considered in the test, the preheated specimens provide slightly lower elastic modulus than the unpreheated specimens, showing only 8% maximum difference. The tensile strength decreases for all testing cases as the increase of the alkaline immersing time, regardless of the prehearing levels. The tensile strength of the preheated specimens is about 90% of the unpreheated specimen for 300 alkali immersion days. However, after 300 alkali immersion days the tensile strengths are almost identical to each other. Such results indicate that the tensile strength and elastic modulus of the structural GFRP reinforcing bars are closely related to alkali immersion days, not much related to the preheating levels. The specimens show a typical tensile failure around the preheated location.

1. Introduction

Numerous studies have highlighted the tensile properties and performance of GFRP bars under high temperature conditions considering fire accident. Their experimental tests on the GFRP bars show that the temperature above the glass transition temperature causes deterioration in the tensile properties of the bars due to the weakening of the resin and the resin-fiber interface [1–8]. In the experiment done by Wang and Kodur [4], the tensile strength retention of the GFRP rebar is only 58% in the case of 200°C exposed temperature level. The test is conducted using the tensile loading machine which is equipped with electric furnace controlling specified high temperatures. Such type of test is called “hot tension test.” Another testing type is “postheating tension test” [9–12]. In postheating tension tests the GFRP bars are firstly exposed to temperatures between 100°C and 400°C for 0.5 to 3 hours. After heating, the bars are cooled down to room temperature level and their tensile strength is evaluated. From the studies adopting the postheating tension, the tensile strength is reduced proportionally to the exposure temperature level. Kumahara et al. [1] compared the results obtained from hot and postheating tension tests, showing that the GFRP reinforcing bars are almost recovered to their original tensile strength until 150°C of exposed temperature level. However, for the exposed temperatures level between 150°C and 250°C, the strength is recovered by about 80% of their original tensile strength. Over 400°C of exposed temperature level, the recovering capacity is almost lost. It indicates that the recovery of tensile properties of GFRP rebar closely depends on the exposed temperature level and cooling process.

Another issue on the GFRP reinforcing bars is a concrete alkaline effect. From the previous studies considering “accelerated aging test” for this issue [13–16], the bars embedded in mortar or immersed in alkaline solutions have a significant deterioration in tensile strength. Cracks and damage at the fiber-resin interface and also at the glass fiber resulting from alkaline fluid infiltration are observed by Scanning Electron Microscopy (SEM) analysis. All the previous studies

Table 1: Outline of experimental program.

	Preheated	Immerged in 40°C alkaline solution			
		For 0 days	For 100 days	For 300 days	For 660 days
Ref	35ea at room temp.	10ea	10ea	10ea	5ea
PH_120	35ea at 120°C	10ea	10ea	10ea	5ea
PH_200	35ea at 200°C	10ea	10ea	10ea	5ea
Sum	105ea	105ea			

mentioned above investigate the performance of GFRP reinforcing bars when they are exposed to either high temperature or concrete alkalinity, without considering the combined situation.

Few or limited studies have been conducted on the combined effects of these two conditions. One such study is conducted by Abbasi and Hogg [2]. In their study, the GFRP bars are firstly immersed for different durations in alkaline solutions at 60°C. Afterwards, the bars are placed in a heating chamber, exposed to temperatures between 80°C and 120°C, and subsequently subjected to tensile forces until failure occurs at specified temperatures. The results show that the GFRP rebar preexposed to alkaline solution has lower retention than the rebar not immersed in alkaline solution, even if both are exposed to identical temperatures. Such reduction is particularly significant at the highest considered temperature of 120°C.

In the present study, unlike the conditioning sequence adopted by Abbasi and Hogg [2], the GFRP specimens are firstly exposed to high temperature and then immersed in alkaline solution. Such scenario is to consider a postfire condition of RC structures consisting of GFRP reinforcing bars. Accelerated aging tests are performed on the preheated or thermally damaged GFRP rebars in order to investigate the effect of concrete alkaline solution on the reduction of the tensile strength and stiffness of the GFRP bars. In the test, the aging days of the GFRP rebars in alkali solution are 100 days, 300 days, and 660 days, which are normal immersion periods considered in the accelerated aging test. Also, two levels of preheating temperature conditions (120°C, 200°C) are considered as similar to the temperature ranges adopted in the previous "postheating tension test" [9–12].

2. Experimental Test Program

2.1. GFRP Bar Specimens. The diameter of the GFRP bars is 9.5 mm and their length is 1.2 m. The bars used in the present tests are manufactured in South Korea, where they are used for strengthening concrete structures. The bars are made of E-glass/vinyl-ester and the fiber volume ratio is 65%. A total of 105 specimens shown in Table 1 are prepared to be mounted in the tensile testing machine.

2.2. Testing Conditions and Setup. The GFRP bar specimens are preheated at two temperature levels: 120°C and 200°C. Specimens preheated at these two temperature levels are hereafter referred to as "PH_120" and "PH_200," respectively. Details of the preheating procedure are described in the following subsection. The glass transition temperature of the

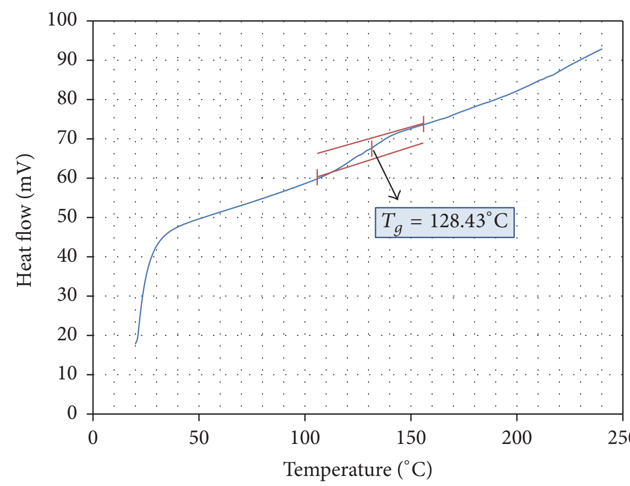


Figure 1: Differential Scanning Calorimetry (DSC) analysis result.

resin contained in the GFRP reinforcing bars is identified through Differential Scanning Calorimetry (DSC) analysis and it is found to be about 128°C as shown in Figure 1. The preheating temperature is set to be slightly below this value (120°C) for the 35 GFRP bar specimens and far above it (200°C) for the other 35 specimens. Unpreheated specimens are also prepared and tested for the comparison purposes, and these specimens are named "Ref" specimens. The total number of the Ref specimens is also 35. Strong alkaline solution having a pH of 12.6 is considered to represent the alkalinity of concrete. Herein, the present study assumes that the damaged parts of concrete due to fire event are replaced with new concrete; thus the GFRP bars are also assumed to be placed in the same concrete environment before and after fire event. The temperature of the alkaline solution is maintained with 40°C. Details of this treatment are described in Section 2.4. As summarized in Table 1, the specimens are subjected to tensile tests just after being immersed for different time durations such as "100 days," "300 days," and "660 days." The condition of zero days (i.e., "0 days" in Table 1) means that the specimens are subjected to tensile tests after exposure to 120°C or 200°C without immersing in alkaline solution. All preheated rebar specimens are cooled down for 3 hours before conducting the tensile test.

2.3. Preexposure to High Temperature: Preheating. Heating tape which is able to raise the temperature up to 250°C is used to preheat the specimens. As shown in Figure 2, the heating tape is wrapped around the center (±30 mm from the center) of the specimens and connected to a temperature

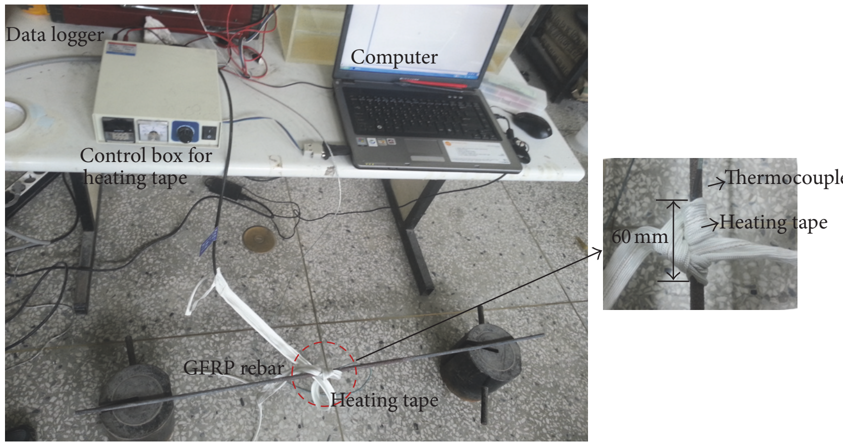


Figure 2: Preheating of GFRP reinforcement bars.

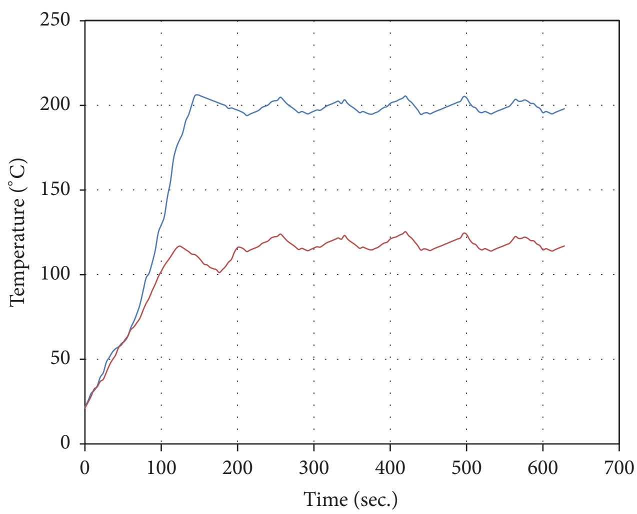


Figure 3: Temperature time histories for preheated specimens.

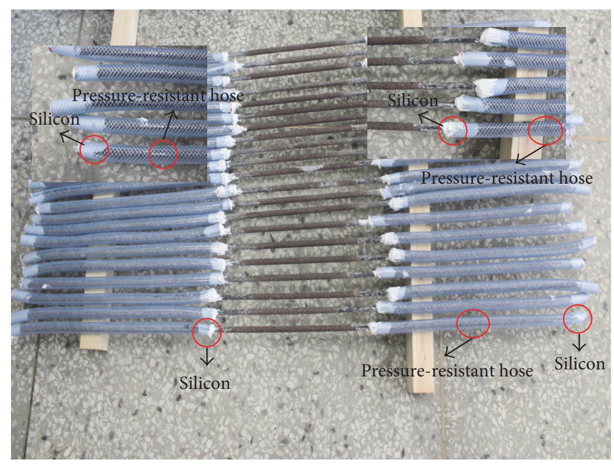


Figure 4: Protection of specimens anchoring parts.

control box to specify the temperature levels. A thermocouple is taped to the surface of the bars and connected to a data logger and computer in order to monitor the temperature of the specimens. The specified maximum temperature is set to 120°C and 200°C, and the heating is applied. After reaching the specified temperature levels the heating tape is removed. This heating procedure is repeated to ensure the same amount and extent of thermal conditioning. Figure 3 shows one example of the temperature history measured on the surface of the specimens. The exposure time to high temperatures is selected based on the reference of Katz et al. [17] which shows that after 10 minutes of exposure time under 120°C~200°C the adhesive strength between concrete and GFRP rebars with the same diameter considered in the present study is significantly decreased due to the slip behavior.

2.4. Immersion in 40°C Alkaline Solution. PH_120 and PH_200 bar specimens, whose length is 1.2 m, are fully immersed in a large plastic cistern containing strong alkaline solution for the predetermined time periods indicated in Table 1. During immersing into the alkaline solution, both ends parts of the specimens are protected to prevent damage since the parts are anchored to the tensile testing machine. For this, as shown in Figure 4, a length of 400 mm at each end of the bar specimens is inserted in pressure-resistant hoses, and then alkali-resistant silicone is inserted inside the hoses for a length of 30 mm to prevent infiltration of the alkaline solution. According to previous studies [14, 15, 18], the temperature of the alkaline solution is usually set to about 40°C or 60°C. In the present study, the alkaline solution, which is 1 Mole NaOH solution, is maintained to be 40°C. While the GFRP bar specimens are immersed into the NaOH alkali solution, the plastic cistern is shielded with cover in order to avoid its evaporation. Moreover, a circulator is used to ensure a uniform temperature distribution of the NaOH solution inside the cistern. The alkalinity of the solution is measured every morning using a pH-meter and maintained to be the designed pH. Figure 5 shows the GFRP bar specimens immersed into the NaOH solution.

2.5. Tensile Tests and Testing Equipment. The bar specimens are anchored to the tensile test machine according to the

Table 2: Tensile strength and elastic modulus.

Specimen ID	Mean (MPa)				SD (MPa)				CoV (%)			
	0 days	100 days	300 days	660 days	0 days	100 days	300 days	660 days	0 days	100 days	300 days	660 days
					Tensile strength							
Ref	644.7	574.8	183.0	114.9	24.3	47.7	8.7	29.3	3.8	8.3	4.7	25.5
PH_120	643.7	582.0	162.8	125.6	38.4	60.2	29.9	23.9	6.0	10.3	18.4	31.9
PH_200	612.8	503.7	159.6	120.7	27.6	47.7	18.0	17.1	4.5	9.5	11.3	14.1
					Elastic modulus							
Ref	53.4	52.0	17.6	16.4	6.8	3.9	1.7	2.7	12.7	7.4	9.8	16.5
PH_120	52.0	51.0	16.2	16.0	3.0	3.2	1.7	2.1	5.7	6.3	10.3	13.1
PH_200	50.2	49.6	16.4	15.2	3.5	3.8	1.3	2.2	6.9	8.0	7.6	14.2

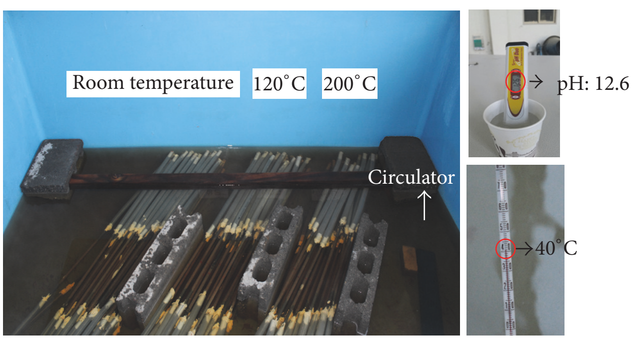


Figure 5: Immersion of GFRP rebar specimens into alkaline solution.

standards specified in ASTM D 3916 [19]. The aluminium plate is used to accommodate the specimens as shown in Figure 6. The specimens are inserted into the aluminium plate and anchored with bolts. Universal Testing Machine (UTM) providing 500 kN maximum loading capacity is used for the tensile tests. The tests are performed under displacement control and the applied loading rate is 5 mm/min. A Linear Variable Displacement Transducer (LVDT) is attached to the bar specimens to measure the axial elongation during loading.

2.6. Calculation of Tensile Strength and Elastic Modulus. The tensile strength (f_u) and elastic modulus (E_L) are calculated using (1) and (2), respectively. The tensile strength is calculated by dividing the ultimate load (P_u) by the cross section area (A) and the elastic modulus is calculated based on the test methods for fiber reinforced polymers described in ACI 440.3R-04 specifications [20]. The parameters P_1 and P_2 are the axial loads corresponding to 25% and 50% of the ultimate load (P_u), respectively. The parameters ε_1 and ε_2 denote the corresponding strains.

$$f_u = \frac{P_u}{A} \quad (1)$$

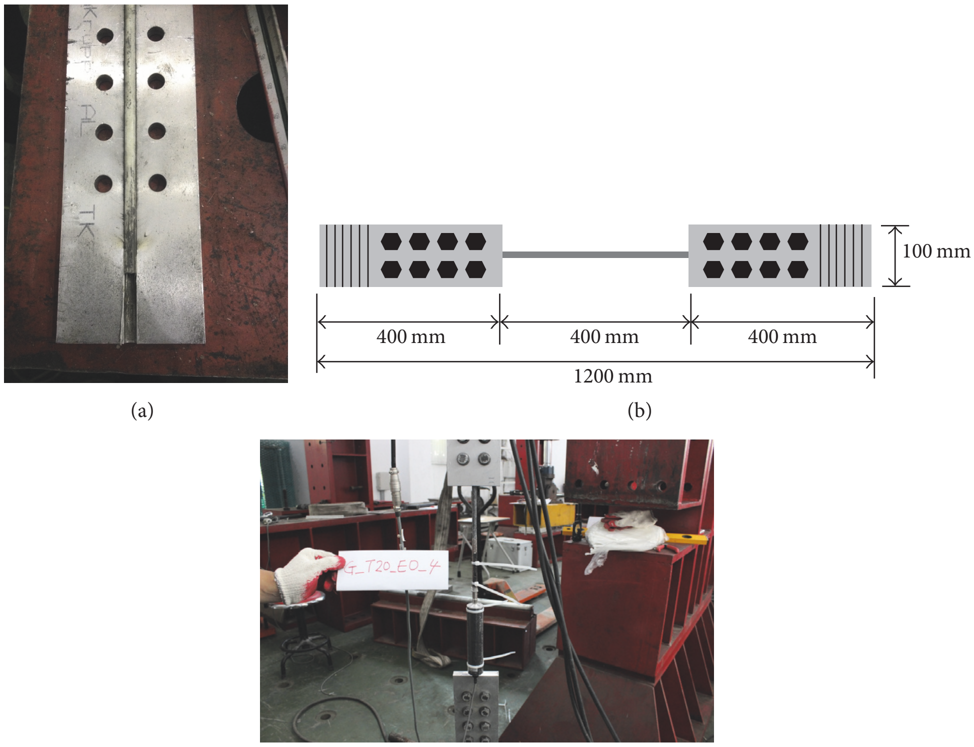
$$E_L = \frac{P_1 - P_2}{(\varepsilon_1 - \varepsilon_2) A}. \quad (2)$$

2.7. Preparation of Optical Microscopic Analysis. Optical microscopy images are acquired using the Leica DM-750M microscope to examine the local damage to the specimens due to preheating and alkaline solution. An additional set of 100 mm long GFRP rebar specimens are prepared for this analysis; these specimens are preheated and immersed in alkaline solution for 30 days. The preheating levels are the exactly same levels considered in the present tensile test. The center of the specimens is cut into short pieces (10 mm long) by using precision cutter and the short pieces are cold-mounted in a 30-mm diameter mounting cup by pouring acrylic resin. In order to acquire clear images, the mounted short pieces are subjected to 8-stage polishing process.

3. Experimental Test Results

For the discussion of the test results, the average tensile strength and elastic modulus are considered, which are summarized in Table 2, including their standard deviations and covariances.

3.1. Alkaline Solution Effects without Exposure to High Temperature (Ref Specimens). The results of accelerated aging test for the "Ref" specimen are compared with those reported in previous works [13–16]. As shown in Figure 7, the tensile strength of the GFPR bar specimens is very similar until 100 immersion days, compared to test results of Chen et al. [15]. Also, it can be recognized that the tensile strength of GRFP bars greatly depends on the resin type, the alkali solution temperature, and the conditioning method in the alkali solution (bare bar or mortar-wrapped bar). The polyester resin is found to have a lower alkali resistance than the vinyl-ester and thermoplastic resins. As expected, a more rapid reduction in the tensile strength is observed in the case of immersion in 60°C alkaline solution than in the case of immersion in 40°C alkaline solution. Comparing the present test results with those of Robert et al. [16], in which the rebar is made of the same resin type and immersed into alkaline solution maintained with identical temperature level, the tensile strength of the bare bars is similar to that of the mortar-wrapped bars until 120 immersion days. However, the mortar-wrapped bar retains about 90% of its original tensile strength until 240 immersion days; on the contrary, the tensile strength of the bare bars is drastically decreased to 30% of the original strength until 300 immersion days.



(a) (b)

(c)

Figure 6: Test-setup assembly: (a) gripping fixture, (b) anchoring detail for tensile test, and (c) installation of LVDT.

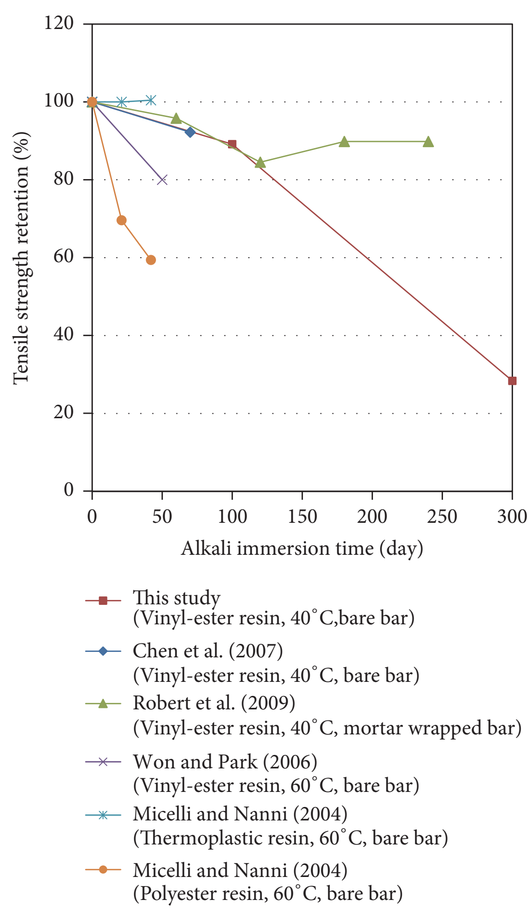


Figure 7: Accelerated aging test results of Ref and comparisons with those presented in referred articles.

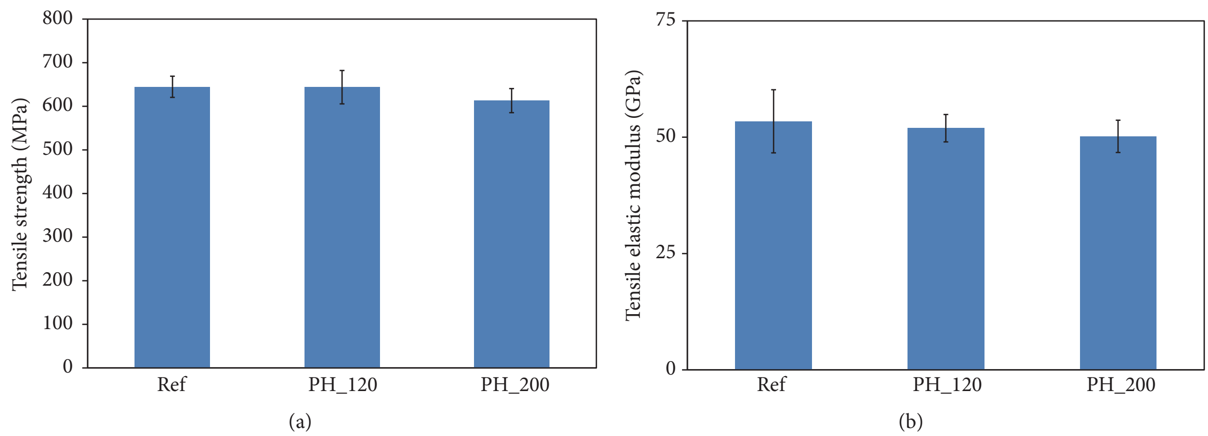


Figure 8: Test results for Ref and PH specimens that were not immersed in alkali solution: (a) tensile strength and (b) elastic modulus.

3.2. Alkaline Solution Effects of Preheated GFRP Bar Specimens (PH_120, PH_200). Figure 8 shows the comparison of tensile strength and elastic modulus of the specimens exposed to high temperatures but not exposed to concrete alkalinity (for zero-day case in Table 1). PH_120 and Ref specimens provide almost the same tensile strength and elastic modulus. However, small reduction in the tensile strength is found in PH_200 specimens. The results indicate that the tensile properties that might be degraded upon exposure to high temperatures are recovered fully for PH_120 specimens during cooling down for 3 hours, while recovering about 95% for PH_200 specimens. Such results are similar to those of the postheating tension test performed in the cited previous study [1].

Figure 9 shows the representative tensile stress-strain curves of the specimens. Despite different preheating temperature levels and different immersion days in alkaline solution, the stress-strain relationships are almost linear in all cases. Figures 9(a) and 9(b) show that the stress-strain curves of Ref and PH_120 specimens obtained at zero days and 100 alkali immersion days are very similar. However, as shown in Figure 9(c), the slope of the tensile stress-strain curve of the PH_200 specimens for 100 immersion days shows slightly lower relationship than that of the zero immersion day (preheated only). For longer immersion periods like 300 days and 660 days, the tensile stress-strain curves are much decreased, compared to those of the zero and 100 alkali immersion days. Also, they show almost identical slope. From the test results, it can be recognized that the elastic modulus (slope of the stress-strain curves) of the GFRP bars is closely related to alkali immersion days, not much related to the preheating levels. Regarding the tensile strength shown in Figure 10, the tensile strength decreases for all testing cases as the immersion time to the alkaline solution increases. Also, there is a big drop in the tensile strength until 300 alkali immersion days. However, after 300 alkali immersion days the tensile strength is slightly decreased. More specifically, the specimen Ref and PH_120 exhibit almost the same tensile strength for all immersion days considered here, while PH_200 specimens provide much less tensile strength than those of Ref and PH_120 specimens until 100 alkali immersion days. After 300 alkali immersion days, however, their tensile strength is almost the same as the other cases.

In order to highlight the relative effects of preexposure to high temperature, the tensile strength and elastic modulus of PH_120 and PH_200 specimens are normalized with the corresponding properties of the Ref specimens and the results are plotted in Figures 11(a) and 11(b). As shown in Figure 11(a), the tensile strength of the preheated specimens is about 90% of Ref specimen tensile strength for 300 alkali immersion days. However, for the specimens tested after 660 immersion days, the tensile strength of the preheated specimens is slightly higher than that of the Ref specimens. Such results indicate that the tensile strength is much affected by the preheating until 300 alkali immersion days, but for longer immersion days the alkaline exposure provides more effect on the tensile strength than the preheating. Figure 11(b) shows that the preheated specimens provide slightly lower elastic modulus than Ref specimens, presenting only 8% maximum difference.

3.3. Failure of Test Specimens. Failure of the specimens without immersing into the alkaline solution is shown in Figure 12. The specimens exhibit a typical tensile failure or rupture induced by tensile forces. When the specimens are ruptured, the delamination of the glass fiber strands is observed in almost the same locations where the heating is applied. The failure of the specimens initiates on the resin matrix at the preheating location and followed through the fiber splitting on the outer layer of the specimens. The fibers are completely ruptured at the preheating location at the end of the testing. Figure 13 shows the tensile failure of the specimens immersed in the alkaline solution for 300 days. The specimens are ruptured at their center near to the preheating location. The delamination or separation of the glass fiber strands is developed with a lesser extent (i.e., smaller area), compared to the rupture length of the specimens preheated only. The lesser extent of separation is developed possibly due to the uneven distribution of the tensile force applied to the specimens. This uneven distribution of the tensile force might be caused by the damage of the resin matrix resulting from the long immersion days in alkaline solution.

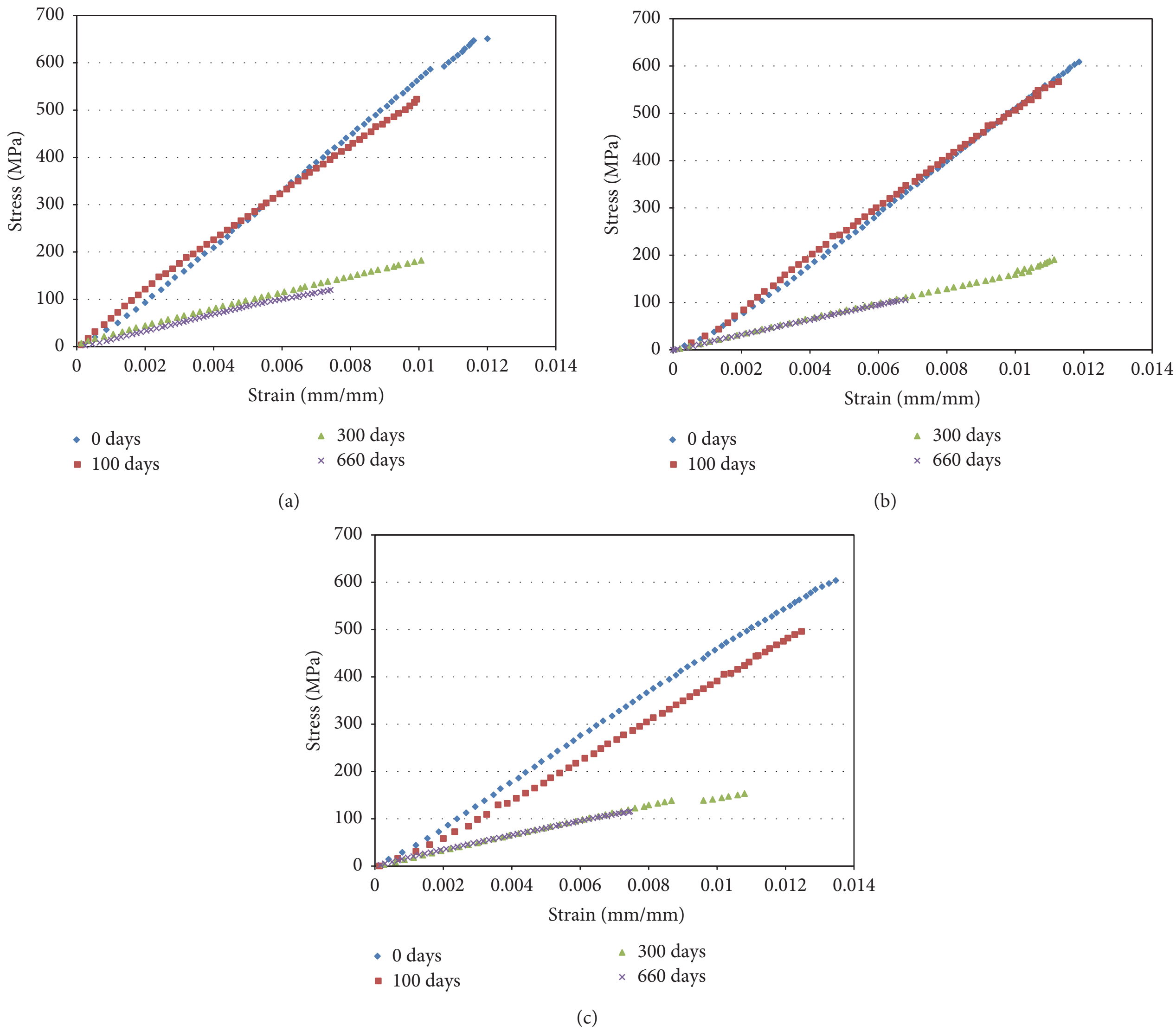


Figure 9: Results of tensile stress-strain curve from experimental test: (a) Ref specimen, (b) PH_120 specimen, and (c) PH_200 specimen.

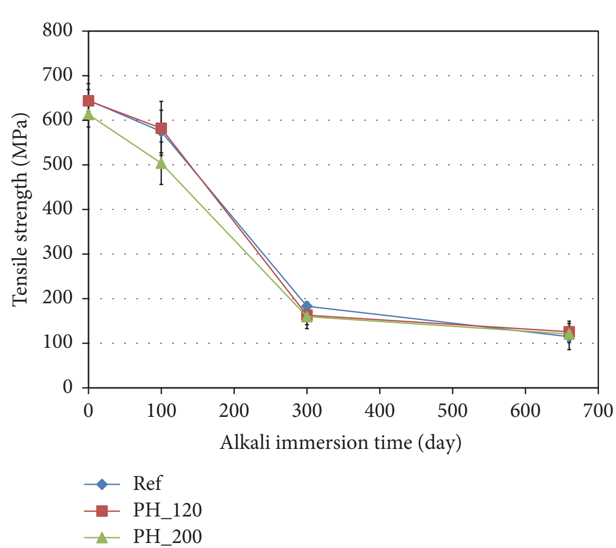
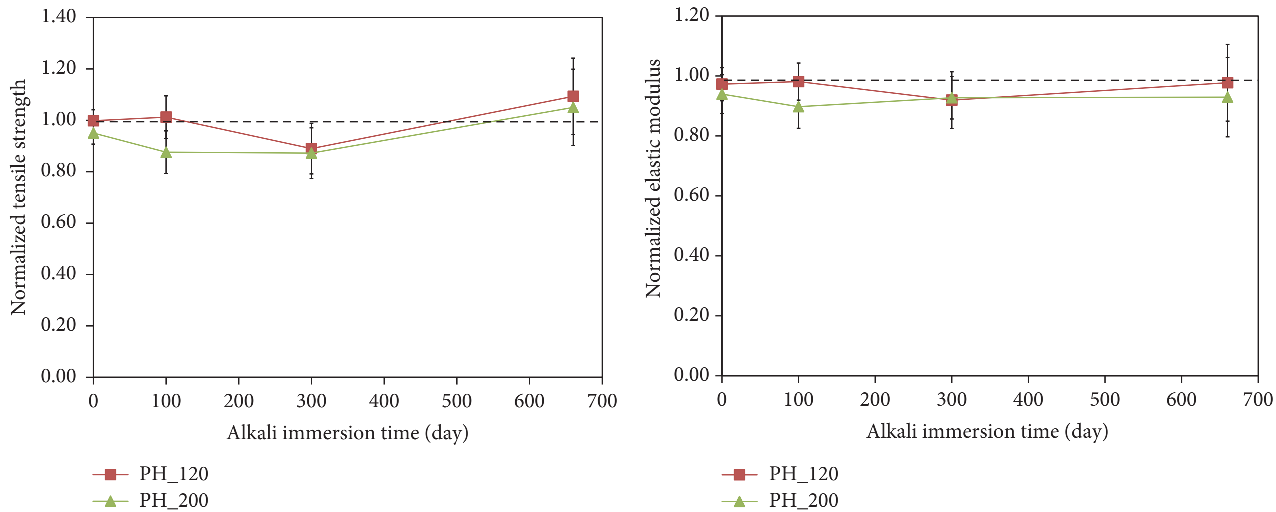
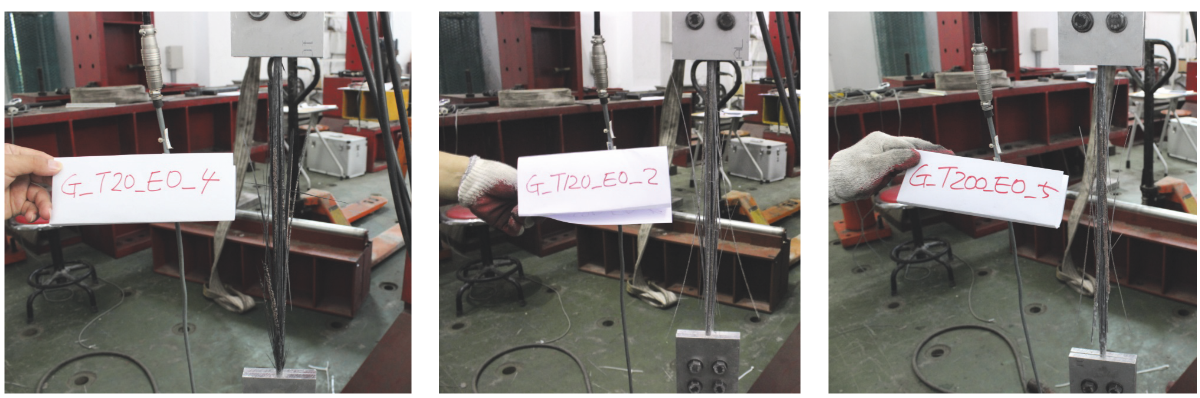


Figure 10: Tensile strength reduction according to alkali immersion time.



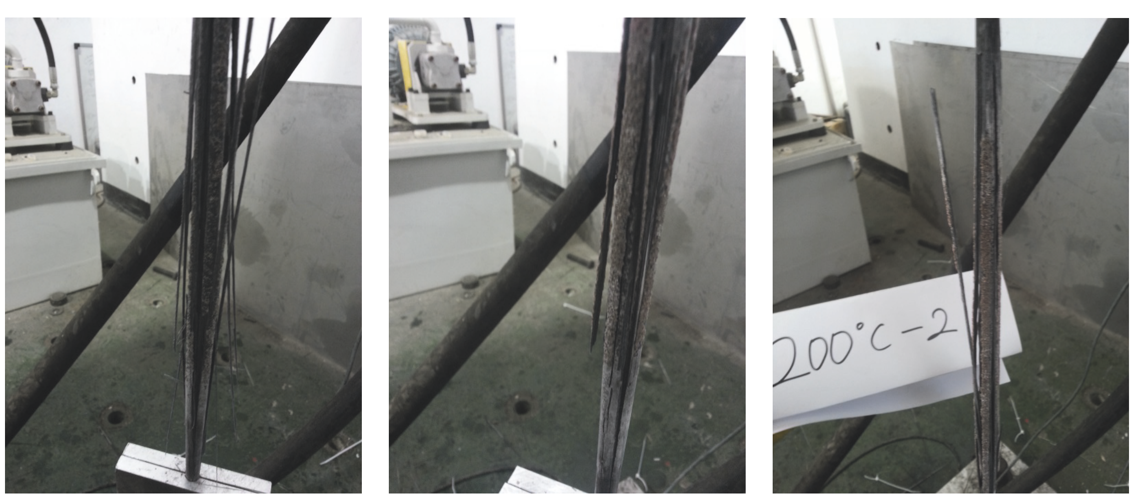
(a) (b)

Figure 11: Comparison of tensile properties: (a) tensile strength and (b) elastic modulus (normalized with Ref specimens).



(a) (b) (c)

Figure 12: Failure of testing specimens without alkaline solution immersion: (a) exposed to room temperature, (b) exposed to 120°C, and (c) exposed to 200°C.



(a) (b) (c)

Figure 13: Failure of specimens immersed into alkaline solution for 300 days: (a) exposed to room temperature, (b) exposed to 120°C, and (c) exposed to 200°C.

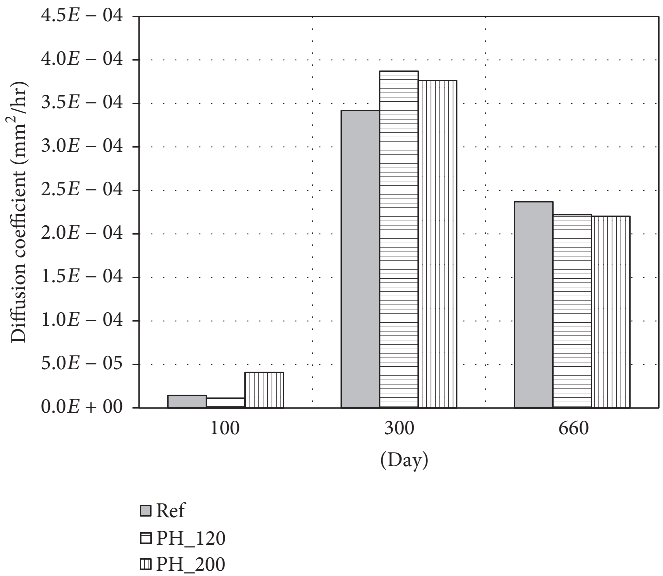


Figure 14: Alkaline solution diffusion coefficient results.

4. Diffusion Coefficient of Alkaline Solution

In severe alkaline concrete environment, the mechanical performance degradation of the GFRP reinforcing bars is closely related to the alkaline solution diffusion coefficient [21–26]. Katsuki and Uomoto [21] suggest the relationship between the tensile strength variation and the alkaline diffusion coefficient of FRP reinforcing bars. The relationship is shown in (3) and (4) which are based on Fick's first law. Putting the tensile strength retention obtained from the test into the left side of (3), the parameter x is determined. Herein, the parameter R_0 is the radius of FRP rebar. The alkaline diffusion coefficient D (mm^2/hr) is determined by substituting the result of x into (4).

$$\frac{\sigma_t}{\sigma_0} = \left(\frac{1-x}{R_0}\right)^2 \quad (3)$$

$$D = \frac{x^2}{2Ct}, \quad (4)$$

where σ_0 and σ_t indicate tensile strength (MPa) before immersing and at certain immersion time, respectively. The parameter x is the depth of penetration from the surface (mm); the parameter C is a relative term describing the alkaline concentration [(mol/liter)/(mol/liter)]. The parameter t is the alkali immersion time (hr) in 40°C with one mol/liter aqueous NaOH. From the analysis results shown in Figure 14, the diffusion coefficients are $1.1 \times 10^{-5}\,mm^2/hr$~$4.1 \times 10^{-5}\,mm^2/hr$ for 100 immersion days, $3.4 \times 10^{-4}\,mm^2/hr$~$3.9 \times 10^{-4}\,mm^2/hr$ for 300 immersion days, and $2.2 \times 10^{-4}\,mm^2/hr$~$2.3 \times 10^{-4}\,mm^2/hr$ for 660 immersion days. In the previous researches, the alkaline solution diffusion coefficients were $2.8 \times 10^{-4}\,mm^2/hr$, $3.2 \times 10^{-3}\,mm^2/hr$, and $3.3 \times 10^{-3}\,mm^2/hr$ for 100, 300, and 660 immersion days, respectively, using the same diameter of the GFRP bar specimens [21–23]. The diffusion coefficient of 100 alkali immersion days is significantly less than the results of previous researches. However, the diffusion coefficients for 300 and 660 immersion days are similar to those of the FRP rebars presented by Katsuki and Uomoto [21], but those are much less than the results of Sen et al. [22] and Trejo et al. [23]. For the 100 immersion days of the testing specimens, the diffusion coefficient of PH_200 specimen is 2.8 to 3.0 times greater than that of other specimens, which indicates the effect of preheating. The diffusion coefficients of 300 and 660 immersion days, however, are not apparently different from each other. Trejo et al. [23] report that more consistent diffusion coefficient can be evaluated from a long term test in which the rebar should be immersed into alkali solution for at least 120 days. This report supports that the diffusion coefficients obtained from the 300 and 660 alkali immersion days are more reliable than the result of the 100 immersion days.

5. Optical Microscopic Analysis

The microscopy images for Ref specimen which are not immersed into alkaline solution are shown in Figure 15. Many voids with a diameter smaller than 10 μm are observed. The voids are formed by air bubbles entrapped between fibers during the pultrusion. However, cracks are not found in the fibers and resin matrix. Figure 16 shows the microscopy images of PH_120 and PH_200 specimens which are not immersed into alkaline solution. Pores with diameters larger than 40 μm are visible between the fibers and in resin-rich areas; also the fibers are cracked as shown in Figure 16. However, the cracks in the resin matrix are found in PH_200 specimen, but not in PH_120 specimen. Figure 17 shows the microscopy images of PH_120 and PH_200 specimens immersed in the alkaline solution for 30 days. For PH_200 specimen, more pores and cracks in the resin and fibers and

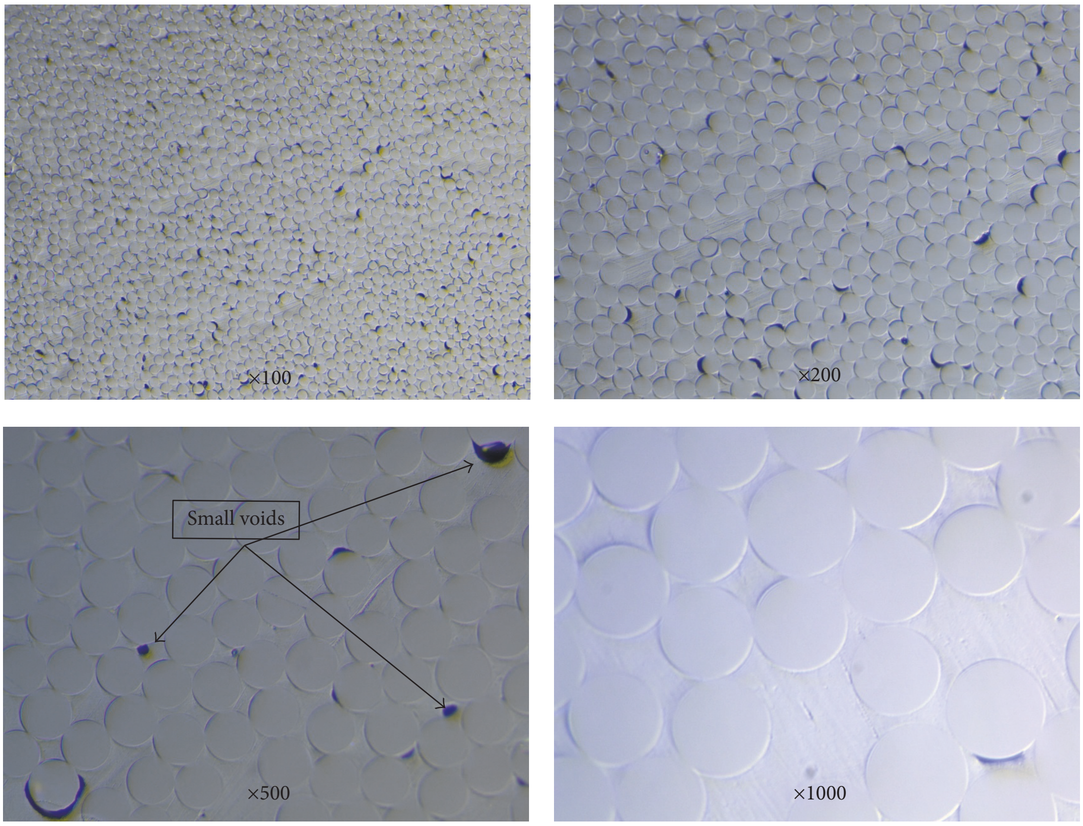
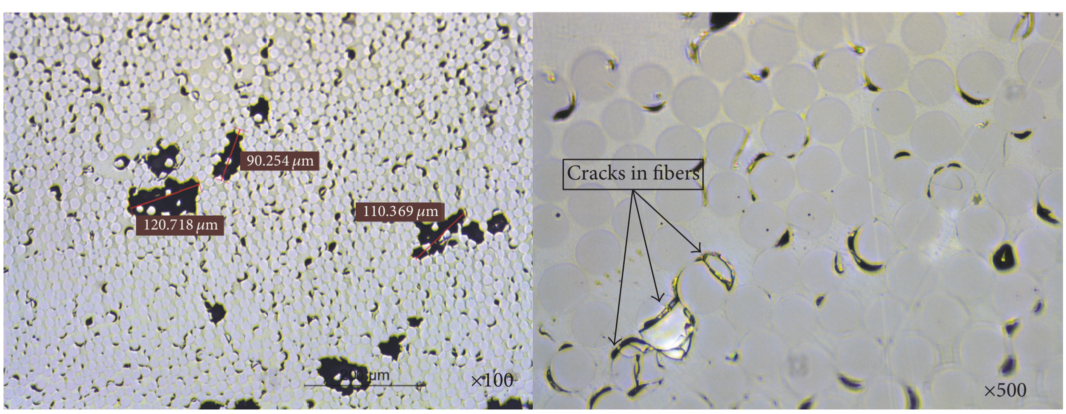
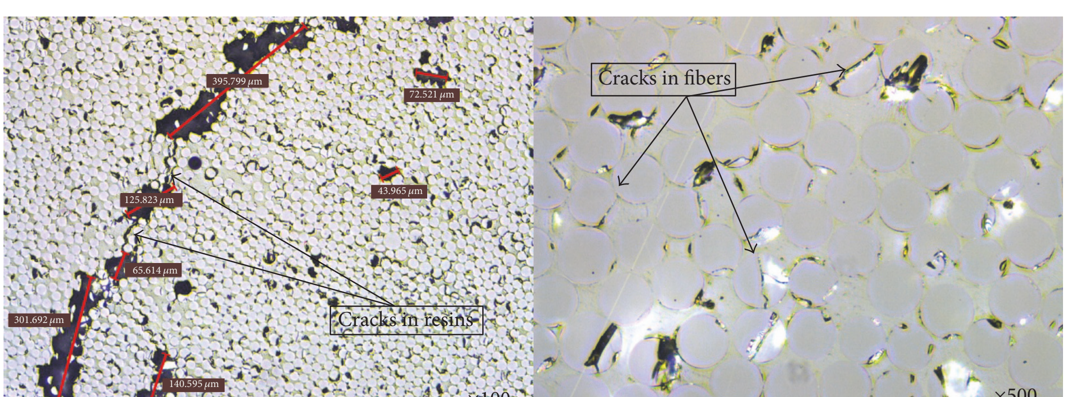


Figure 15: Optical microscopic images of Ref specimen.

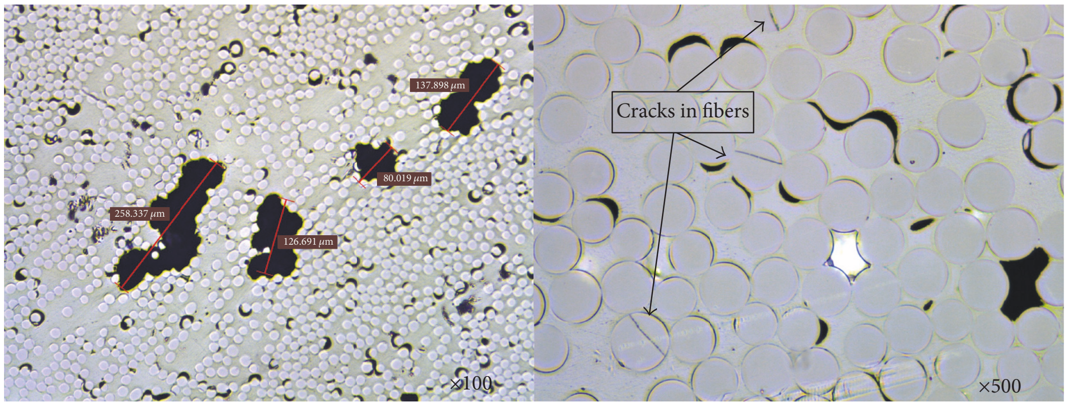


(a)

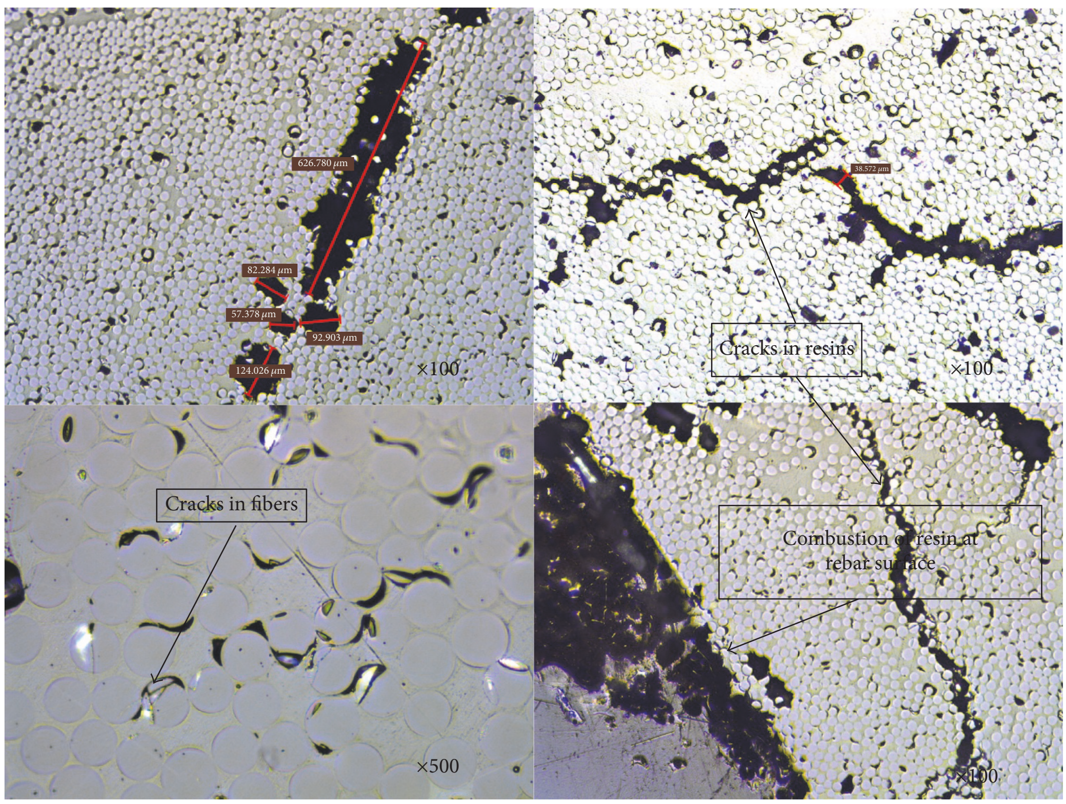


(b)

Figure 16: Optical microscopic images before immersing into alkaline solution: (a) PH_120 and (b) PH_200 specimens.



(a)



(b)

Figure 17: Optical microscopic images after immersing into alkaline solution for 30 days: (a) PH_120 and (b) PH_200 specimens.

even the combustion on the rebar surface are found. However, there is no resin crack developed on PH_120 specimen. Also, the pore sizes of PH_120 specimen are not changed compared to the case without immersing into alkaline solution.

6. Remarks and Conclusions

The purpose of this study is to identify the variation in the tensile properties of the structural GFRP reinforcing bars exposed to high temperature. The tensile tests are performed on the 1.2 m long specimens on the UTM and the total number of the specimens tested is 105. The GFRP bar specimens are preexposed to high temperature (120°C and 200°C) and cooled down to room temperature level. After the process, the specimens are immersed in 1 Mole NaOH alkaline solution to represent the concrete environment for long periods of time (100 days, 300 days, 660 days). From the test results, the preheated specimens provide slightly lower elastic modulus than those of unpreheated specimens and the maximum difference is only 8%. The tensile strength also decreases for all testing cases as the increase of the alkaline immersion time. There is a big drop in the tensile strength until 300 alkali immersion days. The tensile strength of the preheated specimens is about 90% of the tensile strength of the unpreheated specimen. After 300 alkali immersion days, however, the tensile strengths are almost identical to each other. The overall results indicate that the tensile strength and elastic modulus of the GFRP bars are closely related to alkali immersion days, not much related to the preheating levels. It leads to the conclusion that the limited damage caused to the GFRP reinforcing bars by the high temperature applied in this study is not expected to induce a significant deterioration in the tensile performance of the GFRP reinforcing bars as that damage is caused by the infiltration of alkaline components. Therefore, the damage caused by such temperature condition may not necessarily be considered for the strength evaluation of FRP rebars. Incidentally, based on the conclusions herein, it can be recommended that the environmental reduction factor specified in ACI 440.1R-06 [27], with design FRP material properties without considering the exposed temperature conditions, is still available for the strength evaluation of the GFRP rebars when they remained in concrete alkalinity environment after fire accident. One note is that if the sustained tension load is considered during preheating process to represent more real situation, the test results obtained in this study will be varied since the fact that the sustained load increases the micro cracks or voids in the specimens during their exposure to high temperature may happen. The sustained tensile loading effects need to be investigated in the future study.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This research was supported by a grant from the Information & Communication Technology (ICT) Program (code 15SCIP-B066018-03) and Technology Advancement Research Program funded by the Ministry of Land, Infrastructure and Transport of the Korean government (Grant 17CTAP-C117247-02).

References

[1] S. Kumahara, Y. Masuda, H. Tanano, and A. Shimizu, "Tensile strength of continuous fiber bar under high temperature," *ACI Special Publication*, vol. 138, pp. 731–742, 1993.

[2] A. Abbasi and P. J. Hogg, "Temperature and environmental effects on glass fibre rebar: modulus, strength and interfacial bond strength with concrete," *Composites Part B: Engineering*, vol. 36, no. 5, pp. 394–404, 2005.

[3] L. A. Bisby, M. F. Green, and V. K. R. Kodur, "Response to fire of concrete structures that incorporate FRP," *Progress in Structural Engineering and Materials*, vol. 7, no. 3, pp. 136–149, 2005.

[4] Y. C. Wang and V. Kodur, "Variation of strength and stiffness of fibre reinforced polymer reinforcing bars with temperature," *Cement and Concrete Composites*, vol. 27, no. 9-10, pp. 864–874, 2005.

[5] E. J. Bosze, A. Alawar, O. Bertschger, Y.-I. Tsai, and S. R. Nutt, "High-temperature strength and storage modulus in unidirectional hybrid composites," *Composites Science and Technology*, vol. 66, no. 13, pp. 1963–1969, 2006.

[6] M. Robert and B. Benmokrane, "Behavior of GFRP reinforcing bars subjected to extreme temperatures," *Journal of Composites for Construction*, vol. 14, no. 4, pp. 353–360, 2010.

[7] J. R. Correia, M. M. Gomes, J. M. Pires, and F. A. Branco, "Mechanical behaviour of pultruded glass fibre reinforced polymer composites at elevated temperature: Experiments and model assessment," *Composite Structures*, vol. 98, pp. 303–313, 2013.

[8] G. A. Kashwani and A. K. Al-Tamimi, "Evaluation of FRP bars performance under high temperature," *Physics Procedia*, vol. 55, pp. 296–300, 2014.

[9] S. K. Foster and L. A. Bisby, "High temperature residual properties of externally-bonded FRP systems," *ACI Special Publication*, vol. 230, pp. 1235–1252, 2005.

[10] M. Al-Zahrani, S. U. Al-Dulaijan, S. H. Al-Idi, and M. H. Al-Methel, *High temperature effect on tensile strength of GFRP bars and flexural behavior of GFRP reinforced concrete beams, FRPRCS-8*, University of Patras, Patras, Greece, 2007.

[11] Y.-N. Fu, J. Zhao, and Y.-L. Li, "Research on tensile mechanical properties of GFRP rebar after high temperature," *Advanced Materials Research*, vol. 181-182, pp. 349–354, 2011.

[12] S. Alsayed, Y. Al-Salloum, T. Almusallam, S. El-Gamal, and M. Aqel, "Performance of glass fiber reinforced polymer bars under elevated temperatures," *Composites Part B: Engineering*, vol. 43, no. 5, pp. 2265–2271, 2012.

[13] F. Micelli and A. Nanni, "Durability of FRP rods for concrete structures," *Construction and Building Materials*, vol. 18, no. 7, pp. 491–503, 2004.

[14] J.-P. Won and C.-G. Park, "Effect of environmental exposure on the mechanical and bonding properties of hybrid FRP reinforcing bars for concrete structures," *Journal of Composite Materials*, vol. 40, no. 12, pp. 1063–1076, 2006.

[15] Y. Chen, J. F. Davalos, I. Ray, and H. Y. Kim, "Accelerated aging tests for evaluations of durability performance of FRP reinforcing bars for concrete structures," *Composite Structures*, vol. 78, no. 1, pp. 101–111, 2007.

[16] M. Robert, P. Cousin, and B. Benmokrane, "Durability of gfrp reinforcing bars embedded in moist concrete," *Journal of Composites for Construction*, vol. 13, no. 2, pp. 66–73, 2009.

[17] A. Katz, N. Berman, and L. C. Bank, "Effect of high temperature on bond strength of FRP rebars," *Journal of Composites for Construction*, vol. 3, no. 2, pp. 73–81, 1999.

[18] S. U. Al-Dulaijan, M. M. Al-Zahrani, A. Nanni, and T. E. Boothby, "Effect of environmental pre-conditioning on bond of FRP reinforcement to concrete," *Journal of Reinforced Plastics and Composites*, vol. 20, no. 10, pp. 881–900, 2001.

[19] ASTM D 3916-02, *Test Method for Tensile Properties of Pultruded Glass Fiber-Reinforced Plastic Rod*, vol. 08.02, West Conshohocken, PA, USA, 2002.

[20] ACI 440.3R-04, "Guide test methods for fiber-reinforced polymers (FRPs) for reinforcing or strengthening concrete structures," in *Proceedings of the ACI Committee 440*, American Concrete Institute, Farmington Hills, Mich, USA, 2004.

[21] F. Katsuki and T. Uomoto, "Prediction of deterioration of FRP rods due to alkali attack," in *Proceedings of the Second International RILEM Symposium (FRPRCS-2*, pp. 82–89, Ghent, Belgium, 1995.

[22] R. Sen, G. Mullins, and T. Salem, "Durability of E-glass/vinylester reinforcement in alkaline solution," *ACI Structural Journal*, vol. 99, no. 3, pp. 369–375, 2002.

[23] D. Trejo, F. Aguiniga, R. Yuan, R. W. James, and P. B. Keating, "Characterization of design parameters for fiber reinforced polymer composite reinforced concrete systems. Research Report 9-1520-3," Tech. Rep., Texas A&M Univ., College Station, Tex, USA, 2005.

[24] Y. Chen, J. F. Davalos, and I. Ray, "Durability prediction for GFRP reinforcing bars using short-term data of accelerated aging tests," *Journal of Composites for Construction*, vol. 10, no. 4, pp. 279–286, 2006.

[25] P. Gardoni, D. Trejo, and Y. H. Kim, "Time-variant strength capacity model for GFRP bars embedded in concrete," *Journal of Engineering Mechanics*, vol. 139, no. 10, pp. 1435–1445, 2013.

[26] M. Robert and B. Benmokrane, "Combined effects of saline solution and moist concrete on long-term durability of GFRP reinforcing bars," *Construction and Building Materials*, vol. 38, no. 1, pp. 274–284, 2013.

[27] ACI 440.1R-06, "Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars," in *Proceedings of the ACI Committee 440*, American Concrete Institute, Farmington Hills, Mich, USA, 2006.