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Assessment Study of Glass Fiber-Reinforced Polymer Reinforcement Used in Two Concrete Bridges after More than 15 Years of Service

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Corrosion in reinforced concrete (RC) represents a serious issue in steel-reinforced concrete structures; therefore, finding an alternative to replace steel reinforcement with a non-corrosive material is necessary. One of these alternatives is glass fiber-reinforced polymer (GFRP) that arises as not only a feasible solution but also economical. The objective of this study is to assess the durability of GFRP bars in concrete bridges exposed to a real-time weather environment. The first bridge is Southview Bridge (in Missouri) and its GFRP bars have been in service for more than 11 years; the second bridge is Sierrita de la Cruz Creek Bridge (in Texas State) and its GFRP bars have been in service for more than 15 years. To observe any possible mechanical and chemical changes in the GFRP bars and concrete, several tests were conducted on the GFRP bars and surrounding concrete of the extracted cores. Carbonation depth, pH, and chlorides content were performed on the extracted concrete cores to evaluate the GFRP-surrounding environment and see how they influenced certain behaviors of GFRP bars. Scanning electron microscopy (SEM) was performed to observe any microstructural degradations within the GFRP bar and on the interfacial transition zone (ITZ). Energy dispersive spectroscopy (EDS) was applied to check for any chemical elemental changes. In addition, glass transition temperature (TA) and fiber content tests were carried out to assess the temperature state of the resin and check any loss in fiber content of the bar after these years of service. The results showed that there were no microstructural degradations in both bridges. EDS results were positive for one of the bridges, and they were negative with signs of leaching and alkali-hydrolysis attack on the other. Fiber content results for both bridges were within the permissible limits of ACI 440 standard. Carbonation depth was found only in one of the bridges. In addition, there were no signs of chloride attack in concrete. This study adds new evidence to the validation of the long-term durability of GFRP bars as concrete reinforcement used in field applications.

Keywords: chloride content; durability; energy-dispersive X-ray spectroscopy (EDS); Fourier-transform infrared spectroscopy (FTIR); glass fiber-reinforced polymer (GFRP); glass transition temperature (TA); pH; scanning electron microscopy (SEM).

INTRODUCTION

Corrosion of steel reinforcement represents a major issue within the civil engineering industry, as the cost of repairs in the United States, Canada, and several European countries makes up a substantial percentage of the infrastructure allocated expenditures of these countries.[1] Several methods such as cathodic protection, epoxy-coated bars, and galvanized steel were implemented, yet these methods have not been entirely successful to stop corrosion.[2] Thus, considering the difficulties and costs of corrosion repairs, the direction to find non-corrosive alternative materials is of primary importance to replace steel reinforcement. One of these alternatives is glass fiber-reinforced polymer (GFRP). GFRP bars have been applied successfully as a main reinforcement in quite a few concrete structures as they have high-strength to-weight ratio and are non-corrosive, in addition to being economically feasible.[3] Some of these GFRP concrete structures include barriers,[4] parking garages,[5] storage structures for wastewater treatment,[6] and marine structures.[7] However, the use of GFRP as a main reinforcement requires additional field validation.[8] Despite the fact that there has been significant research on laboratory-based chemical and mechanical testing, creep, and natural weathering of composites, limited research closely related to real-time field exposure scenarios has been performed. Thus, field-related durability data needs to be proactively gathered and made available for standard writing organizations.[9]

Using accelerated laboratory tests to assess the GFRP durability performance by exposing GFRP concrete to an alkaline environment does not resemble the conditions of those exposed to a real-time field exposure.[2] Accelerated tests are significantly harsher on GFRP bars than real-time field exposure. In 1998, Porter and Barnes[10] conducted accelerated experiments on GFRP bars to determine their long-term tensile strength. Alkaline solution was used on the bars with a temperature of 60°C (140°F) for 3 months. The test results showed that after alkaline exposure, the residual strengths of bars were between 34 and 71%. In 2004, Nkurunziza et al.[11] implemented the combined effect of sustained loadings (up to 40%), chemical solution (de-ionized water or alkaline solution), and high temperature (between 55 and 75°C [131 and 167°F]) on 9.5 mm diameter GFRP bars. The test results showed that de-ionized water-exposed and alkaline-exposed specimens lost 4% and 11% of their original strength, respectively.

On the other hand, a more reliable indication of the durability of GFRP bars can be taken from monitoring the performance of existing GFRP-reinforced concrete structures. Therefore, durability studies on GFRP bars extracted from bridges have become the preferred process of evaluation.

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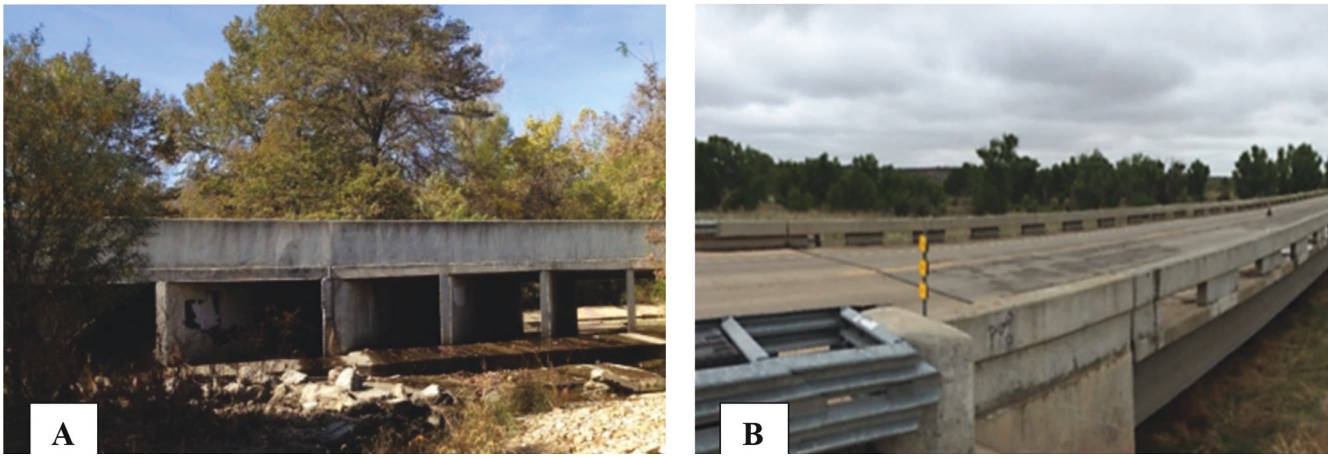

Fig. 1—(a) Southview Bridge, Rolla, MO; and (b) Sierrita de la Cruz Creek Bridge, Amarillo, TX.

In 2007, Mufti et al. conducted a durability study on GFRP bars extracted from five bridges across Canada after being in service for over 8 years.[12] Several tests were performed on the specimens to investigate their microstructural, chemical, and mechanical performance. The results showed that, from the scanning electron microscopy (SEM) examination, a bond was observed between the GFRP and concrete, while from Fourier-transform infrared spectroscopy (FTIR), and differential scanning calorimetry tests, neither hydrolysis nor significant changes in glass transition temperature took place. Gooranorimi et al.[8] assessed the durability of GFRP bars in an existing bridge in Texas. After 15 years of service, tests were conducted on these bars including SEM, energy dispersive X-ray spectroscopy (EDS), short bar shear (SBS), fiber content, and glass transition temperature (TA). The test results showed no microstructural deteriorations in the bars, and no change in their chemical compositions. The TA and the fiber content results were close to the control bars values, while the short bar shear results were inconclusive.[8]

In the current study, another durability study was carried out on GFRP specimens extracted from the same bridge that Goornorimi et al.[8] used to conduct their study, but this time, the specimens were taken from another location of the bridge. In addition, another bridge in a different state (Missouri) was added to the list of durability investigation to enrich and validate the current durability documents. Several GFRP bars extracted from the two bridges—which have been in service for over 11 and 15 years respectively—were investigated. The tests were conducted on the GFRP bars, including SEM, EDS, FTIR, TA, and fiber content. The test results were compared to control bars available from one bridge and to test results conducted on the same bridges, but on different cores at a different laboratory/university. Control bars from the same inventory installed in the bridge tested the same year the GFRP bars were installed during construction. Besides the GFRP tests, concrete surrounding the GFRP bars were also evaluated to observe the environment surrounding the GFRP bars and thus to see how they influenced a certain behavior/failure of the bar. The concrete tests involved carbonation depth, pH, and chlorides content and were performed on portions of the cores that contained the GFRP bars.

RESEARCH SIGNIFICANCE

The significance of this research is to increase the database of field-obtained durability data and to provide more technical information about the durability of GFRP bars. Durability data of GFRP bars embedded in concrete structures that have been in service for a decade or more is very limited. To encourage the construction industry to implement GFRP bars, more detailed and updated durability information needs to be present in design standards and guidelines. Therefore, this study aims to add more information about the durability performance of GFRP bars used as a reinforcement material for structural applications.

SOUTHVIEW AND SIERRITA DE LA CRUZ CREEK BRIDGES

Southview Bridge is located on Carter Creek in Rolla, MO, shown in Fig. 1(a). The original bridge was one-lane and consisted of four box culverts and topped with steel-reinforced concrete deck of a 254 mm (10 in.) thickness. An expansion occurred in 2004 by replacing the existing sidewalk with a new one and adding another lane that consisted of four-box culverts and topped with glass fiber-reinforced concrete deck. The expansion phase involved removing the curb from the existing deck to allow extending the bridge total width from 3.9 to 11.9 m (12.8 to 39 ft). The new resulting width of the bridge is 9.1 m (30 ft).[13] GFRP reinforcement with 19 mm (3/4 in.) diameter was used as a main reinforcement and 13 mm (1/2 in.) diameter was implemented for shrinkage and temperature reinforcement in the deck.[2] Also, 10 mm (3/8 in.) diameter GFRP bars were used as prestressing tendons. Figure 2 shows the cores locations. The bridge is exposed to a range of temperature between –5 and 35°C (22 and 95°F) during the year. Also, it experiences regular wetting, drying, freezing, and thawing cycles. In addition, deicing salt is applied to the bridge deck surface in winter months. The temperature range and precipitation (from 1981 to 2015) are shown in Fig. 3.

The second investigated bridge was Sierrita de la Cruz Creek Bridge and is located north-west of Amarillo, TX. Figure 1(b) shows the Sierrita de la Cruz Bridge. The bridge was severely corroded, so it was considered structurally deficient, therefore a bridge replacement was necessary. This bridge was the first bridge in the State of Texas that imple-

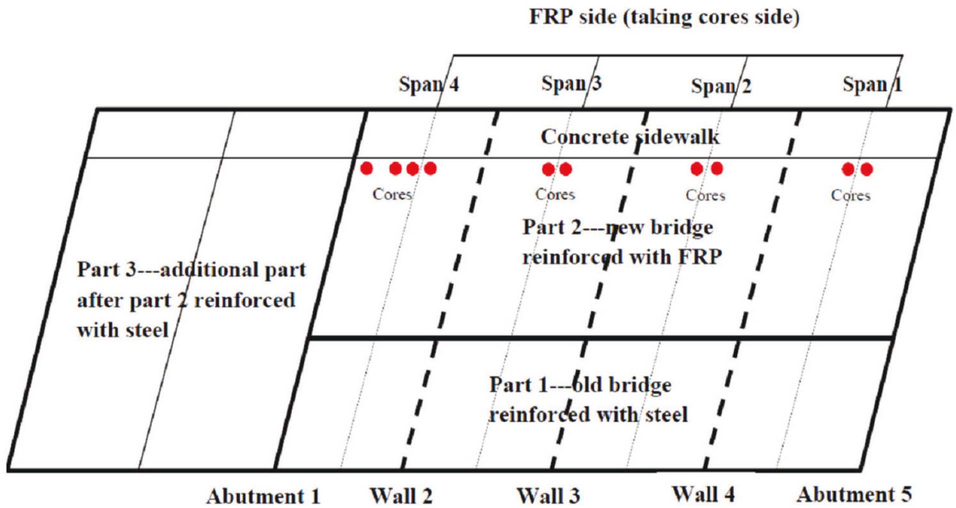

Fig. 2—Core locations of Southview Bridge.

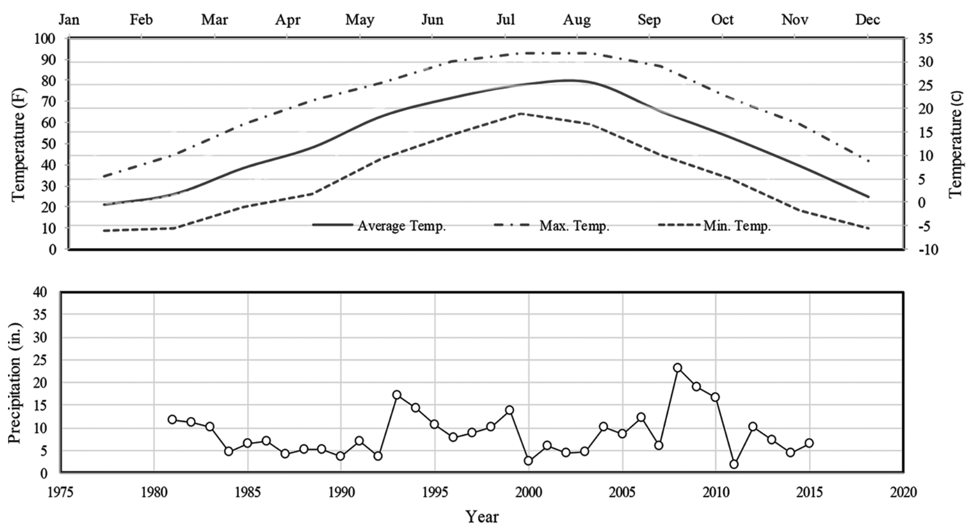

Fig. 3—Temperature range and precipitation of Rolla, MO, from 1980 to 2015.[14,15]

mented GFRP bars. The GFRP reinforcement was used in the deck of the bridge and the construction work took place in 2000. The bridge is 24 m (79 ft) long and 14 m (46 ft) wide. GFRP bars with 16 mm (5/8 in.) and 19.0 mm (3/4 in.) diameter were used in only two spans out of the seven spans total. To assess and monitor the behavior of GFRP bars, witness GFRP bars were implanted during construction at the overhang, midspan, and control joints where they were planned to be extracted at different times of their service life without compromising the structural integrity of the bridge deck.[8] Figure 4 shows the location of the cores. It should also be noted that these locations were seated where de-icing salts tend to concentrate along the guard rail from roadway salt spray. The temperature in Amarillo ranges from –3 to 39°C (26 to 102°F). In addition, the bridge is exposed to frequent wetting, drying, freezing, and thawing cycles. Figure 5 shows the temperature range and precipitation (from 1981 to 2015) of Amarillo, TX.

Sand coating was used in all GFRP bars installed in these bridges to provide a proper bond to surrounding concrete. In addition, the GFRP bars were made of E-glass fibers and vinyl-ester resin.

SAMPLE EXTRACTION, PREPARATION, AND CONDITIONING

Concrete cores of 102 mm (4 in.) diameter with encapsulated GFRP bars were extracted from the bridges in 2015. A total of 10 cores were taken from the deck of Southview Bridge in the following manner: two cores from each of span one, two, and three, and four cores from span four. On the other hand, five cores were extracted from the overhang of Sierrita de la Cruz Bridge. In both bridges, the core holes were filled immediately after the core extraction with a fast-curing durable cementitious grout. The extracted cores were then sent to the laboratories of the collaborated universities. Two cores, CM1 and CM2, from Southview Bridge and one core, CT, from Sierrita de la Cruz Bridge were sent to the laboratory of Missouri University of Science and Technology for examinations. In both bridges, all the extracted GFRP bars were 19 mm (3/4 in.) diameter. Figure 6 shows one core from each bridge and Table 1 shows the GFRP bars' information.

The preparation of a specimen varies from one test to another. Because some of the tests required only a tiny piece of material to study, each core was cut into several slices parallel to bar-length orientation. Next, each slice that

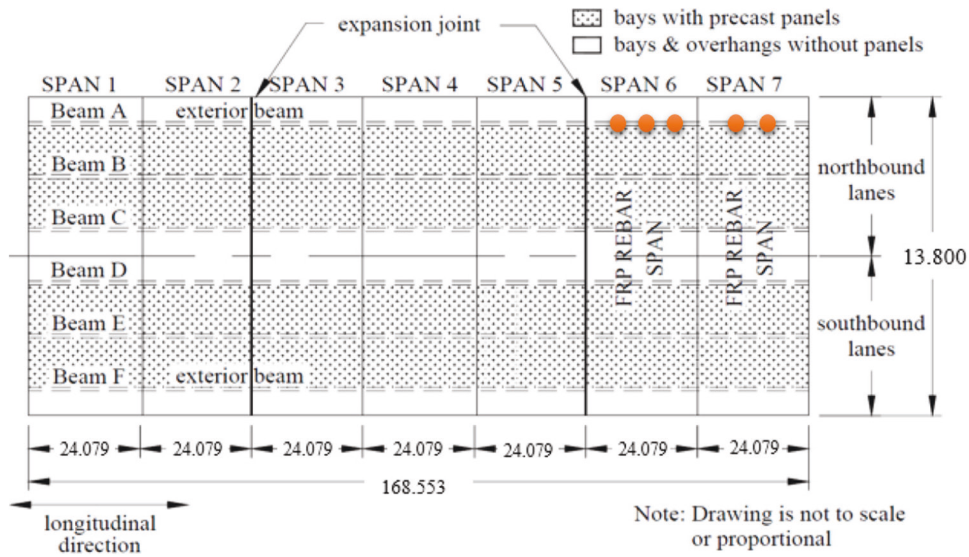

Fig. 4—Cores locations of Serrita de la Cruz Creek Bridge.

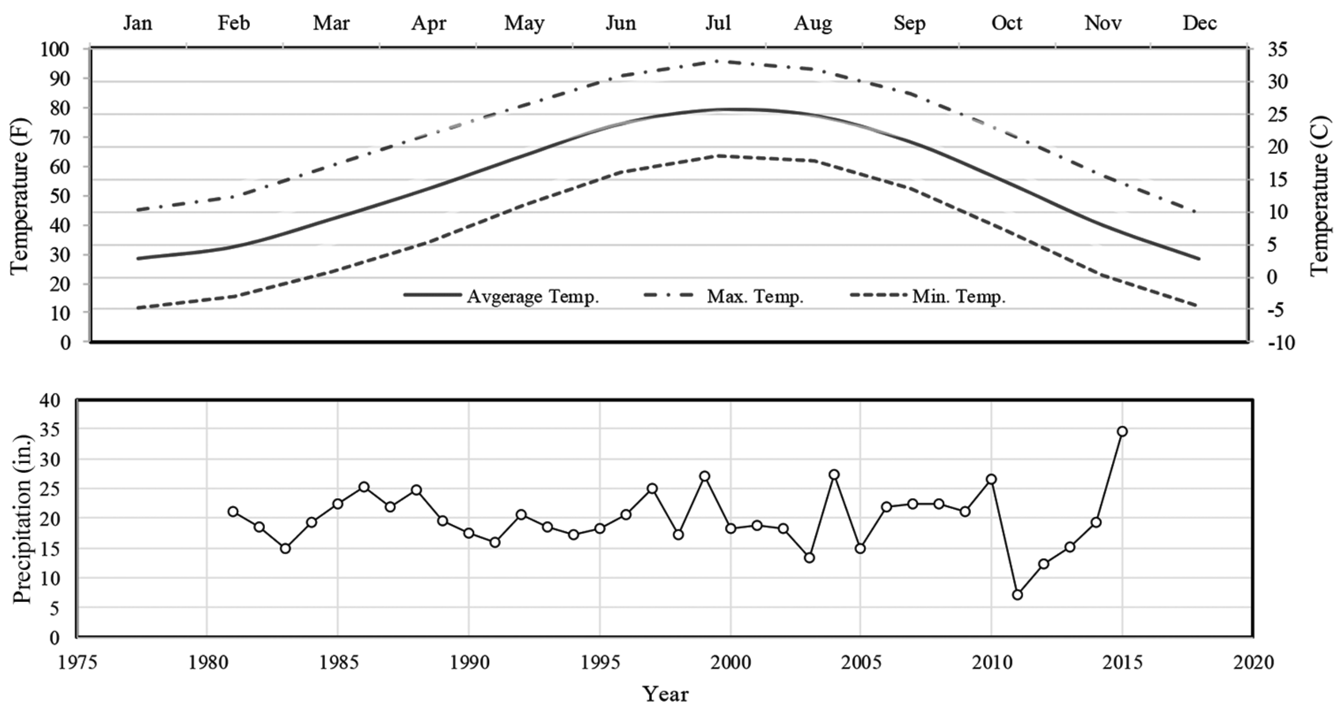

Fig. 5—Temperature range and precipitation of Amarillo, TX, from 1980 to 2015.[14,15]

contained GFRP bar was cut into several slices until what was left was a GFRP bar with a little concrete surrounding it. Some of these samples were kept whole with no concrete removed and some had the concrete stripped from the GFRP bar. It completely depended on the test that was being conducted on that piece. Figure 7 depicts some of the sample's preparations. In SEM and EDS, after cutting the GFRP specimens to a 13 mm (1/2 in.) thick piece, the surface of GFRP specimens was smoothed using different levels of sandpaper (for example, 180, 300, 600, 800, and 1200 grit) and was then polished for an extra surface smoothness. After that, an oven at 50°C (122°F) was used to keep the specimens dry. Also, because GFRP is nonconductive material, a gold coating was used on the specimens to make them conducive and sensitive to electrons that would be exerted from the SEM apparatus. For FTIR testing, very

Table 1—Properties of GFRP bars used in bridges

Bridge location	Bridge	Core ID	GFRP reinforcement number and diameter	Fiber type	Resin type	Bridge core location
MO	South-view	CM1	No. 6 (0.75 in.) (19 mm)	E-glass	Vinyl ester	Midspan
		CM2	No. 6 (0.75 in.) (19 mm)	E-glass	Vinyl ester	Midspan
TX	Sierrita de la Cruz Creek	CT	No. 6 (0.75 in.) (19 mm)	E-glass	Vinyl ester	Bridge overhang

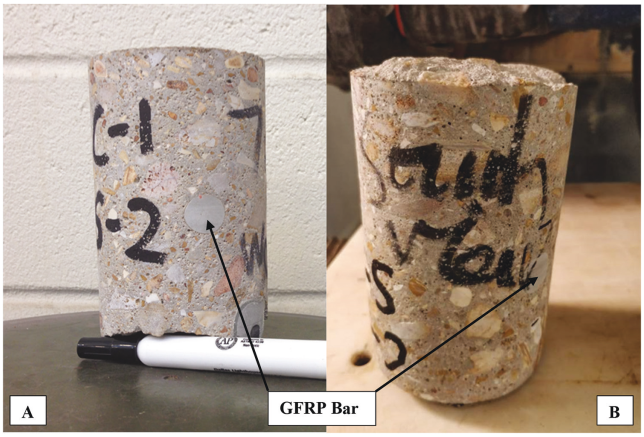

Fig. 6—Cores from: (a) Southview Bridge, Rolla, MO; and (b) Sierrita de la Cruz Creek Bridge, Amarillo, TX.

tiny chunks, of approximately 5 mg (0.0002 oz.), were cut from the GFRP specimens and were then grinded with KBr to enhance the level of spectrum detection.[12] The mixture was then compressed to make a thin film to be used later in the FTIR device. In TA test, small chunks, approximately 15 mg (0.0005 oz.), were taken from the GFRP specimens and were then placed inside an aluminum pan that was later sealed mechanically and situated inside the differential scanning calorimetry (DSC) device for TA testing. Preparations for the fiber content test are mentioned in its section. Specimens were conditioned first by keeping them in a hermetically sealed environment and second, for 2 days before testing, by exposing them to 40°C (104°F) temperature to maintain a controlled (standardized) environment.

CONCRETE EXAMINATION

To have a complete assessment of the GFRP bars, the surrounding concrete was also examined. The tests used for concrete in this study were, pH, chloride content, and carbonation depth.

pH test

The test of pH quantifies alkalinity level in concrete. In portland cement-based concrete, pH of concrete ranges between 11 and 12.[16] The value of pH on concrete surface falls because of the reaction of the carbon dioxide from the atmosphere and alkalis in the concrete. To measure pH level, there are two methods: Grubb procedure and ASTM F710.[17] The Grubb procedure was applied in this study where powder, approximately 2 g, was taken from the surface of concrete core and then mixed with distilled water in a 1:1 mass ratio. After mixing the distilled water with the concrete powder, a 60-second set-time was given to let the mixture become a thick muddy-like solution. Next, pH strips were used to determine the alkalinity of the solution. The test was conducted three times per core. For Southview Bridge, pH test results were 13, 12.9, and 13.2, which were considered high for concrete of this age. It could be due to the ingress of hydroxide ion from exposing the concrete to an alkaline-based environment. In Sierrita de la Cruz Creek Bridge, the pH results were 11, 11.1, and 11.1, which satisfied the expectation for that type of concrete and age.

Fig. 7—Preparations of specimens: (a) air drying; (b) oven drying; (c) sonic bath; and (d) drilling to get concrete powder.

Figure 8 shows concrete pH measurements of one of the specimens. Table 2 shows the pH test results.

Carbonation depth

Concrete cover provides a protective layer to steel reinforcement against corrosion, but the cover is normally exposed to the atmosphere. Carbonation takes place when carbon dioxide in the atmosphere reacts with alkalis of concrete.[2] It lowers concrete pH from approximately 12 to 9 or less, which makes the concrete layer relatively acidic. It has been proposed that corrosion happens when the carbonation depth is equal to the concrete depth.[18] There are several factors that influence the carbonation rate including: the mixture design, cement composition, concrete porosity, ambient temperature, CO_2 concentration, relative humidity, and existing cracks.[19] To conduct the test, RILEM CPC-18[20] was used where the depth of carbonation was determined by spraying a 1% of phenolphthalein-70% ethyl alcohol solution to a fresh cut of the concrete surface. The solution is colorless if the ambient atmosphere is acidic. However, once it hits an alkaline environment where the pH is approximately 9 or higher, it will turn purple. The results of the carbonation depth indicated that, in Southview Bridge, there was no carbonation depth found, but in Sierrita de la Cruz Creek Bridge, a carbonation depth of 13 mm (1/2 in.) was observed. Even though the pH results of Sierrita de la Cruz Creek Bridge were not low enough to induce carbonation attack, carbonation was detected. It is most likely because the collected powder was from an unaffected area; therefore,

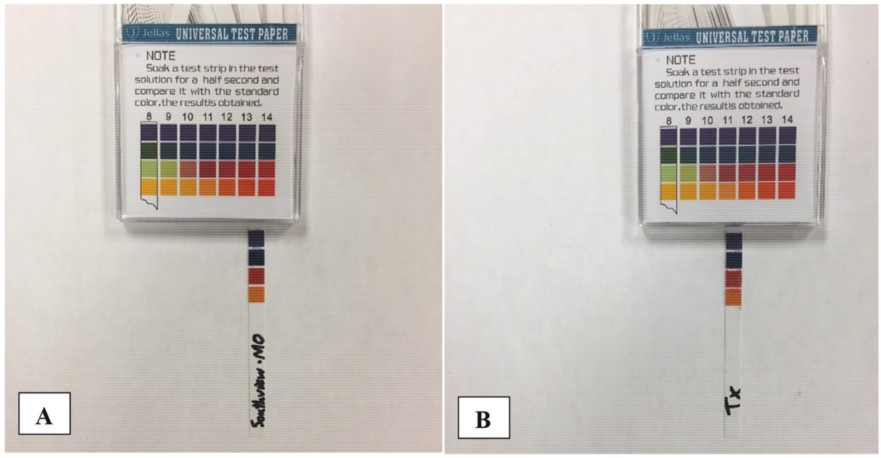

Fig. 8—pH test measurements: (a) Southview Bridge; and (b) Sierrita de la Cruz Creek Bridge.

Table 2—Concrete test results

Bridge	Cores ID	pH	Carbonation depth, mm (in.)	Chloride content, %
Southview	CM1	13	0 (0)	0.0033
	CM2	13	0 (0)	0.0094
Sierrita de la Cruz Creek	CT	11-12	13 (0.5)	0.0031

the resulting pH was relatively high for concrete of this age. Figure 9 and Table 2 show the carbonation depth results.

Chloride content

Chloride testing is crucial for concrete as chloride is considered one of the main causes of reinforcement corrosion.[19] Chlorides attack the light oxide film that forms over the reinforcement due to the alkaline-based environment of concrete and therefore result in corrosion of reinforcement. There are two techniques to determine chloride content, namely acid-soluble and water-soluble techniques. Acid-soluble analysis is used to determine the total content of chlorides including both chlorides trapped inside the concrete voids and the ones that damage the oxide film of reinforcement.[21] The water-soluble method provides only the chlorides content that deteriorated the oxide film. In this study, the acid-soluble approach was used to determine chlorides content. To implement this approach, rapid chlorides testing (RCT) equipment was implemented. One and a half grams (0.05 oz.) of concrete powder were taken from the cores at three different locations. They were then put into small coned-shaped containers and pressed in using a short plastic wire. After that, the powder was emptied in chloride-agent vails and left out to react with the agent. After 24 hours, the calibration step took place where different concentrations of chlorides were used. A voltage reading in mV was measured from each concentration and then used to draw a chlorides content curve. After that, an mV reading was taken from each vail tested and then compared to the curve to find the chlorides content concentrations. The degree of significance of these resulted concentrations was then compared to an associated chart to see if the content is high, low, or negligible. Per Broomfield, the chlorides content can be neglected as long as the content is less than 0.03%, content is considered low when it is between 0.03 and 0.06%, is considered moderate if between 0.06 and 0.14%, and is high if over 0.14%.[22] In both bridges, it was found that the chlorides content was within the negligible rates, as every vial had less than 0.03%. Table 2 shows the chlorides content results.

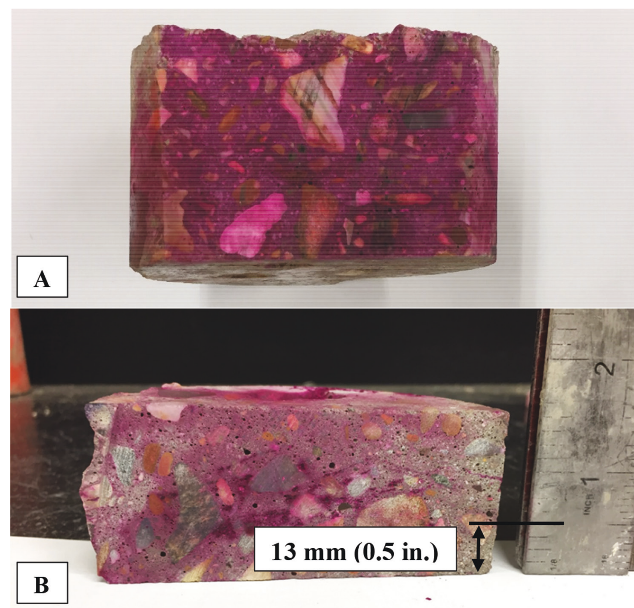

Fig. 9—Carbonation depth test: (a) Southview Bridge; and (b) Sierrita de la Cruz Creek Bridge.

GFRP EXAMINATION

Five tests were conducted on the GFRP bars to assess their durability performance. The tests were as follows: SEM, FTIR, EDS, TA, and fiber content.

Scanning electron microscopy (SEM)

To observe any existence of microstructural degradations, SEM testing was carried out. Two 25.4 x 25.4 x 6.35 mm (1 x 1 x 0.25 in.) slices were taken from Southview Bridge core and one 25.4 x 25.4 x 6.35 mm (1 x 1 x 0.25 in.) slice was taken from Sierrita de la Cruz Creek Bridge core. Before using the SEM test, the samples were prepared following the procedure mentioned in the "Sample Extraction, Preparation, and Conditioning" section of this paper. Different

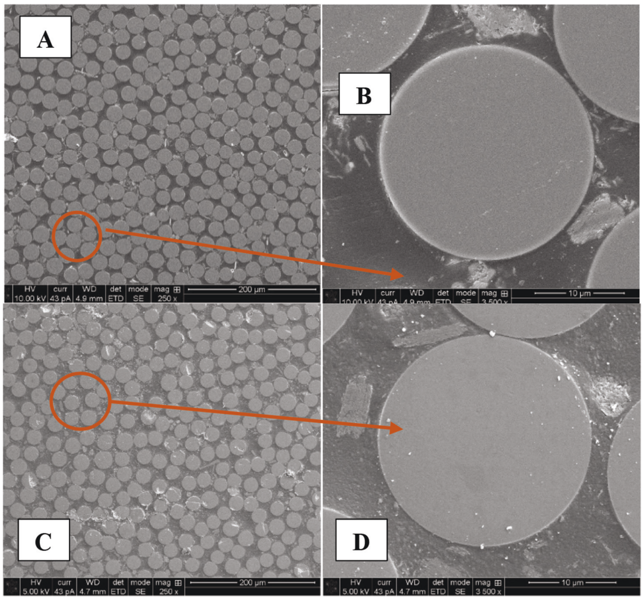

Fig. 10—SEM images of undamaged specimens: (a) Sierrita de la Cruz at 250× magnification; (b) Sierrita de la Cruz at 3500× magnification; (c) Southview at 250× magnification; and (d) Southview at 3500× magnification.

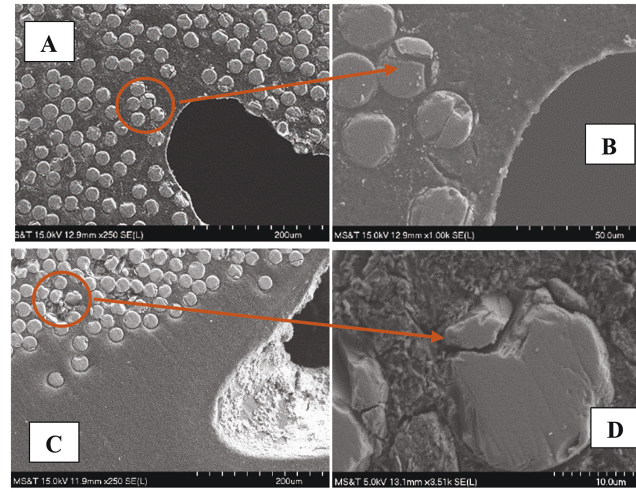

Fig. 11—SEM images of cracked specimens: (a) Southview at 250× magnification; (b) Southview at 3500× magnification; (c) Sierrita de la Cruz at 250× magnification; and (d) Southview at 3500× magnification.

magnification grades were employed to examine not only the GFRP bars but also the interfacial transition zone (ITZ) between the concrete and GFRP bar. The main reason for the scanning was to see if there was any microstructural degradation in the GFRP bars and areas in the vicinity of concrete in terms of fiber and resin morphological changes and/or cracks. Images were taken from different locations in each specimen to give a comprehensive view of the specimen. The SEM images depicted that there were no microstructural degradations in fibers, resin, and the neighboring areas of the GFRP bars. Fibers were not damaged and no loss in the cross-sectional area of fiber took place. Furthermore, there was no bond loss between the fibers and resin, and there were no gaps at GFRP-concrete interface (Interfacial Transition Zone). Figure 10 shows representation of the scanned images. It is important to note that, in SEM analysis, sample preparation is very crucial and has a significant impact on the results, as lack of proper preparation may give false results. For example, exposing a specimen to high temperatures (over 55°C [130°F]) at the conditioning stage may result in gaps at the interfacial transition zone of GFRP and concrete. Furthermore, uncontrolled pressure at sand papering stage may damage cross section of fiber and leave dents in the matrix. Figure 11 shows an example of a damaged specimen. One good indication that the damage was due to preparation was that there were cracks all over the specimens and they were distributed evenly.

Energy dispersive X-ray spectroscopy (EDS)

This test was used to determine site specific elemental concentrations. Concrete pore solution is highly alkaline, as it has Na^+, K^+, and $OH^–$. It is known that Si of fiber dissolves in high alkaline.[12] In addition to alkalis coming from concrete pore water solution, there are alkalis that are a constituent of the fiber itself. When there is an abundant of $OH^–$, the pH rises, and leaching process might occur. Leaching is the process of extracting alkalis out of fiber resulting in affecting Si network of fiber and thus forming SiOH product. The produced SiOH is a gel-type product that is less dense than the original Si network and has the ability to transform water and alkalis.[23,24] In addition to the investigation of main elements of fiber and resin matrix, EDS was implemented to check for alkalis attack. EDS cannot detect elements with atomic number lower than Na; therefore ,OH cannot be detected, but they might defuse together for neutrality.[12] That said, appearance of Na, Ca, and/or K in the resin matrix can be a sign of alkalis migration from concrete pore solution to the glass fibers. A 10 to 20 KeV electron beam was applied on the same specimens used for SEM analyses. In EDS testing, the results were shown as plot where its y-axis shows the number of X-rays sent by the apparatus and its x-axis shows the level of energy of those counts.

In both bridges, the fibers' chemical composition showed no signs of zirconium (Zr), therefore it confirms that the GFRP bars were not alkaline-resistant (AR).[24] Additionally, the main elements of fiber including Al, Ca, Si, Na, and O were found. Besides these elements, Mg was found too in both bridges and that indicates the GFRP bars were not ECR-glass.[8] Elements such as Au and Pd were also detected in the resin and fiber, which is an indication for coating (gold sputtering) to make the surface of GFRP bar from non-conductive to semi-conductive, so the SEM and EDS apparatus can work. For the resin matrix, the main element, C, was found in both bridges. In Sierrita de la Cruz Creek Bridge, alkaline elements such as Na, Mg, Al, and Ca were found in the resin. In addition, Si was found too. The appearance of alkaline and Si in resin are not welcomed, as their existence can be an indication for alkali-hydrolysis attack and a leaching problem.[24] However, in Sierrita de la Cruz Bridge, these elements were found in the control bars too, therefore there is a significant chance that these observed elements were part of filler. Figure 12 shows the EDS results

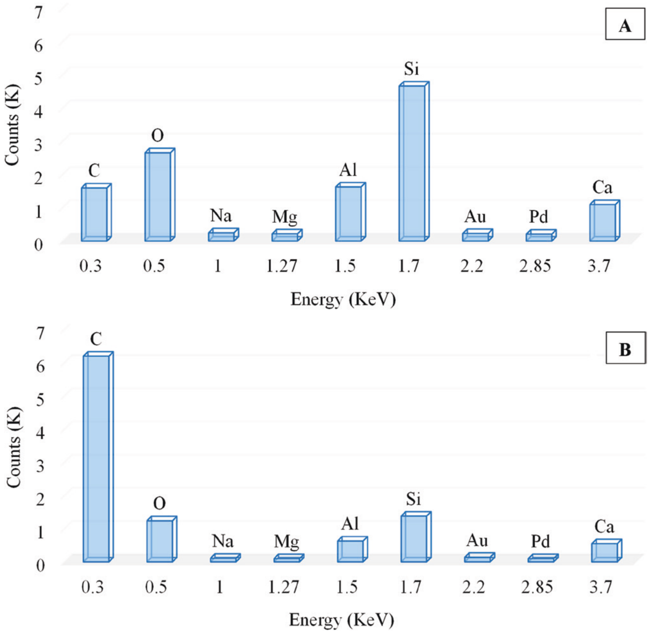

Fig. 12— EDS analysis of Sierrita de la Cruz Creek Bridge: (a) fiber; and (b) resin.

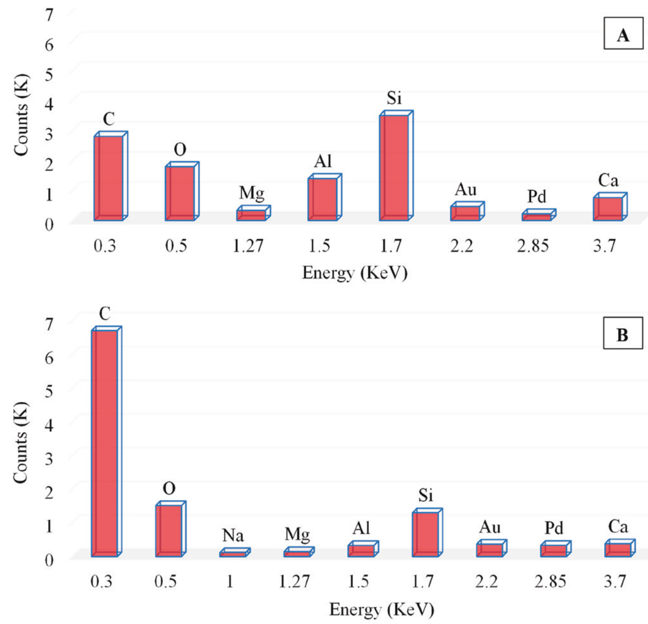

Fig. 13—EDS analysis of Southview Bridge: (a) fiber; and (b) resin.

of the fiber and resin of Sierrita de la Cruz Creek Bridge. Additionally, and to support this claim, the pH of the bridge was not even high enough to induce alkali-hydrolysis attack. Furthermore, carbonation depth was observed, and thus, these signs moderately confirm that these elements were part of the filler of GFRP bar. In Southview bridge, alkaline elements and Si were found in the resin as well. The difference this time from Sierrita de la Cruz Bridge is that the tested pH of Southview Bridge was high, and carbonation was not observed. Additionally, Na was observed only in the resin. Thus, the appearance of Na and Si in the resin can clearly indicate to an alkaline-hydrolysis attack and leaching problem. To contrast, Si sometimes is used as part of a filler in resin. Bank et al.[25] stated that the existence of Al, Si, and PO43$^-$ in the resin matrix is a sign of a filler. These two elements, Al and Si, and one compound, PO43$^-$, form a filler called alumino-silicate phosphate (ASP). Each of Al, and Si were seen in the resin, but there were no signs for the PO43$^-$. Therefore, to make sure these alkalis and Si from alkalis attack, FTIR test was carried out to observe the level of OH in the resin matrix. EDS results of Southview Bridge are shown in Fig. 13.

Fourier transform infrared spectroscopy (FTIR)

Glass fiber is weak against alkaline and acid environment. In fact, glass fibers do not do well if the alkaline concentration is 2 mol/L or more. Hydroxyl group (OH) is very active in alkaline environments and can induce alkali-hydrolysis attack on resin. Cross-links in thermoset resins, such as vinyl-ester, are the weakest connection in the resin structure and are the ones susceptible to damage if alkali- hydrolysis attack takes place.[12] When attack occurs, resin degrades and loses its ability to transfer stress properly to the fibers and thus GFRP system fail. Because alkalis were detected in Southview Bridge, and the pH test was high enough to suspect alkali-hydrolysis attack, FTIR was carried out. In addition, FTIR was conducted to Sierrita de la Cruz Creek Bridge only for checking, as the pH levels were low enough to induce carbonation attack rather than being high enough to induce alkali-hydrolysis. FTIR test was applied to monitor the changes in the amount of OH. If alkali-hydrolysis occurs, new OH are generated and as a result infrared band of OH increases and becomes higher than the normal infrared band of OH.[26] Additionally, because EDS only works with elements having an atomic number equal to or higher than Na, and OH has an atomic number smaller than that of Na, FTIR was used to check for OH level. The normal range of the hydroxyl group (OH) is between 3000 and 3600 cm^{-1}.[25] To conduct the test, little fractures approximately 2 g from the GFRP bar were taken and were then ground with bromide potassium (KBr). Halide, such as, KBr does not show any signs of absorption spectrum in IR because of its 100% transmission window; thus, it provides a more reliable FTIR test result. Then the ground powder was compressed to form a light transparent sheet that was placed later in the FTIR device to obtain the measurement. The output reading was in terms of plot between the intensity and wavenumber that presents the inverse of the wavelength.

In the Southview Bridge, OH was found to be a little over 3700 cm^{-1}, which now clearly indicates that alkali-hydrolysis and leaching were taking place. Regarding Sierrita de la Cruz Creek Bridge, OH was found to be approximately 3600 cm^{-1}, which met the normal range of OH group. It was anticipated to be on the high side, because even though carbonation was found when its concrete was tested, the pH test was not lower than 11. Representative results are shown in Fig. 14.

Glass transition temperature (TA)

Glass transition temperature can be defined as the temperature region where the resin physical characteristics change from hard to soft material.[27] The importance of TA comes

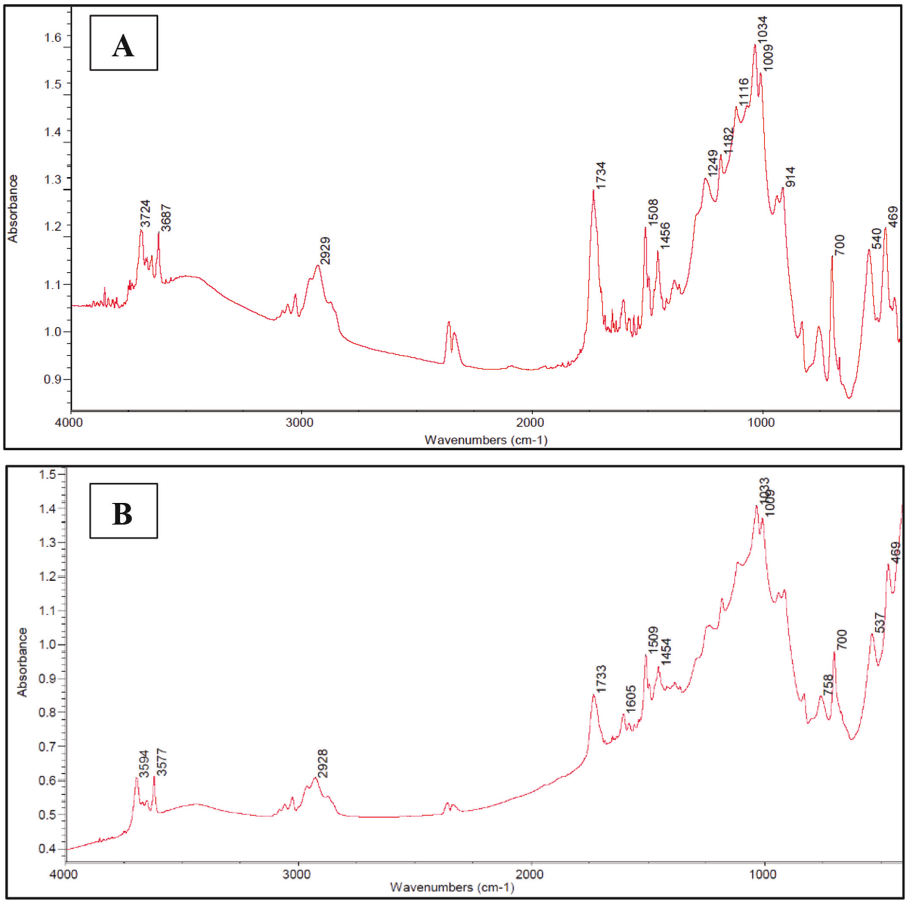

Fig. 14—FTIR analysis of: (a) Southview Bridge; and (b) Sierrita de la Cruz Creek Bridge.

from its indication for material thermal stability, polymer structure, and mechanical properties. In composites, there are two glass transition temperatures, one for fiber and the other for resin. Because the TA of the fiber is substantially higher than that of the resin matrix, only the resin is of main concern during the investigation of TA. Surrounding environment of composites has significant impact on TA, as it can substantially reduce it.[28] To contrast, wet environment where OH is abundant can be very deleterious on TA due to plastification. The OH group is the reason for plastification, as it can induce alkali-hydrolysis attack on resin. This attack destroys the Van der Waals bonds of resin, and thus plastification takes place.[12] In addition, Micelli and Nanni[9] stated that there are solid signs that the deterioration rate of polymer composites subjected to fluid environment is highly related to the rate of fluid sorption, which is strongly affected by elevated temperatures.

Frequent exposure of composites to high temperature can lead to what is called thermal softening (reduction in TA).[28] Thermal softening results in reduction of not only elastic modulus, but also fiber strength. The matrix properties of polymeric composites are considerably affected by temperature increase rather than fiber properties. It was found that the axial mechanical properties (strength and modulus) of fibers, situated on 0° degree to the applied load, were not affected by the increase in temperature. However, those situated perpendicular to the other fibers had mechanical properties that were significantly affected by the temperature increase. In addition, it was found that resin (vinyl-ester) of composites can resist high temperature up to 40°C, however the exposure should not be for a long term.[28]

Another important aspect in TA is level of curing. In 2015, Kumar et al.[29] discussed in their work the effect of curing ratio on TA, as it was found that composites with optimum cure ratio were expected to have a higher TA than those with lower cure ratio. Kumar et al. also defined the optimum curing ratio as the level of curing required in a material to achieve its mechanical, thermal, and durability properties for a certain application.[29] In addition, ACI 318-08 permitted any composite product as long as it is 100% cured.[31] In contrast, CSA S807-10 permitted only GFRP bars with curing ratio of at least 95%.[32] Glass transition temperature tests can be performed using either dynamic mechanical analysis (DMA) or DSC. In this study, DSC was used to evaluate the TA temperature of both bridges. ASTM E1640 was used as a standard.[33] The specimens were cut into very little chunks containing approximately 10 mg (0.0004 oz.) each of the GFRP bars. Next, they were placed inside a TA instrument for TA measurement where the temperature ramp was 5°C (41°F) per minute. The temperature was elevated up to 200°C (392°F) from room temperature and then cooled back down using the same ramp of 5°C (41°F) per minute. All the results showed a significant reduction in TA temperature of approximately 25°C (77°F) from the original TA for vinyl-ester resin which is approximately 100°C. This reduction could be due to the increase in OH. Regarding the Sierrita de la Cruz Creek Bridge, vinyl-ester was also used for the resin matrix of the bar. TA results for this bridge were

Table 3—Test results of glass transition temperature (TA)

Southview Bridge	CM1	Number of samples	3
		Average temperature, °C (°F)	72 (162)
		Coefficient of variation, %	6.94
	CM2	Number of samples	3
		Average temperature, °C (°F)	75 (167)
		Coefficient of variation, %	3.32
Sierrita de la Cruz Creek Bridge	TA-Control Bars	Number of samples	3
		Average temperature, °C (°F)	81 (178)
		Coefficient of variation, %	16.9
	CT	Number of samples	3
		Average temperature, °C (°F)	74 (165)
		Coefficient of variation, %	9.19

Note: CM1 and CM2 are cores from Southview Bridge tested in for this study at Missouri S&T; TA is control bars from Sierrita de la Cruz Creek Bridge; and CT is Cores from Sierrita de la Cruz Creek Bridge tested at Missouri S&T.

Table 4—Results of fiber content test

Southview Bridge	CM1	Number of samples	3
		Fiber content, %	69.9
		Resin content, %	30.1
		Coefficient of variation, %	4.32
	CM2	Number of samples	3
		Fiber content, %	71.8
		Resin content, %	28.2
		Coefficient of variation, %	3.34
Sierrita de la Cruz Creek Bridge	α – Control Bars	Number of samples	2
		Fiber content, %	80.5
		Resin content, %	19.5
		Coefficient of variation, %	2.2
	CT	Number of samples	3
		Fiber content, %	81.6
		Resin content, %	18.4
		Coefficient of variation, %	3.07

Note: CM 1 and CM2 are cores from Southview Bridge tested in for this study; α is control bars control cores from Sierrita de la Cruz Creek Bridge; and CT is cores from Sierrita de la Cruz Creek Bridge tested at Missouri S&T.

approximately 70°C (176°F), which is 10°C (212°F) less than the TA conducted on control bars. However, the FTIR results exhibited that OH levels were within normal range[34] (3000 to 3600 cm^{-1}), and the EDS test did not show any change in the chemical properties of either the fiber or the resin. The hygrothermal environment that surrounded the GFRP bars could be the reason behind this reduction of the TA magnitude. Results are shown in Table 3.

Fiber content test

Fiber content is directly related to the mechanical performance of GFRP bars.[30] This test can be used only with polymer-matrixes and with fibers where a high-temperature exposure does not affect them.[35] The fiber content test, also called the Burn-off, is designed to determine the ignition loss of cured resin. ASTM D2584 was applied to conduct the experiment.[36] The specimens were cut into little pieces of approximately 5 g (0.18 oz) each and then weighed. The specimens were then burnt in a muffle furnace at 575°C (1010°F) until the resin disappeared. After that, the burnt specimens were then weighed again. The percentage weight difference yields the fiber content. The results are shown in Table 4. The results of Southview Bridge showed a fiber content percentage of 70% and 72% for the CM1 and CM2 specimens, respectively. Even though, there were no control bars, the results were in match with fiber content limit stated in ASTM D7957 standard for GFRP bars in concrete.[37] Despite the fact that there were signs for leaching in Southview Bridge specimens, there were no signs for a loss in the fiber content. It is most likely because the leaching process was at its early stage, as the Si levels in resin, from the EDS test, were not high. For Sierrita de la Cruz Creek Bridge, the results showed a fiber content of 82%, which was close to tests conducted on control bars. This result was expected in that bridge, as there were no signs for any chemical changes. Therefore, it can be concluded that there was no loss in the fiber content of both bridges.

CONCLUSIONS AND RECOMMENDATIONS

Glass fiber reinforcement is a promising solution to replace steel reinforcement and hence avoid corrosion problems. However, GFRP has not been studied thoroughly especially when it comes to durability performance under field conditions. Thus, in this study, durability of GFRP bars taken from two bridges in the United States after over 11 and 15 years of service were evaluated. The experiments were performed on two bridges: Southview Bridge in the state of Missouri and Sierrita de la Cruz Creek Bridge in the state of Texas. The following observations and recommendations can be drawn from these tests:

1. pH of concrete: For Southview Bridge, the pH level was 13 which is high for such a concrete (for example, for most bridge decks in the United States, a 6000 psi cement-based reinforced concrete). High pH indicates high OH and increases the chance for resin and fiber attacks. For Sierrita de la Cruz Creek Bridge, it was 11 to 12, which is within the normal range for such concrete.

2. Carbonation depth: Carbonation is something undesirable in reinforced concrete (RC) structures, as it can lead to corrosion issues. For Southview Bridge, the tests were conducted on different parts of the core and showed no significant depth of carbonation. For the Sierrita de la Cruz Creek Bridge, carbonation was present with depth of 13 mm (0.5 in.) from the weather-exposed surface. It is believed that it took place due to the alkaline environment surrounding the concrete.

3. Chloride content: For both bridges, the test results showed that chlorides were within the negligible limits (less than 0.03%).

4. Scanning electron microscopy (SEM): For both bridges, no microstructural degradation was found in the GFRP bars where the scanning was conducted. All fibers were complete, and the resin was properly and fully bonded to the fibers. Also, there was no loss in the cross-sectional area of fibers. In addition, the interfacial transition zone (ITZ) between the concrete and the glass fiber matrix was fully intact. However, cracks did appear in one specimen, but are believed to be due to the improper preparation of the sample.

5. Energy dispersive X-ray spectroscopy (EDS): This test was conducted to observe the chemical elemental changes in the bar. In both bridges, the main elements of fibers were found to include Al, Ca, and Si. In addition, the main element of resin, C, was found too. No Zr was found in both bridges which confirms those bars were not alkali resistant. Also, it indicates that the bars tested were vinyl ester-based bars as per their manufacturer claim. In both bridges, Mg was found and that confirms that there were not ECR-glass fibers. No signs for chemical attack were found in Sierrita de la Cruz Creek Bridge, even though alkaline was found not only in fibers but also in resin. It was believed those alkalis in resin were due to filler of the GFRP. On the other hand, the EDS results of Southview Bridge showed significant signs for alkali-hydrolysis attack as Na was found only in the resin. Also, Si was detected in the tested resin as well which it can be taken as a clear sign for leaching.

6. Fourier transform infrared spectroscopy (FTIR): In Southview Bridge, the results showed that the spectra of the OH group was high (slightly over 3700 cm^{-1}) which confirms that the alkalis elements found in EDS test of resin were from alkali-hydrolysis attack. For Sierrita de la Cruz Creek Bridge, the results were within the normal range at approximately 3600 cm^{-1}. Also, it was expected to be normal as the pH test was not high.

7. Glass transition temperature (TA): Glass transition temperature of both bridges were less than control bars and the ASTM standard of GFRP bars in concrete. For Sierrita de la Cruz Creek Bridge, TA results were about 70°C (158°F) and were less than the controlled ones that scored 80°C (176°F). This reduction is possibly due to the hygrothermal environment that surrounds the bridge. For the Southview Bridge, there were no control bars, but since vinyl-ester was used as a resin in this bridge, the results were instead compared to the ASTM E1640 standard that states a TA of 100°C (212°F) for such a resin. The TA for the tested specimens was found to be approximately 75°C (167°F), much lower than the ASTM standard. This significant reduction is due to alkali-hydrolysis attack and the moderately high temperatures that the bridge has been exposed to.

8. Fiber content: For both bridges, the results agreed with the fiber mass content limit mentioned in ASTM D7957 for quality control and certification. It was expected to not see any fiber content issues with Sierrita de la Cruz Creek Bridge, as no indications for chemical changes were detected. However, for Southview Bridge, it was expected to see fiber content changes, but apparently there were no changes due to the early stage of the leaching attack.

Sample size presented itself as a critical limitation in this study. Even though all the required tests were properly conducted, the number of specimens needed to affirm certain behavior could not be achieved. The conclusions determined in this study cannot be generalized due to the limited sample size of some of the tests but lays the foundation and framework to collect and develop durability data sets. To increase the current durability data reliability, more bridges should be considered for this kind of research in the future to improve durability-related requirements in the design codes and standards.

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REFERENCES

1. Mufti, A.; Onofrei, M.; Benmokrane, B.; and Banthia, N., "Report on the studies of GFRP durability in concrete from field demonstration structures," *Proceedings of the 3rd International Conference on Composites in Construction - CCC 2005*, May 2014, 2005, pp. 11-13.

2. Wang, W., "Durability Behavior of Fiber Reinforced Polymer and Steel Reinforced Polymer for Infrastructure Applications." Missouri University of Science and Technology, Rolla, MO, 2017.

3. Achillides, Z., and Pilakoutas, K., "Bond Behavior of FRP Bars Under Direct Pullout Conditions," *Journal of Composites for Construction*, ASCE, V. 8, Apr. 2004, pp. 173-181. doi: 10.1061/(ASCE)1090-0268(2004)8:2(173)

4. El-Salakawy, E., and Benmokrane, B., "Concrete Bridge Barriers Reinforced with Glass Fiber-Reinforced Polymer Composite Bars," *ACI Structural Journal*, V. 100, No. 6, Nov.-Dec. 2003, pp. 815-824.

5. Ahmed, E. A.; Benmokrane, B.; and Sansfaçon, M., "Case Study: Design, Construction, and Performance of the La Chancelière Parking Garage's Concrete Flat Slabs Reinforced with GFRP Bars," *Journal of Composites for Construction*, ASCE, V. 21, No. 1, 2017, p. 05016001. doi: 10.1061/(ASCE)CC.1943-5614.0000656

6. Mohamed, H. M., and Benmokrane, B., "Design and Performance of Reinforced Concrete Water Chlorination Tank Totally Reinforced with GFRP Bars: Case Study," *Journal of Composites for Construction*, ASCE, V. 18, No. 1, 2014, p. 05013001. doi: 10.1061/(ASCE)CC.1943-5614.0000429

7. Manalo, A.; Benmokrane, B.; and Park, K.; and Lutze, D.,"Recent Developments on FRP Bars as Internal Reinforcement in Concrete Structures," *Concrete in Australia*, V. 40, 2014, pp. 46-56.

8. Gooranorimi, O.; Bradberry, T.; Dauer, E.; Myers, J.; and Nanni, A., "FRP Reinforcement for Concrete: Performance Assessment and New Construction," Vol 1, 2016.

9. Micelli, F., and Nanni, A., "Durability of FRP rods for concrete structures," *Construction and Building Materials*, V. 18, No. 7, 2004, pp. 491-503. doi: 10.1016/j.conbuildmat.2004.04.012

10. Porter, M., and Barnes, B., "Accelerated Durability of FRP Reinforcement for Concrete Structures," 1st International Conference on Durability of Fiber Reinforced Polymer for Construction, 1998, pp. 191-202.

11. Nkurunziza, G.; Benmokrane, B.; Debaiky, A.; and Masmoudi, M., "Effect of Creep and Environment on Long-Term Tensile Properties of Glass FRP Reinforcing Bars," 4th International Conference on Advanced Composite Materials in Bridges and Structures, Calgary, AB, Canada, 2004.

12. Mufti, A.; Onofrei, M.; Benmokrane, B.; Banthia, N.; Boulfiza, M.; Newhook, J.; Bakht, B.; Tadros, G.; and Brett, P., "Durability of GFRP Reinforced Concrete in Field Structures." Proceedings of the 7th International Symposium on Fiber Reinforced Polymer Reinforcement for Concrete Structures - FRPRCS-7, 2007, pp. 889-895.

13. Fico, R.; Galati, N.; Prota, A.; and Nanni, A, "Southview Bridge Rehabilitation in Rolla, Missouri," 2006, 194 pp.

14. NCDC, "National Climatic Data Center," Available at: http://www.ncdc.noaa.gov.

15. NWSF, "National Weather Service Forecast," Available at: http://www.weather.gov.

16. Grubb, J.; Limaye, H.; and Kakade, A., "Testing pH of Concrete: Need for a Standard Procedure," *Concrete International*, V. 29, No. 4, Apr. 2007, pp. 78-83.

17. ASTM F710-08, "Standard Practice for Preparing Concrete Floors to Receive Resilient Flooring," ASTM International, West Conshocken, PA, 2008, 6 pp.

18. Nanni, A.; De Luca, A.; and Zadeh, H., *Reinforced Concrete with FRP Bars*, CRC Press, Boca Raton, FL, 2014, 406 pp.

19. Sagues, A, "Carbonation in Concrete and Effect on Steel Corrosion," Report No. WPI 0510685, University of South Florida, Tampa, FL, 1997, 266 pp.

20. RILEM. "CPC-18 Measurement of Hardened Concrete Carbonation Depth," *Materials and Structures*, V. 21, No. 6, 1988, pp. 453-455. doi: 10.1007/BF02472327

21. Missouri University of Science and Technology, "Self-Consolidating Concrete (SCC) for Infrastructure Elements—Hardened Mechanical Properties and Durability Performance," Report cmr 13-003, Rolla, MO, 2012, 959 pp.

22. Broomfield, J. P., *Corrosion of Steel in Concrete*, second edition, Taylor and Francis, London, UK, 2007, 294 pp.

23. Barkatt, A, "Issues in Predicting Long-Term Environmental Degradation of Fiber-reinforced Plastics.," *Environmental Effects on Engineered Materials*, 2001, pp. 419-458.

24. Kamal, A. S. M., and Boulfiza, M., "Durability of GFRP Rebars in Simulated Concrete Solutions under Accelerated Aging Conditions," *Journal of Composites for Construction*, ASCE, V. 15, No. 4, 2011, pp. 473-481. doi: 10.1061/(ASCE)CC.1943-5614.0000168

25. Bank, L. C.; Puterman, M.; and Katz, A., "The Effect of Material Degradation of Bond Properties of FRP Reinforcing Bars in Concrete," *ACI Materials Journal*, V. 95, No. 3, May-June 1998, pp. 232-243.

26. Robert, M.; Cousin, P.; and Benmokrane, B., "Durability of GFRP Reinforcing Bars Embedded in Moist Concrete," *Journal of Composites for Construction*, ASCE, V. 13, No. 2, 2009, pp. 66-73. doi: 10.1061/(ASCE)1090-0268(2009)13:2(66)

27. Epoxy Technology Inc, "Glass Transition Temperature for Epoxies," http://www.epotek.com, 2012.

28. Nkurunziza, G.; Debaiky, A.; Cousin, P. B. B.; and Benmokrane, B., "Durability of GFRP Bars: A Critical Review of the Literature," *Progress in Structural Engineering and Materials*, V. 7, No. 4, 2005, pp. 194-209. doi: 10.1002/pse.205

29. Kumar, D. S.; Shukla, M. J.; Mahato, K. K.; Rathore, D. K.; Prusty, R. K.; and Ray, B. C., "Effect of Post-Curing on Thermal and Mechanical Behavior of GFRP Composites," 4th National Conference on Processing and Characterization of Materials, 2015.

30. Benmokrane, B.; Nazair, C.; Loranger, M. A. M. A.; and Manalo, A., "Field Durability Study of Vinyl-Ester-Based GFRP Rebars in Concrete Bridge Barriers," *Journal of Bridge Engineering*, ASCE, V. 23, No. 12, 2018, pp. 1-13. doi: 10.1061/(ASCE)BE.1943-5592.0001315

31. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary," American Concrete Institute, Farmington Hills, MI, 2008, 471 pp.

32. Canadian Standards Association (CSA), "Specification for Fibre Reinforced Polymers, (CAN/CSA S807-10)," Rexdale, ON, Canada, 2010, 44 pp.

33. ASTM E1640-13, "Standard Test Method for Assignment of the Glass Transition Temperature by Dynamic Mechanical Analysis," ASTM International, West Conshocken, PA, 2013, 6 pp.

34. Mohrig, J. R.; Hammond, C. N.; and Schatz, P. F., *Techniques in Organic Chemistry*, third edition, W.H. Freeman and Company, 2006, 468 pp.

35. Agarwal, B.; Broutman, L.; and Chandrashekhara, K., *Analysis and Performance of Fiber Composites*, third edition, Wiley, New York, 2015, 576 pp.

36. ASTM D2584-02, "Standard Test Method for Ignition Loss of Glass Strands and Fabrics 1," ASTM International, West Conshocken, PA, 2002, 3 pp.

37. ASTM/D7957M-17, "Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement," ASTM International, West Conshocken, PA, 2017, 5 pp.