

See discussions, stats, and author profiles for this publication at:
<https://www.researchgate.net/publication/241565547>

Durability of GFRP Reinforced Concrete in Field Structures

ARTICLE

CITATIONS

9

READS

226

9 AUTHORS, INCLUDING:



Aftab Mufti

University of Manitoba

152 PUBLICATIONS **808**

CITATIONS

SEE PROFILE



Nemy Banthia

University of British Colum...

248 PUBLICATIONS **2,563**

CITATIONS

SEE PROFILE

Durability of GFRP Reinforced Concrete in Field Structures

by A. Mufti, M. Onofrei, B. Benmokrane, N. Banthia,
M. Boulfiza, J. Newhook, B. Bakht, G. Tadros,
and P. Brett

Synopsis: Recently, ISIS Canada studied the durability of GFRP in concrete in several field structures across Canada. The objective of the study was to provide the engineering community with the results of the performance of GFRP materials that have been exposed to the concrete environment in built structures. Cores of GFRP-reinforced concrete were removed from five field structures. Analytical methods, namely optical microscopy, scanning electron microscopy and energy dispersive x-ray, differential scanning calorimetry and infrared spectroscopy, were used to determine the composition of GFRP after being subjected to the alkaline environment of concrete for five to eight years. Three research teams from four Canadian universities performed microanalyses of the GFRP and surrounding concrete independently. Results indicate that no deterioration of GFRP took place in any of the field structures. No chemical degradation processes occurred within the GFRP due to the alkalinity of the concrete. The overall conclusion of the study is that GFRP is durable in concrete. Also, it was concluded that the CHBDC was conservative in its first edition by not permitting GFRP as primary reinforcement. As a result of the study, the second edition of the CHBDC, currently in the final stages of approval, permits the use of GFRP as primary reinforcement.

Keywords: alkalinity; concrete; durability; field structures; GFRP

1362 Mufti et al.

Dr. Aftab Mufti is Professor of Civil Engineering at the University of Manitoba and President of ISIS Canada, a Network of Centres of Excellence. He is also President of the International Society for Health Monitoring of Intelligent Infrastructures (ISHMII) and Chair of the technical subcommittee of the CHBDC dealing with fibre reinforced structures.

Dr. Maria Onofrei is Adjunct Professor of Civil Engineering at the University of Manitoba. Formerly Senior Research Scientist (Material Science) with Atomic Energy of Canada Ltd, her research expertise is in durability and long-term performance of advanced composite materials for civil engineering construction.

ACI member **Dr. Brahim Benmokrane** is an NSERC Research Chair Professor in FRP Reinforcement for Concrete Structures at Université de Sherbrooke, Quebec, Canada. He is a member in the Canadian Standards Association committees on FRP structural components and FRP reinforcing materials for buildings (S806) and bridges (S6), and ACI Committee 440 FRP Reinforcement.

FACI **Dr. Nemkumar Banthia** is a Professor and Distinguished University Scholar at the University of British Columbia. He chairs ACI Committee 544 on Fiber Reinforced Concrete and is active in many of ACI's other committees. He was awarded the ACI Wason Medal in 1997.

Dr. Mohamed Boulfiza is an Assistant Professor in the Civil Engineering Department of the University of Saskatchewan in Saskatoon, Canada. His research interests include durability mechanics of concrete structures, constitutive modeling of cement-based materials, computational mechanics, and materials testing.

ACI member **Dr. John Newhook** is an Associate Professor of Civil Engineering at Dalhousie University and a member of the ISIS Canada Research Network. He is a member of ACI Committees 440 and 342 and is active in research related to FRP reinforcement and structural health monitoring.

Dr. Baidar Bakht is President of JMBT Structures Research Inc. He was the chair of the Technical Committee of the 1st edition of the Canadian Highway Bridge Design Code and has been active in bridge-related research for the last four decades.

Dr. Gamil Tadros, a Consultant for the ISIS Canada Research Network, is a bridge designer with many important Canadian bridges to his credit. He is a member of the technical subcommittee of the CHBDC dealing with fibre-reinforced structures.

Mr. Peter Brett, with a B.Sc. from University of Birmingham and a M.Eng. from the University of Western Ontario, has extensive bridge experience with the BC Ministry of Transportation, including the Alex Fraser & Lions' Gate Bridges. Until his retirement as Director of Bridge Engineering, he supported research into the application of FRPs in bridge design and rehabilitation.

INTRODUCTION

The review of the ISIS Canada Research Network of Centres of Excellence¹ recommended that since Canada has invested significant resources in building innovative concrete structures with GFRP reinforcement, ISIS Canada should undertake a study of the performance of GFRP using cores taken from structures that have been in service for the last 5 to 8 years. Following this recommendation, ISIS Canada established this research project in 2004, which studied concrete cores with GFRP taken from field structures.

GFRP has been a preferred material for concrete reinforcement in North America because of its economical competitive advantage, its resistance to corrosion, electromagnetic immunity, and high strength to weight ratio and excellent fatigue performance^{2,3}.

Numerous and to some extent contradictory statements concerning the durability of GFRP in an alkaline concrete environment have been published in technical literature. Unlike other FRPs, GFRP are considered to be susceptible to alkalis. Accelerated laboratory tests were generally used to study the durability of GFRP in concrete. In these tests, GFRP specimens were brought into contact with simulated concrete pore water solution with high pH levels and temperature elevated to 80°C. Changes in the mechanical properties after exposure to alkaline solutions at elevated temperatures were used as a measure of the durability of the GFRP. Mechanical tests suggested after exposure to alkaline solution, GFRP experienced a decrease in the elastic modulus, tensile, shear and bond strengths^{4,5,6,7}. Based on the results from studies carried out in pure NaOH solution Uomoto⁸ recommended that GFRP should not be used as internal reinforcement in concrete. All the tests, whether accelerated or non-accelerated, were conducted in the laboratory in an alkaline environment, which is very different from the concrete environment found in actual structures in the field⁹.

In contrast with the results mentioned above, the results from other experiments suggested no mechanical or physical deterioration in the GFRP after a 12-month exposure to alkaline solutions at 20-38 °C¹⁰ and after 2-years exposure to a tropical climate on a test platform off Japan's coast¹¹. Research carried out in the Euroconcrete project¹² indicated that GFRPs resist the alkaline environment well, with no significant degradation during a 12-month test period. One of the overall conclusions of the Euroconcrete project was that GFRPs are suitable for use in a concrete environment.

The objective of the study described in this paper was to provide data on the performance of GFRP that has been used in many structures across Canada.

METHODOLOGY USED IN THE STUDY

Experienced contractors were employed to extract cores from five in-service structures under the supervision of senior engineers. The extracted cores with GFRP were

sent for analysis to three independent research teams of material scientists from the universities of Manitoba, Sherbrooke, British Columbia and Saskatchewan.

Field structures

The five field structures chosen in this study have been subjected to a wide range of environmental conditions, as elaborated in the following.

The Hall's Harbor Wharf (Fig. 1) was the first marine structure in Canada to be built using ISIS Canada technology and design concepts¹³. The wharf, located on the Bay of Fundy shore in Nova Scotia, comprises steel-free precast concrete panels with GFRP bars and concrete pile cap beams reinforced with a hybrid GFRP-steel bar system. Concrete with a compressive strength of 45 MPa was used in the panels and beams. The structure is 5 years old and operates under the following environmental conditions: thermal range +35 to -35°C; wet and dry cycles, splash and tidal salt water; frequent freeze-thaw cycles.

The Joffre Bridge (Fig. 2), located in Sherbrooke, Québec, over the St-Francois River, contains GFRP bars as reinforcement in the 45 MPa concrete in the sidewalks and the traffic barriers¹⁴. In this structure, the GFRP material is a ribbed-deformed GFRP C-Bar. The structure is 7 years old and operates under the following environmental conditions: thermal range +35 to -35°C; wet and dry cycles; freeze-thaw cycles; de-icing salt.

The four-span Chatham Bridge, located in Chatham, Ontario, contains in the two outer spans steel-free deck slabs to which the barrier walls are attached by means of double-headed stainless steel bars. 35 MPa ordinary concrete reinforced with NEFMAC™ glass fiber G-13 grid at a pitch of 100x100 mm is used in the barrier walls¹⁵. The structure is 8 years old and operates under the following environmental conditions: thermal range +30 to -24°C; wet and dry cycles; frequent freeze-thaw cycles; de-icing salt.

The Crowchild Trail Bridge, located in Calgary, Alberta, utilized ribbed-deformed GFRP C-Bar as reinforcement in the barrier walls and deck slab¹⁶. Concrete with a compressive strength of 35 MPa was used in the barrier walls and deck slab. The structure is 8 years old and operates under the following environmental conditions: thermal range +23 to -15°C; freeze-thaw cycles; de-icing salt.

The Waterloo Creek Bridge, located on Vancouver Island, British Columbia, has barrier walls reinforced with GFRP and connected to the steel-free deck slab with double-headed steel bars. Concrete with a compressive strength of 35 MPa was reinforced with NEFMAC™ GFRP in the barrier walls¹⁷. The structure is 6 years old and operates under the following environmental conditions: thermal range +23 to 0°C; frequent freeze-thaw cycles; de-icing salt.

The GFRP rods and grids in all of the selected structures were made of E-glass and vinylester matrix.

From each of the five structures, at least 10 cores of GFRP reinforced concrete were removed at various locations in the structure. Figure 3 shows a barrier wall of the Chatham Bridge, from which cores were removed. The cores had a diameter of 75 mm and a length varying between 140 and 180 mm. All cores removed from one structure can be seen in Fig. 4.

Analytical methods and sample preparation

Five analytical methods were used to evaluate the composition of GFRP and surrounding concrete: optical microscopy (OM), scanning electron microscopy (SEM), energy dispersive x-ray (EDX), differential scanning calorimetry (DSC) and Fourier transformed infrared spectroscopy (FTIS).

The OM was used to examine the interface between the GFRP and concrete. Samples containing GFRP and concrete were cut from each core and carefully smoothed using a #500 sandpaper. The entire surface of each sample was examined and photos taken at random locations.

SEM was used for detailed examination of the glass fiber/matrix interface and individual glass fibers. The specimens used in SEM analyses were also analyzed by EDX, which detects potential chemical changes in the matrix and glass fibers due to the ingress of alkali from the concrete pore solution.

Chemical changes of the matrix were characterized by FTIS. Small sections of the GFRP extracted from the cores were crushed and ground into a powder. The pellet method with spectroscopic grade potassium bromide (KBr) was used to obtain the infrared spectra.

Changes in the glass transition temperature, T_g , of the matrix due to exposure to concrete environmental conditions were determined using DSC. The T_g measurements were carried out on small pieces cut from the GFRP extracted from the cores. The measurements were carried out in air between 40 and 200°C at a heating rate of 10°C/min.

RESULTS AND DISCUSSIONS

The results obtained by all three-research teams were very similar. A complete documentation of all three sets of data is given elsewhere¹⁸.

Optical microscope observation

OM examinations were used to assess the bond between GFRP and concrete, it being noted that this bond is likely to deteriorate first due to alkalis from concrete, as explained in the following. The presence of delaminated zones at the GFRP/concrete interface can facilitate the accumulation of water at the interface and consequent formation of localized areas with different moisture contents, alkalinity, thus accelerating the degradation of the GFRP. Different combinations of exposure conditions such as alkalinity, temperature, moisture, freeze-thaw cycles and cyclic loading, can also lead to the deterioration of the GFRP/matrix bond because of the deterioration of the matrix.

OM examinations of the interface between the GFRP and concrete of the cores from the five field structures exposed to natural environmental conditions show no loss of bond between the GFRP and concrete. Figures 5 and 6, showing OM results for cores from the Crowchild Trail and Chatham bridges, respectively, are typical of all OM observations. It can be seen in these figures that there are no gaps between the GFRP and concrete, thus confirming a good bond between the two materials.

The OM analyses confirmed that after 5 to 8 years exposure to alkalinity, freeze-thaw and wet-dry cycles, de-icing salts, salt water and thermal loading, had no effect on the integrity of GFRP/concrete interface.

Scanning electron microscopy and energy dispersive x-ray analyses

SEM and EDX were used to determine in detail the effect of exposure on the constituent materials of the GFRP. SEM examination of cores from all five structures confirmed that there was no sign of any damage to the FRP. A micrograph of the cross-section of a GFRP bar from the Crowchild Trail Bridge is presented in Fig. 7, in which it can be seen that at the plane under examination, the fibers have not lost any cross-sectional area. Similarly, a micrograph of a longitudinal section of a GFRP sample from the Chatham Bridge, presented in Fig. 8, shows no degradation of the fibers in the direction of the fiber axes. Although the entire surface of each specimen was examined, attention was focused primarily to areas close to the GFRP/concrete interface.

Results from SEM analyses presented in Figs. 7 and 8 are typical of all other SEM analyses, which have shown that the individual fibers are intact with no gaps between fibers and the matrix. There is no evidence of deterioration of the glass/matrix interface. A good contact between individual glass fibers and the matrix, between sand grains and the matrix as well as between concrete and the matrix was observed for all specimens. The SEM analyses confirmed that the GFRP in the five structures did not show any evidence of attack from the alkali in concrete.

It is well known that silica glass dissolves in strong alkaline solutions such as the concrete pore solution. In order to attack glass fibers, alkalis from the concrete pore solution must ingress first into the polymer matrix. When the glass fibers degrade as the result of various processes such as dissolution, leaching, and ion exchange, the chemical composition of the glass and matrix change. The EDX was used to assess such potential chemical changes in the matrix and glass fibers. Examples of EDX spectra are discussed in the following.

From two of the examined structures, samples of GFRP were saved and kept in storage for possible future investigation. These samples, referred to herein as the control specimens, provide an opportunity to compare the chemical composition of the GFRP extracted from in-service structures; the latter specimens are referred as the 'in-service' specimens. The EDX spectra of the in-service and control GFRP specimens from the Joffre Bridge are presented in Figs. 9 and 10, respectively. It can be seen that the matrix in both specimens contains mainly carbon, as it should. However, some additional elements such as Si, Al, and Ca have also been detected. Since the EDX spectrum of the

in-service specimen is almost identical with that of the control specimen, the presence of elements other than C in the matrix could be attributed to contamination introduced during the preparation of the specimens for the microscopic examination.

The concrete pore water solution consists mainly of Na^+ , K^+ with OH^- as counter ion. Other elements present in the solution are either very insoluble (Ca^{2+}) or have low solubility (Mg, Al, Si, Fe and SO_4^{2-}). Since the EDX cannot detect elements lighter than sodium, the OH^- ion cannot be detected. However, the OH^- ions and cations, Na^+ , K^+ , will diffuse together for charge neutrality to be satisfied. Therefore, a strong indication of alkali migration from a concrete pore solution toward the glass fibers would lead to the presence of Na or K in the matrix (Figs. 9 and 10). Observations on several specimens indicated that neither Na nor K is present in the matrix.

Infrared spectroscopy

The durability of the matrix is governed to a large extent by the chemical nature of the structure of the polymeric chain. In their structure, all resins have ester bonds, which are the weakest link of the polymer. A possible degradation mechanism of the matrix is the alkali hydrolysis of the ester linkages. Due to the alkaline environment in concrete, alkali hydrolysis is expected to some extent. During the hydrolysis reaction, the OH^- induces ester linkage attack and the resin chain is broken. Consequently, the structure of the resin is disrupted and the material properties are changed. The resin material degrades and eventually will not be able to transfer stresses to the glass fibers and to protect the glass fibers against alkaline attack. Changes in the amount of hydroxyl groups present in the composite material provide insight into the hydrolysis reaction. The relative amount of hydroxyl groups in the specimens were measured by determining the ratio of the maximum of the band corresponding to the hydroxyl groups at 3430 cm^{-1} and the band corresponding to the carbon-hydrogen groups at 2900 cm^{-1} in the FTIR spectra. The C-H content is assumed to be constant. Since the vinyl ester resins naturally contain hydroxyl groups, all the spectra present a strong absorption band in this region. Typical results of the FTIR analysis of control and in-service GFRP samples from Hall's Harbor Wharf are presented in Figs. 11 (a) and (b), respectively. It can be seen that there is no significant change in the spectra of the two specimens. Table 1 lists the content ratio of OH/CH for the control and in-service specimens from the Joffre Bridge and the Hall's Harbor Wharf. The results show very little changes in hydroxyl content in the in-service specimens. In effect, the OH/CH ratio decreases in the in-service sample indicating that the hydrolysis reaction did not occur in the specimens during the exposure to natural environmental conditions.

Differential scanning calorimetry

The properties of GFRP are governed by the properties of both constituents the glass and polymer matrix. The glass transition temperature, T_g , an important physical property of the matrix, is not only an indicator of the thermal stability of the material, but it is also an important indicator of polymer structure and mechanical properties. For example moisture in the matrix reduces T_g of the matrix due to plastification as the result of breakage of the Van der Waals bond between the polymer chains. The swelling stresses associated with moisture uptake, or the presence of alkalis, can cause permanent damage

in the matrix such as cracking, hydrolysis, and fiber-matrix debonding. The glass transition temperature values for the GFRP specimens removed from the field structures are presented in Table 2. Where possible the results were benchmarked to control specimens.

The results for the Hall's Harbor Wharf control specimen indicated a difference between the values of the T_g in the two heating runs indicating that the matrix in the GFRP ISOROD rod was not fully cured. In the 2nd heating run the resin was fully crosslinked and the T_g value increased from 105°C in the 1st run to 125°C. However, the T_g value for the exposed specimens did not show any significant change between the two heating runs, suggesting that the post-cure of the matrix occurred in the concrete structure. It is quite likely that the completion of the crosslinking process was due to structure exposure to high temperature during summers. The control samples on the other hand were stored at room temperature that did not initiate the post-curing process. Overall, the T_g results indicate that the structure of the matrix has been not disrupted by the exposure conditions at the Hall's Harbor Wharf. Similarly, no significant differences in the T_g values were observed for the control and in-service specimens for the Joffre Bridge. However, it should be noted that the T_g value for the 16 mm diameter GFRP C-Bar was 108°C which, even fully cured, was low compared with the T_g value for other GFRPs used in the Hall's Harbor Wharf and Crowchild Trail Bridge. The low value is attributed to manufacture formulation. High T_g values, ranging between 123 and 128°C, were measured for the 9 mm diameter GFRP C-bar. The T_g values for both types of GFRPs suggest no structural disruption of the matrix due to exposure to natural conditions at the Joffre Bridge. The thermographs for 9mm control and in-service specimens from the Joffre Bridge are presented in Figs. 15 (a) and (b). The results indicate that GFRP material was fully cured and the thermograph for the in-service specimen (Fig. 12a) was very similar to the thermograph for the control specimen (Fig. 12b).

For the Chatham, Crowchild Trail and Waterloo Creek bridges, control specimens were not available and the effect of service conditions on these GFRP composites could not be evaluated comparatively. However, the T_g results for the GFRP C-Bar material used in the Crowchild Bridge suggest that the material was fully cured. The same is not the case for the GFRP grid sample extracted from Chatham Bridge, in which the T_g measured in the first and second runs was 98 and 116°C, respectively.

A similar behavior was observed for the GFRP grid sample extracted from Waterloo Creek Bridge. The T_g obtained during the first run was 40°C lower than that in the second run: 78°C vs. 117°C, indicating that the materials in both Chatham and Waterloo Creek bridges were not fully cured.

ACCELERATED TESTS VERSUS FIELD PERFORMANCE

The results of the study on samples removed from in-service structures are not in agreement with the results obtained in accelerated laboratory studies. Three reasons for this anomaly are discussed in the following.

The use of high temperatures, ranging from 60°C to 80°C, in accelerated tests is not relevant in the context of making service life predictions for most engineering structures that operate under much lower temperatures.

The configuration of the leaching system that controls the kinetics of glass dissolution in laboratory experiments is completely different from that in concrete structures. In the case of a GFRP bar immersed in a bath solution, the conditions are equivalent to the infinite supply of the leachant or its rapid replenishment. The solubility limit of glass elements such as Si and Al is controlled by hydroxyl concentration and by the diffusion coefficient in the matrix; the concentration gradients between the glass and the solution remain high over the entire duration of the experiment. The leachant volumes or the replenishment rates within the concrete pore solution in a GFRP-reinforced concrete system, on the other hand, are very small because of several reasons: (a) the porosity of concrete is low, being about $\eta \sim 0.35$; (b) with the exception of submerged piers and hydro dams, the concrete pores are only seldom fully saturated so that the diffusion coefficients are a fraction of their values for saturated conditions; and (c) not all pores in concrete are connected. For all these reasons, the kinetics of glass dissolution in most reinforced concrete structures, are different from the kinetics for infinite leachant in laboratory experiments. Due to increasing solute concentrations of glass elements, Si and Al, in the aqueous phase and decreasing concentration gradient between the glass and concrete pore solution, the effective rate of matrix dissolution slows. Eventually, back-reactions and saturation effects ought to become important phenomena that control the glass dissolution mechanism.

The pH of pore solutions in accelerated laboratory tests was usually kept constant at a very high value. In reinforced concrete structures, the pH decreases with time.

CONCLUSIONS

Based on the results of the analyses described above, it can be stated that there was no degradation of the GFRP in the concrete of structures exposed to natural environmental conditions for durations of 5 to 8 years.

From the optical microscope examination results, it can be confirmed that a good bond exists between the GFRP and concrete. The good quality, consistency and integrity of the GFRP/concrete interface indicate exposure to wet-dry cycles, freeze-thaw cycles and de-icing salt had no adverse effect on the GFRP. The matrix in all the GFRPs was intact and unaltered. Results from the Fourier transformed infrared spectroscopy and differential scanning calorimetry analyses, corroborating the results from the optical microscope examinations, indicate that neither hydrolysis nor significant changes in the glass transition temperature of the matrix took place after exposure to the combined effect of the concrete alkaline environment and the external natural environmental conditions for 5 to 8 years.

The results from scanning electron microscopy and energy dispersive X-ray analyses confirm that there is no degradation of the GFRP in the concrete structures.

1370 Mufti et al.

The overall conclusion of the research project is that GFRP is durable in concrete. Also, the team concluded that the CHBDC in its first edition was conservative in not permitting GFRP as the primary reinforcement. The second edition of the code, currently in the final stages of approval, permits the use of GFRP as primary reinforcement.

ACKNOWLEDGMENTS

The financial support of the ISIS Canada Network of Centres of Excellence for the work reported in this paper is gratefully acknowledged. The assistance of technical staff at the universities of Manitoba, Sherbrooke, British Columbia and Saskatoon is also acknowledged gratefully.

REFERENCES

1. Meier, U. and Brönnimann, R., 2003, "ISIS Canada Research Network, Intelligent Sensing for Innovative Structures," *External Research Assessment Report*. Swiss Federal Laboratories for Materials Testing and Research (EMPA), Dübendorf, Switzerland.
2. Memon, A.H. and Mufti, A.A., 2004, "Fatigue Behaviour of Second Generation Steel-Free Concrete Bridge Deck Slab," *Proceedings of the Second International Conference on FRP Composites in Civil Engineering (CICE 2004)*, Adelaide, Australia.
3. Sheikh, S. and Homam, M., 2004, "A Decade of Performance of FRP-Repaired Concrete Structures," *Proceedings of the ISIS-SHM 2004 Workshop*. Winnipeg, Manitoba, Canada.
4. Porter, M. L. and Barnes, B. A., 1998, "Accelerated Durability of FRP Reinforcement for Concrete Structures," *Proceedings of the 1st International Conference on Durability of Fiber Reinforced Polymer (FRP) Composite for Construction. CDCC'98*, Sherbrooke, (Quebec) Canada.
5. Bank, L. C. and G. Russell T., 1995, "Accelerated Test Methods to Determine the Long-Term Behavior of FRP Composite Structures: Environmental Effects," *Journal of Reinforced Plastics and Composites*. V. 14, pp. 559-587.
6. Sen, R., Mullins, G., and Salem, T., 2002, "Durability of E-Glass/ Vinylester Reinforcement in Alkaline Solution," *ASI Structural Journal*. V. 99, No. 3, pp. 369-375.
7. Bank L.C., Gentry, T.R., Barkatt, A., Prian, L., Wang, F. and Mangla, S. R., 1998, "Accelerated Aging of Pultruded Glass/vinylester Rods," *Proceedings of the 2nd International Conference on Fiber Composites in Infrastructure, ICCI;V. 2*, pp. 423-437.
8. Uomoto, T., "Durability of FRP as Reinforcement for Concrete Structures," *Advanced Composite Materials in Buildings and Structures 3rd International Conference*, Ottawa, Ontario, Canada, pp. 3-14.

9. Mufti, A.A., Onofrei, M., Bakht, B., and Banthia, V., 2003, "Discussion Paper on Durability of E-Glass / Vinylester Reinforcement in Alkaline Solution. *American Concrete Institute Structural Journal*, V. 100, No. 2, pp. 265.
10. Tomosawa, F. and Nakatsuji, T., 1997, "Evaluation of ACM Reinforcement Durability by Exposure Test," *Non-Metallic (FRP) Reinforcement for Concrete Structures, Proceeding of 3rd International Symposium*. Sapporo, Japan, V. 2, pp. 139-146.
11. Clarke, J. L. and Sheard, P., 1998, "Designing Durable FRP Reinforced Concrete Structures," *Proceedings of the 1st International Conference on Durability of Fiber Reinforced Polymer (FRP) Composite for Construction*. Sherbrooke, Quebec, Canada, pp. 13-24.
12. Sheard, P., Clarke, J.L., Dill, M., Hammerslely, G. and Richardson, D., 1997, "EUROCONCRETE - Taking Account of Durability for Design of FRP Reinforced Concrete Structures," *Non-Metallic (FRP) Reinforcement for Concrete Structures, Proceeding of 3rd International Symposium*. Sapporo, Japan, V. 2, pp. 75-82.
13. Newhook, J.P., Bakht, B. and Mufti, A.A., 2000, "Design and Construction of a Concrete Marine Structure Using Innovative Technology," *Proceedings of the 3rd International Conference on Advanced Composite Materials in Bridges and Structures*. Canadian Society for Civil Engineering, pp. 777-784.
14. Benmokrane, B., Rahman, H. and Mukhopadhyaya, P., 2000, "Use of Fiber Reinforced Polymer Reinforcement Integrated with Fiber Optic Sensors for Concrete Bridge Deck Slab Construction," *Canadian Journal of Civil Engineering*. V. 27, No. 5, pp. 928-940.
15. Aly, A., Bakht, B. and Schaeffer, J., 1997, "Design and Construction of Steel-fee Deck Slab in Ontario," *Annual Conference of Canadian Society for Civil Engineering*, V. 6, pp. 81-90.
16. Tadros, G., Tromposch, E. and Mufti, A. A., 1998, "Superstructure Replacement of Crowchild Trail Bridge," edited by L. Dunaszegi, Calgary, Alberta, Canada. *5th International Conference on Short and Medium Span Bridges*, Calgary, Alberta, Canada, pp. 499-506.
17. Tsai, P. and Ventura, C.E., 1999, "Waterloo Creek Bridge Project", *Field Assessment Report No. 2*, University of British Columbia, Vancouver, BC, Canada.
18. Mufti, A., Onofrei, M., Benmokrane, B., Banthia, N., Boulfiza, M., Newhook, J., Bakht, B., Tadros, G., and Brett, P., 2005, "Studies of Concrete Reinforced with GFRP Specimens from Field Projects," *ISIS Canada Research Network Technical Report*. Winnipeg, Manitoba, Canada.

1372 Mufti et al.

Table 1 – Ratio of OH/CH for control and specimen from structure

Structure	GFRP	OH/CH for	
		Control specimen	In-service specimen
Joffre Bridge (barrier wall)	C-BAR (9 mm dia.)	0.64	0.60
Joffre Bridge (barrier wall)	C-BAR (16 mm dia.)	0.50	0.46
Hall's Harbor Wharf (beams)	ISOROD (16 mm dia.)	0.97	0.91

Table 2 – Glass Transition Temperatures, T_g

Structure	GFRP	Specimen	T_g for 1 st run, °C	T_g for 2 nd run, °C
Hall's Harbor Wharf	GFRP ISOROD (16 mm dia.)	Control	105	125
		In-service	123	125
Joffre Bridge (barrier wall)	GFRP C-BAR (16 mm dia.)	Control	107	108
		In-service	107	108
	GFRP C- BAR (9 mm dia.)	Control	123	126
		In-service	127	128
Crowchild Trail Bridge (barrier wall and deck slab)	GFRP C-Bar	In-service	126	129
Chatham Bridge (barrier wall)	NEFMAC™ grid	In-service	98	116
Waterloo Creek (barrier wall)	NEFMAC™ grid	In-service	78	117



Figure 1 – Hall's Harbor Wharf.



Figure 2 - Joffre Bridge.



Figure 3 – Barrier wall of Chatham Bridge.



Figure 4 – Cores from one structure.

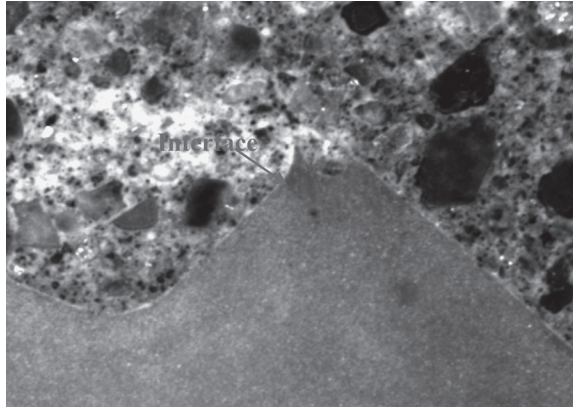


Figure 5 – OM image of cross-section of GFRP from Crowchild Trail Bridge

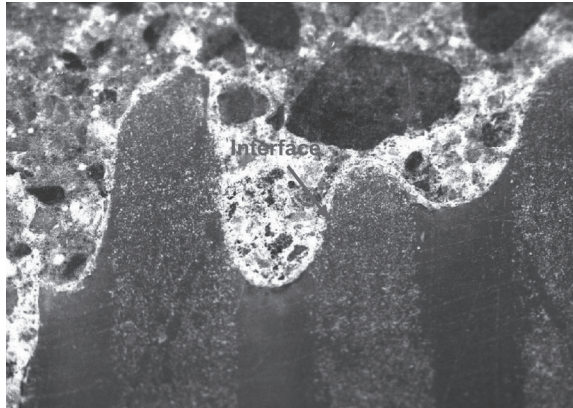


Figure 6 – OM image of cross-section of GFRP from Chatham Bridge.

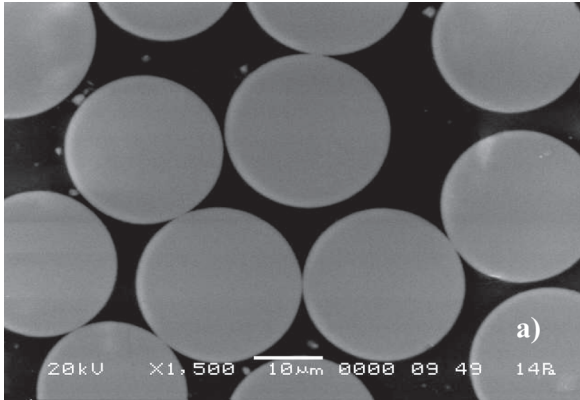


Figure 7 – Micrograph of cross-section of GFRP from Crowchild Trail Bridge.

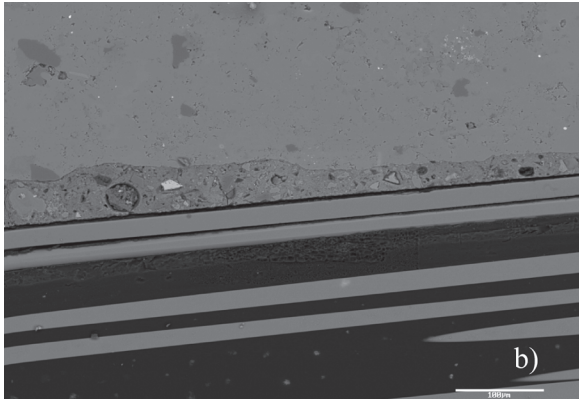


Figure 8 – Micrographs of longitudinal section of GFRP from Chatham Bridge.

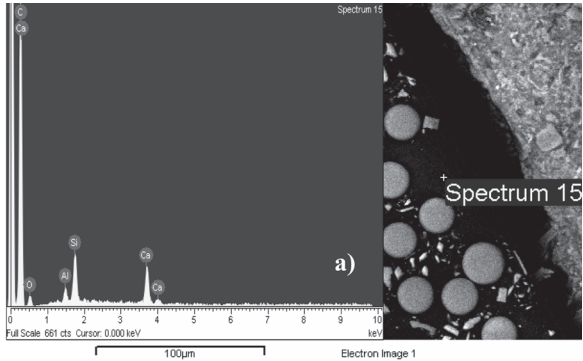


Figure 9 – EDX spectra of in-service specimen from Joffre Bridge.

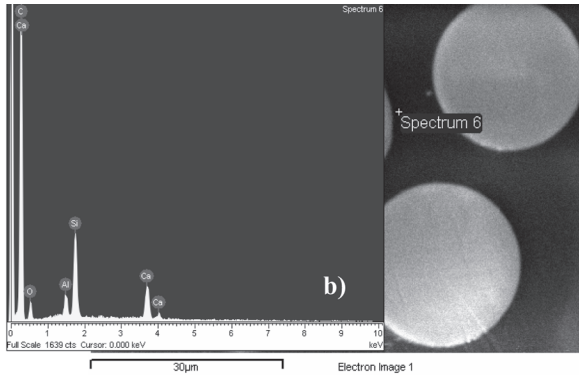


Figure 10 – EDX spectra of control specimen from Joffre Bridge.

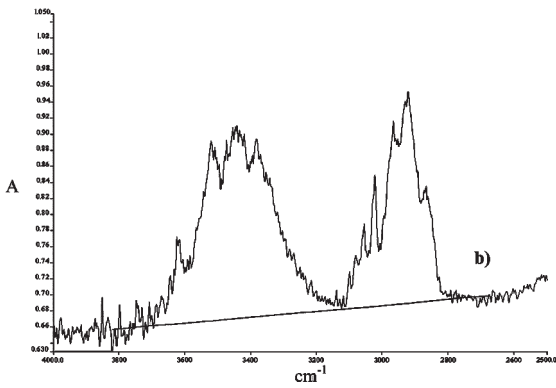
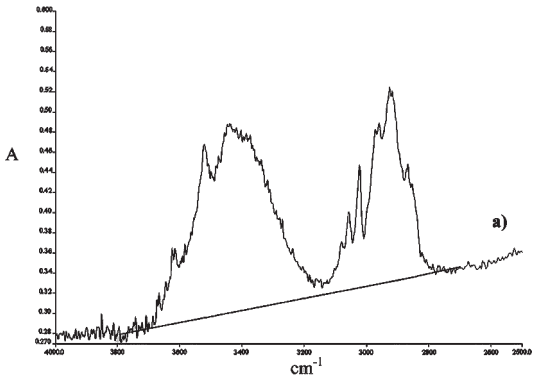


Figure 11 – FTIR spectra of GFRP from Hall's Harbor Wharf: (a) control specimen, and (b) in-service specimen.

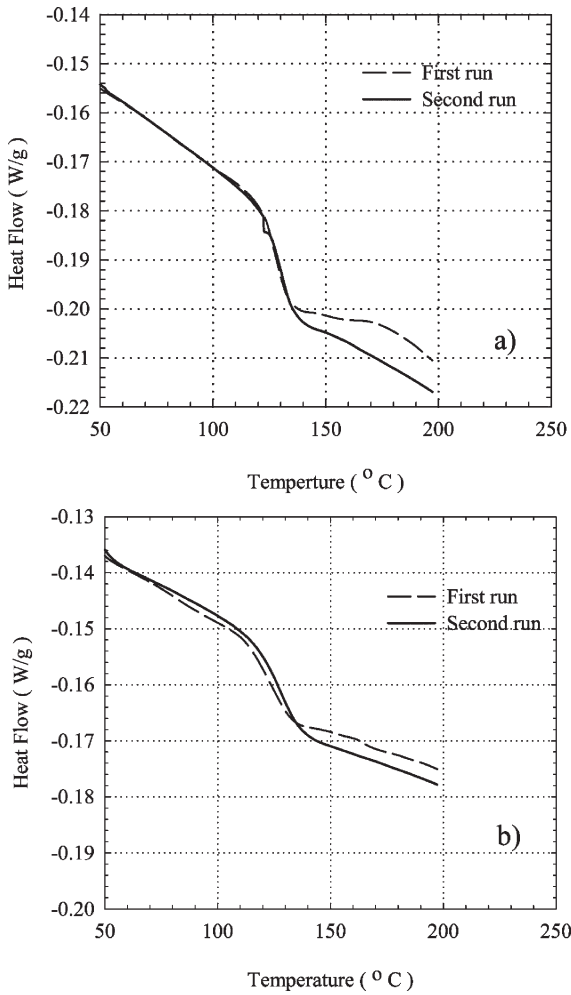


Figure 12 — Thermographs for GFRP from Joffre Bridge: (a) in-service specimen, and (b) control specimen.

