Use of Glass FRP Reinforcing Bars instead of Steel Bars in CRCP in Quebec

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Abstract

In North America, there is a persistent problem of the deterioration of steel-reinforced concrete which has limited the service life and increased the maintenance cost of such structures. The first Canadian continuous reinforced concrete pavement (CRCP) built on a highway was constructed in 2000 in the province of Quebec. Some cores taken in the first CRCP section five years after construction were already showing some corrosion in the longitudinal reinforcement at the crack location. Many options were then analysed in 2005 to resolve this problem and galvanised steel was selected as reinforcement for the next projects. One other non-corrosive reinforcement alternative is glass fibre reinforced polymer (GFRP). Fifteen (15) slab sections over an area of 150 m in three-lanes of Highway 40 Eastbound in Montreal (Quebec) were constructed using the newly developed CRCP system with GFRP reinforcement. In addition, 3 slab sections were reinforced using steel bars for comparison purposes. The main objective of this research project is to implement the technology and design of GFRP reinforcing bars in order to demonstrate their ability to meet all CRCP requirements.

Introduction

Since the early 1990s, pavement design specifications have been the object of a major turnabout at the Ministry of Transportation of Quebec (MTQ) in Canada. The structural design and frost protection of all pavements type in accordance with local climatic and traffic conditions were the targets. Since then, many efforts have been made to find better lasting concrete pavements. The first Canadian continuous reinforced concrete pavement (CRCP) built on a highway was constructed in 2000 in the province of Quebec. At that time, projects engineers and experts tried to adapt the design of this type of concrete pavement from other countries to the severe wet-freeze climate of Quebec. Since 2000, nearly 50 km of CRCP have been constructed in Quebec with steel bars as reinforcement.

In 2005, problems encountered along the construction of some sections of CRCP reinforced with steel bars, for example a deficiency of concrete cover over the steel bars, worried the engineers concerning long term performance of CRCP (Thébeau and Davidson 2006). Some core samples taken in the first CRCP section five years after construction were already showing corrosion in the longitudinal reinforcement at the transverse crack location. Since Quebec climatic conditions are harsher than most of other countries using CRCP for many years, it is hard to extrapolate what would happen there in terms of pavement performance based on the data coming from elsewhere. Data from a maintenance unit in Montreal indicates that up to 65 tons of salt per

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year can be spread on a 1-km two-lane stretch. By way of comparison, this represents three times the amount of salt that Illinois DOT uses on its roads.

Many options were then analysed in 2005 to resolve this problem and galvanised steel was selected as reinforcement for the next projects. One other non-corrosive reinforcement alternative is glass fibre reinforced polymer (GFRP) that has been used for many years by MTQ in concrete bridges, but it had never been studied on a trafficked CRCP highway. For this reason, the MTQ and the University of Sherbrooke initiated a pioneer research project involving the application of GFRP bars to CRCP slabs in September 2006. The pavement in question was constructed on Highway 40 Eastbound in Montreal. The main objective of this research project is to implement the technology of GFRP reinforcing bars and to demonstrate their ability to meet all CRCP requirements. Furthermore, it is important to assess the short- and long-term performance of both CRCP and GFRP bars and to improve and validate the current design guidelines under different service loading and environmental conditions.

This paper summarizes mainly the objectives of the research project and construction details of eighteen full-scale CRCP sections using GFRP bars. Since the pavement has a relatively young age, the performance is roughly discussed.

Questions and Answers about Glass Fibre Reinforced Polymer bars in CRCP

Straight up to the start, many questions had to be answered before thinking about using this material for the first time in a highly trafficked CRCP slabs. First, GFRP bars are very stable in concrete. This has been proven by several laboratory and field studies (Mufti et al., 2007a, b). This is why the Canadian Highway Bridge Design Code (CAN/CSA-S6-06) accepted the use of GFRP bars as a primary reinforcement in concrete bridge deck slabs and several other structural elements in concrete bridges. The GFRP V-ROD™ bars used in the HW-40 project were manufactured by a process called pultrusion. The pultrusion process generally consists of pulling continuous roving through a resin bath or impregnator and then into performing fixtures where the section is partially shaped and excess resin and air is removed. Then it goes into a heated die where the section is cured continuously. To ensure good bond with concrete, the surface of the bars is sand coated (ISIS Canada, M03-2001, Pultrall 2007). Table 1 shows the structure properties of GFRP bars used in this study according to the manufactured Pultrall (2007) standards.

Table 1 - Structural properties of straight GFRP V•ROD™ bars (Pultrall 2007)

Bar Size	Diameter (mm)	Area (mm^2)	Modulus of Elasticity (GPa)	Guaranteed Tensile Strength * f_{fu}^* (MPa)
No. 6	19.1	285.1	47.6	656
No. 7	22.2	387.9	46.4	625
No. 8	25	506.7	51.0	611

* f_{fu}^* = Average tensile strength minus three times standard deviation (ACI 440.1R-06)

Repairing of damaged slabs reinforced with GFRP bars is currently under investigation. For the moment, one of the recommended solutions is by cutting the damaged area of pavement and installing new GFRP anchorage bars using resin or cement grout in holes drilled in the existing pavement. The recycling of concrete reinforced with GFRP bars is another important advantage of this type of reinforcement. Indeed, the concrete containing GFRP bars can easily be crushed and be reutilized as aggregates for roads and highways. In addition, the resin and the fibres (components of FRP bars) do not have any negative effect on recycled material. It was proven that the GFRPs have much lower environmental effects compared to steel (Katz, 2004).

Research Objectives and Phases

Considerable data is available regarding the effect of steel reinforcement ratio and bar size on the performance of CRCP. Also, considerable data is available concerning the use of FRP in different concrete structures. However to date, no experimental work has been done for CRCP reinforced with GFRP composite bars (Walton and Bradberry 2005). According to ACI Committee 440 (2006), no experimental data is available on CRCP or slabs on ground reinforced with FRP bars.

The main objectives of this study can be listed as follows:

- To investigate the behavior of CRCP with GFRP bars and to compare with those reinforced with steel bars (in terms of cracking, strains and stresses).
- To introduce design equations for the use of GFRP reinforcing bars as reinforcement for CRCP.
- To develop an analytical model using non-linear finite element analysis for CRCP reinforced with GFRP bars.

The specific objectives are to determine the effect of:

- The reinforcement ratio, reinforcement type, reinforcement spacing, bar diameter and pavement thickness on the crack width and spacing.
- The depth of reinforcement from the surface on cracking and stress in the pavement,
- Uniformly induced crack spacing on the performance of the CRCP.
- The GFRP bond characteristics on cracking and stress in the pavement.
- The presence of more than one layer of longitudinal reinforcement on the performance of CRCP reinforced with GFRP bars.

To fulfill the objectives of this research, an extensive research project is currently on going at the University of Sherbrooke through the demonstration project on HW-40 in collaboration with the MTQ. The research program includes three phases as follows:

- Phase 1: Design, instrumentation and construction of 18 full-scale CRCP sections implemented on HW-40.
- Phase 2: Monitoring and periodically testing of the 18 full-scale CRCP sections for a 24-month period following the completion of construction.
- Phase 3: Analytical modeling using the finite element method to predict the performance of CRCP with GFRP reinforcing bars.

Design Approach and Structural Details of CRCP sections

The pavement design in Quebec follows two steps; the first one is structural and the second one is frost protection. For the structural step, the CRCP design consists of two primary components: pavement thickness and reinforcement ratio. For the HW-40 project, various aspects were considered for the evaluation of the pavement thickness (AASHTO 1993): design traffic loading, design pavement life, concrete properties, sub-grade and sub-base, drainage, and previous CRCP projects done by MTQ on HW-13 (2000) and HW-40 (2003 to 2005). HW-40 is located in Montreal on the strategic network of the MTQ. The equivalent single axle load (ESAL) estimated for the design period of 30 years was 230 millions (concrete). It has been decided that a 280 mm thick CRCP is needed for most of the slab sections.

The next step is to determine the reinforcement required with GFRP bars. Four equations were used to calculate the proposed longitudinal reinforcement ratio: Vetter's 1933, AASHTO 1972, USDT 1996, and ACI 440.1R-06. Although the first three were proposed for CRCP reinforced with steel, they were used in this study through changing the input parameters to be compatible with GFRP properties. The only equation proposed for slabs on ground reinforced with GFRP bars was ACI 440.1R-06. However, there is no experimental work to support it. In light of the previous approaches and equations, 1.2 % was chosen to be the proposed reinforcement ratio. Moreover, the range of reinforcement ratios was from 0.77 % to 1.57 %. The steel reinforcement ratio used on the contract was 0.77%.

In order to assure the well design of CRCP, three limits need to be checked: crack width, crack spacing, and stress in the reinforcement. In this study, three methods were used (AASHTO 1986, Gilbert 1992, and CRCP-10 software) to check these limits as shown in Table 2.

Table 2 - Check of the design limits for CRCP with GFRP bars (Proposed design)

	AASHTO, 1986	Gilbert, 1992		CRCP-10, 2001	
		*High Bond Slip	**Low Bond Slip	*High Bond Slip	**Low Bond Slip
Crack width (mm)	0.25	0.26	0.52	0.38	0.48
Crack spacing (m)	0.43	0.56	1.08	0.73	0.73
Stress in GFRP bars (MPa)	98	211	206	79	65

*High Bond slip 14.8 MPa, **Low Bond slip 7.5 MPa

Moreover, Table 3 shows the reinforcement configuration and investigated parameters for each test section at the demonstration project of HW-40.

Table 3 - Reinforcement configuration and investigated parameters for the CRCP research project, HW-40 (Montréal)

Series	Investigated Parameters	Slab	Slab Thickness (mm)	Longitudinal Rein. Ratio (%)
A	Reinforcement Ratio (Different Spacing)	A1	280	1.05
		A2		1.16
		A3 (A2)		1.16
		A4		1.32
B	Transverse Reinforcement Ratio	B	280	1.16
C	Reinforcement Ratio (Fixed Spacing)	C1	280	1.57
		C2		1.06
D	One Bar	D1	280	1.27
		D2 (D1)		1.27
		D3		0.97
		D4		0.77
E	Crack Control (Saw cut each 1.2 m)	E1	280	1.16
		E2		1.03
F	Thickness	F	350	0.93
G	Two Layers	G	350	0.93
S	Steel	S1, S2, S3	280	0.77

The typical pavement structure for the CRCP slabs reinforced with GFRP bars versus the standard slabs by MTQ reinforced with steel are shown in Figure 1. In this project, 450 mm of MG-112 was used for sub-base, 150 mm of MG-20 was used for the base and 100 mm of open graded drainage layer (OGDL) stabilized with cement was used for the drainage layer under the slab.

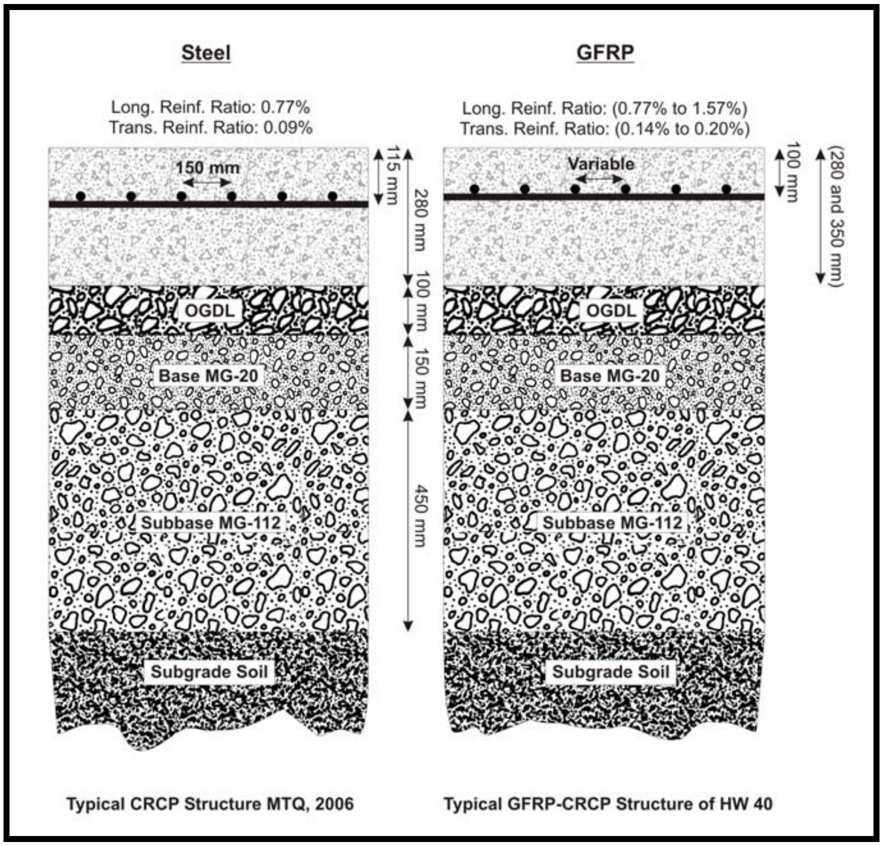

Figure 1 - Typical pavement structure of the test sections

Construction and Instrumentation of Test Sections

CRCP Construction. The construction work of the demonstration project started in August 2006. The test sections were included at the end of the 6-km reconstruction project of HW-40. Anchorages were constructed at both ends of the 150-m sections with at least 3 reinforced lugs. Each shoulder was made of 5-m jointed plain concrete pavement (JPCP); this is the standard for CRCP projects in MTQ.

GFRP V-ROD™ bars No. 6, 7 and 8 were used for the longitudinal and transverse reinforcement of fifteen slab sections. As shown in Figure 2, the handling of GFRP bars is much easier than steel. The reinforcement placement started with the center lane by placing the horizontal reinforcement bars crosswise at a 30° angle to the transverse line and spaced 520 mm center-to-center. Afterwards, longitudinal bars were placed according to the designed plan.

Figure 2 – Handling of GFRP reinforcement bars

Figure 3 shows the GFRP reinforcement bars ready for concrete paving: on the left, section C2 (center lane) is made of one row of GRFP bars No. 8 and on the right, section G (right lane) with two layers of GRFP bars no. 6.

Figure 3 – GFRP reinforcement bars in one layer and 2 layers

According to MTQ standards, galvanized steel bars were used as reinforcement for three slabs (S1, S2 and S3) which have been constructed for comparison purposes. In these reference slabs, steel bars No. 6 and No. 5 were used for longitudinal and transverse reinforcement respectively.

Concrete Type IIIA was used for the demonstration project according to MTQ specifications as shown in Table 4. The target compression strength for this concrete mix was 35 MPa at 28-days.

Table 4 – Concrete characteristics

Concrete Type	Cement content (kg/m^3)	Water/ Cement Ratio	Aggregate size (mm)	Air content (%)	Air Entraining Admixture (ml/100 kg)	Slump Range (mm)
35 Comp. 4.5 Flex. 20 mm Air Grant Type IIIA	340	0.45	10-20 Granite 5-14 Granite	5-8	60.00	40 ± 20

The contractor had a mixing plant set up near the job and the concrete arrived at the project in dump trucks. A paving train with a slip-form paver featuring a GOMACO-GT6300 was used to cast the concrete. The first day of concrete placement was on Tuesday, September 29, 2006, starting with the second lane casting a quantity of 168 m^3 of concrete. Later, the concrete placement was done for the first lane on Monday, October 2, 2006 casting 188 m^3 of concrete as shown in Figure 4. Friday, October 6, 2006 was the final day for the third lane casting a quantity of 208 m^3. It is to be noted that an error in the plans occurred because dowels were planned between the S sections and the East anchorage. To correct this mistake, bars were drilled through the anchorage slab at the last minute before the pouring of the concrete. Finally at the end of October 2006, HW-40 including the demonstration sections was opened to traffic.

Figure 4 - Casting of the concrete over GFRP bars in left lane

Instrumentation of the CRCP Slabs. A variety of sensors was installed in this project in order to monitor the early-age behavior and repeated load effect on the performance of the CRCP slabs. The set of instruments that were used to collect the data on this project included embedded electrical strain gages for measuring the strain in the concrete and reinforcement (steel and GFRP bars) as shown in Figure 5.

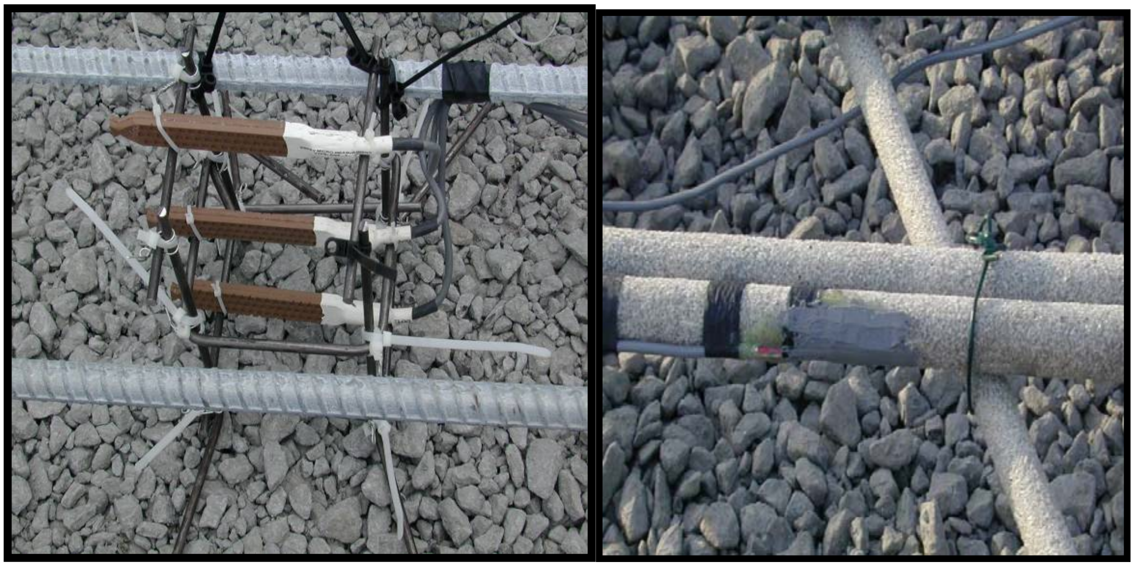

Figure 5 - Electrical strain gage in concrete and on GFRP bars

In addition, thermocouples were used for temperature measurements inside the concrete as shown in Figure 6.

Figure 6 – Four (4) thermocouples wires mounted on chair

Moreover, Fiber Optic Sensors (FOS) were used in this project to ameliorate the difference between electrical gages and FOS ones. Four types of FOS were installed in this project including FOS for measuring the strain in the reinforcement (Fabry-perot, and Fiber Bragg Grating Sensors), FOS Thermocouples Type (OTP-P) and the Brillouin sensors as shown in Figure 7.

Figure 7 - Fibre Optic Distributed Brillouin Sensors (FODBS)

Pavement Performance

A pavement performance monitoring program was launched by the MTQ in 1992, similar to the American Long Term Performance Program (LTPP). The main goals of this program are to improve pavement performance and lifespan, and to optimize the resources allocated for road construction and maintenance.

In supplement to the surveys discussed above for research project, performance monitoring of all the test sections in great detail is done by means of the following surveys:

- Distress mapping of all the 25-m sections.
- Crack width and end joint measurements.
- Longitudinal profile measurements (IRI).
- Transverse profile (rut) measurements.
- Coring and sampling.
- Deflection measurements on the slab (FWD).
- Measurements of salt penetration into the concrete.

CRCP Performance

The CRCP slabs were at an age of one year at the time of writing this article. Until now, the preliminary overall understanding is that the slabs have performed in a satisfactory manner as shown in Figure 8. No major distress has been observed such as: pumping, spalling and punch-out failure of the CRCP slabs. Monitoring of the slabs has started from the first day of construction in order to enable the researchers to investigate the early-age behavior and repeated load effect on the performance of the CRCP slabs.

Figure 8 - Overall view for HW-40

Pavement temperature

Temperature is the most formidable force to which CRCP is subjected. It is responsible for constantly changing the conditions of stress and strain during construction and throughout the full life of the pavement. In this project, 5 groups of thermocouples were installed in 5 slabs (A3, D1, D3, E1, and F). Each group consisted of 4 wires distributed in regular manner through the pavement depth (80, 130, 180, and 230-mm from the pavement surface). Figure 9 shows the average concrete temperature variation measured by one of these groups (slab-E1) versus time. During the first year after construction, no major differences were found between the recorded temperatures from the five groups. The recorded absolute annual temperature variation was about 45°C and the maximum average differential temperature between top and bottom thermocouples reached 5°C during the winter season which is a relatively high value compared to northern states in US (Illinois, and Taxes) where CRCP is widely used (Kohler, E. and Roesler, J., 2006).

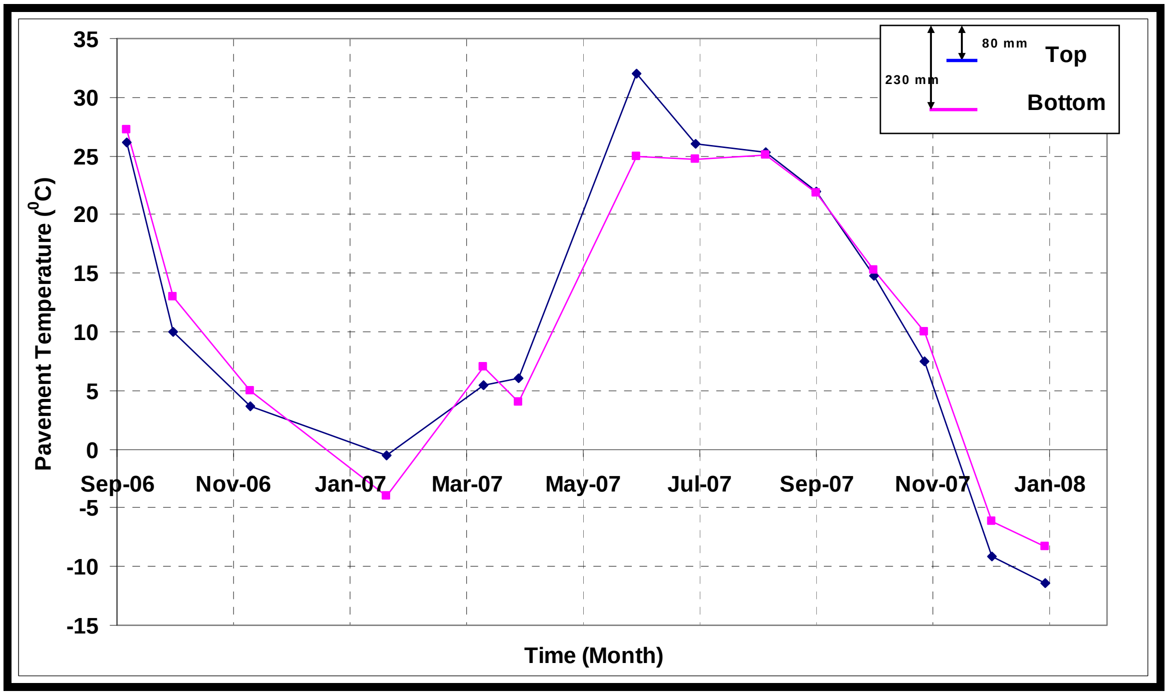

Figure 9 - Average concrete temperature variation of CRCP slabs during the first year after construction

Pavement stress

Stresses in CRCP slabs are considered one of the most important factors to understand its performance. Since the installed instrumentation measures strain, it is necessary to use the strain data to determine the stresses. Figure 10 shows typical measured strains in reinforcement as well as in concrete versus time for selected CRCP slab A4 (1.2% reinforcement ratio). The close relationship between crack formation and strain values in CRCP slabs is visible in this figure: Zone I shows the first 6 months of slab A4. Through this zone, 5 cracks were formed (No.1) causing the strain values in the uncracked sections of the slab to be low during this period. Four months later, strain values started to increase with no new crack development. Formation of only one crack (No.2) in zone II shows a significant effect in reducing strain values in this zone. The strain values started to increase again 3 months later with no new cracks; however, it was reduced by the formation of 2 new cracks (No.3) in zone III.

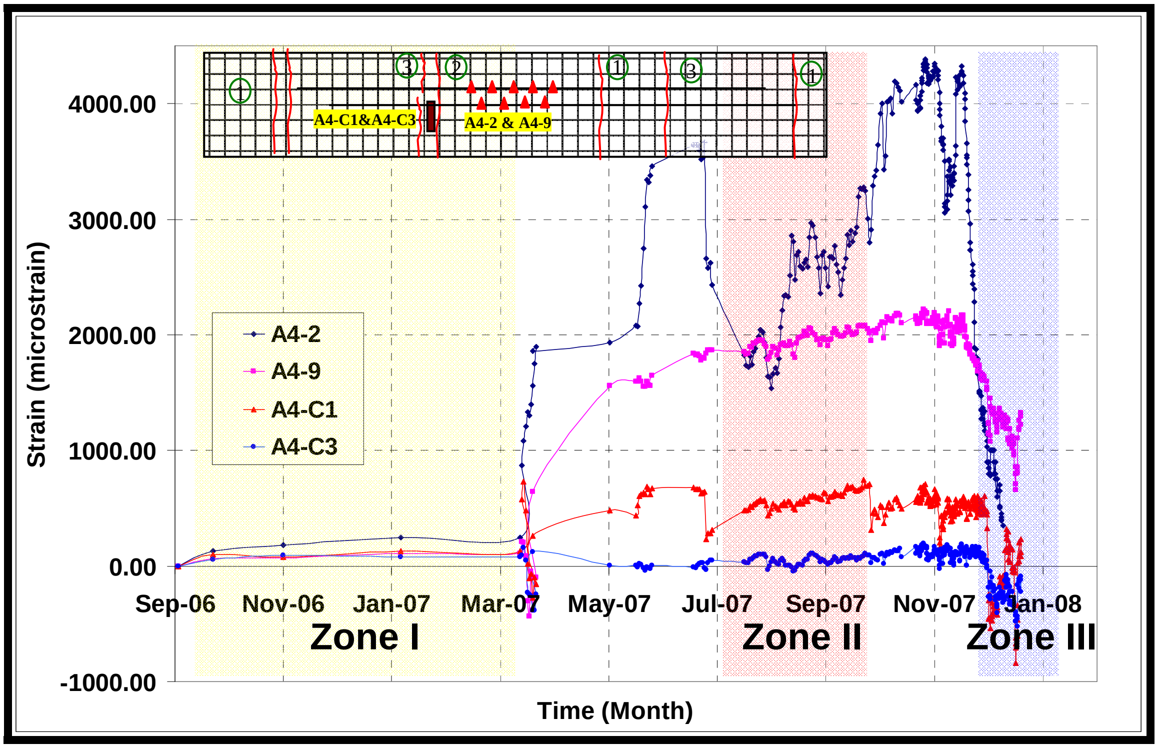

Figure 10 - Strain in reinforcement and in concrete versus the time for slab A4 (1.2 %)

Through this period, the maximum strain value was 4100 μs in the reinforcement and 170 μs in the concrete strain gages that considered within design limits of ACI 440.1R-06. In general, the strain values in this stage can not be taken as a measure for the expected sustained strain values because of the probability of propagation of new cracks in the near future that will release the stresses in CRCP slabs.

Crack Spacing and Crack Width

Crack spacing and crack width are acknowledged as the most critical issues on the performance of CRCP slabs. In this study, tracking of crack propagation and crack width on the surface of the CRCP slabs has been investigated in order to monitor their effect on the early-age performance of CRCP slabs. The survey started 20 days after casting of the CRCP slabs and was repeated in a regular manner (each 2 months). In this survey, a mapping wheel and crack comparator were used for crack spacing and crack width measurements respectively. Recently, for adequate high accuracy of crack width measurements, a digimatic indicator (Mitutoyo type) was used to show the exact change in the crack width with a resolution of 10^{-4} mm.

Figure 11 shows the average crack spacing and crack width for CRCP slab C2 during the first year after construction. It was expected that the reinforcement ratio would be the dominant effect on the average crack width and the average crack spacing of the CRCP slabs. However, due to slabs early age (one year) as well as high temperature variation, no clear relationship with respect to crack formation and the reinforcement ratio has been observed. However, it is expected with time that the reinforcement ratio will show a more significant effect with respect to crack width and crack spacing.

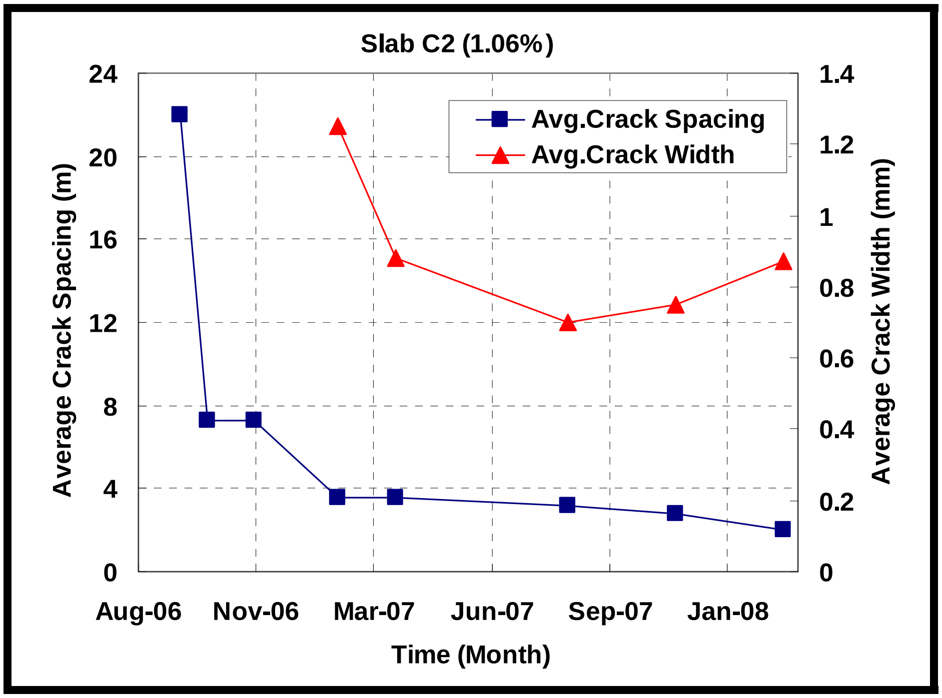

Figure 11 - Average crack spacing and average crack width for CRCP slab C2

However, it was observed that the temperature variation through the first year showed a significant effect on the performance of the slabs. It can be noted from Figures 9 and 11 that there is a relationship between pavement temperature and both average crack spacing and average crack width. As the temperature decreased (from September 2006 to February 2007 and from September to February 2008), new cracks formed in the slabs and the average crack spacing decreased, while average crack width increased. However, as temperature increased (from February to June 2007) no new cracks were formed in the slabs; consequently the average crack spacing stayed constant, and the average crack width decreased.

The latest results, measured in February 2008, show that the average crack spacing varied between 1.5 to 4 m in most CRCP slabs reinforced with GFRP. In addition, the average crack width varied between 0.7 to 0.9 mm which is less than the AASHTO design limit of 1 mm. It is also matching the average crack width values (0.9 mm) recorded for steel CRCP slabs.

Conclusions

This paper presents the objectives of the research project, questions and answers about the use of GFRP in CRCP, design, instrumentation, construction details, properties od used materials, and preliminary results of eighteen full-scale CRCP sections on HW-40 Eastbound (Montreal) reinforced with GFRP bars. Based on the construction details and the preliminary monitoring results, the following conclusions can be drawn:

- Following one year in service, the preliminary overall behavior of the CRCP slabs is satisfactory. No major distress has been observed such as pumping, spalling and punch-out failure of the CRCP slabs.
- It was observed that the variation in weathering conditions has a profound effect on the early age behavior in most GFRP-CRCP slabs.
- Until now, the reinforcement ratio did not show any significant effect on the behavior of the CRCP slabs (crack width and crack spacing). This could be due to the early age of the slabs and it is expected with time that the reinforcement ratio will show a more significant effect.
- The latest results show that the average crack spacing varies between 1.5 and 4.0 m in most CRCP slabs. In addition, the average crack width varies between 0.7 and 0.9 mm which is less than the AASHTO design limits.
- The final results of this test project could contribute in implementing the use of GFRP bars in concrete pavement. In addition, it will introduce pioneer results to the literature on the using of GFRP bars in CRCP.

In the next months, we expect to have interesting data and find better trends showing the relation between the concrete and the GRFP reinforcement. Furthermore, we hope to be able to have a design method for this kind of concrete pavement in time for our next CRCP projects in Quebec. This will able us to conduct Life Cycle Cost Analysis for different options and choose the best one that could resist the longest to our harsh climate here in Quebec.

This paper is dedicated to the memory of the co-author, Mohamed Eisa, who passed away unexpectedly at the age of 29.

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