FRPs for the rehabilitation of concrete beams exhibiting alkali-aggregate reactions

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ABSTRACT

A recently established technique for strengthening reinforced concrete structures is the external bonding of fibre reinforced polymers (FRPs). Indeed, this promising rehabilitation technology has the potential to be one of the most effective repair methods in the future. This paper deals with the use of FRPs as a rehabilitation method for concrete beams affected by alkali-aggregate reactions (AARs). Numerous corrective techniques have been developed to inhibit alkali-aggregate reactions in concrete structures. However, most of the existing techniques do not allow the structures to recover their initial mechanical properties.

In order to investigate the effectiveness of FRPs for beams exhibiting alkali-aggregate reactions, laboratory simulations are required. In this study, the effectiveness of FRPs as external reinforcement for reinforced concrete beams affected by AARs is investigated. The time schedule for the installation of the FRPs and for the flexural tests was determined in order to evaluate the composite's contribution in reducing AAR-related beam expansion and to assess the effect of FRP on flexural strength.

The effect of AARs on the behaviour of beams depends on the internal steel reinforcement, which reduces the concrete expansion and thus diminishes losses in mechanical properties. Futhermore, the development of AARs is inversely proportional to the size of the specimens. In our study we have used small-scale reinforced concrete beams (100 x 150 x 1220 mm) with two different longitudinal steel ratios (0.24 and 0.42% respectively). The concrete mix and the exposure conditions have been selected to rapidly develop the AARs. This investigation focuses on the measurements of strength variations. Also, experimental measurements of beam expansion with time will be discussed.

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INTRODUCTION

Alkali-aggregate reactions (AARs) are chemical reactions that occur between the concrete interstitial solution and reactive aggregates when the alkali content in the concrete and the relative moisture exposition are high. The commonly known symptoms of AARs are expansion, cracking, scaling, gel exudation, pop outs and early concrete degradation [1].

The loss of mechanical properties in reinforced-concrete structures, because of the unavoidable development of AARs in concrete, is a problem that must be faced all around the world, and Canada does not escape this problem. For instance, in Eastern Canada alone, over 1000 structures, most of them bridges, are known to be affected by this type of severe degradation [2].

The objective of the work presented here is to evaluate the efficiency of composite materials used as external reinforcement for RC-beams affected by AARs. Efficiency is determined by measuring the concrete expansion and the increase of flexural strength of the beams.

EXPERIMENTAL PROGRAM

Beam Specimens

For this research program, 38 small-scale beams (100 mm x 150 mm x 1220 mm) were fabricated, with the internal steel configuration shown in Figure 1. Since AARs are known to be affected by the amount of internal steel reinforcement, two different ratios of longitudinal steel reinforcement are being investigated here. Rebars with a 6 mm diameter were selected for 22 beams, and 16 beams were reinforced with 4 mm rebars. Steel ratios of 0.24% and 0.42% were achieved with the indicated dimensions. Shear failure of the beams under loading is prevented with internal stirrups made of 6 mm bars spaced at 75 mm c/c.

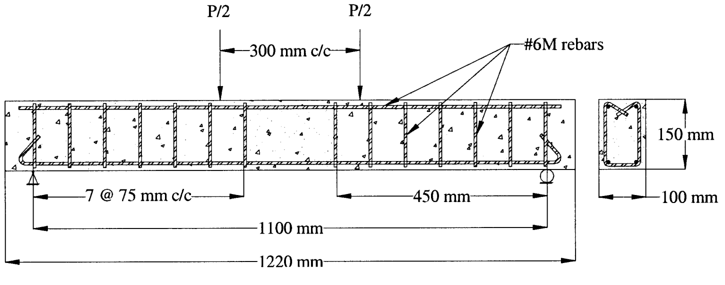

Figure 1. Beam details

Figure 2 shows the configuration of the 24 beams strengthened externally with two layers of MBrace CF-130, a carbon-fibre reinforced polymer (CFRP) material. At the extremities of the beams, U-shaped external stirrups are installed to improve the anchorage of the longitudinal reinforcement, and to prevent debonding of the CFRP when it is submitted to the four-point bending test. These stirrups are made of Fibrwrap SEH51-Tyfo, a glass-fibre reinforced polymer (GFRP) product. Since the only function of the stirrups is to prevent delamination, they are installed only shortly before testing.

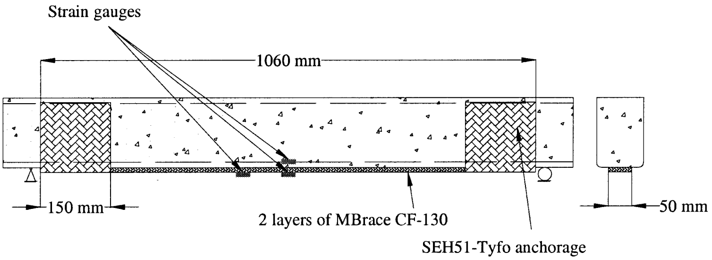

Figure 2. External reinforcement with composite materials

The CFRP schedule of installation is shown in Table 1. In the cases where the table shows that four specimens were tested, two beams with moderately reactive aggregates have been cast to compare their behaviour with that of similar beams with highly reactive aggregates.

Table 1. List of the beams for the research program

	Longitudinal Steel			
	4 mm (0.24%)		6 mm (0.42%)	
	Composite configurations		Composite configurations	
Time schedule for the installation of the composite materials and for the flexural tests	None	2 layers	None	2 layers
Test after 28 days	2	-	2	-
Installation after curing, test after 6 months	2	2	2	2
Installation after curing, test after 12 months	2	2	4	4
Installation after 6 months, test after 6 months	-	2	-	2
Installation after 6 months, test after 12 months	-	2	-	4
Installation after 12 months, test after 12 months	-	2	-	2

Total number of specimens: 38

Concrete

Two concrete mix designs were selected in order to develop AARs rapidly: one with reactive aggregates and another with moderately reactive aggregates. NaOH was added to both concrete designs to increase the alkali content to 1.25% of the cement weight. Table 2 shows the average compressive strength and elastic modulus evaluated at seven days, 28 days, six months and twelve months. These tests have been performed on standard concrete cylinders (100 mm diameter, 200 mm height).

Table 2. Concrete properties

Reactive concrete

	7 days	28 days	6 months	12 months
f'c (MPa)	30.1	34.2	43.9	42.2
E (GPa)	24.3	24.4	21.9	22.8

Moderately reactive concrete

	7 days	28 days	6 months	12 months
f'c (MPa)	28.0	32.9	42.8	45.4
E (GPa)	19.4	20.3	23.1	21.7

Steel Reinforcement

Five samples of 4 mm and 6 mm rebars were tested under uniaxial tension. The rebars exhibited an average yield stress of 600 MPa and an elastic modulus of 200 GPa.

Composite Materials

Mechanical properties for the two composite materials used in this research program are the following, according to the manufacturer's data sheets:

- Carbon-epoxy : MBrace CF-130, ultimate strength = 3550 MPa, elastic modulus = 235 GPa, ultimate strain = 0.015, thickness = 0.165 mm

- Glass-epoxy : Fibrwrap SEH51, ultimate strength = 552 MPa, elastic modulus = 27.6 GPa, ultimate strain = 0.020, thickness = 1.3 mm

We already know that the properties of CFRPs are not affected in a significant way by this kind of exposure conditions [3]. Uniaxial tests have been done on CFRP coupons (15 x 250 mm) with the ASTM D3039/D3039M-95a standard test method after six and twelve months of exposure to validate the manufacturers information.

Exposure Conditions

The exposure conditions for the beams were 38°C and 100% of relative moisture for a period of six months or one year, depending on the specimens. These conditions were selected in combination with the concrete properties in order to produce accelerated AARs at a significant rate.

Test Setup

During exposure, the expansion of 20 beams was measured on a monthly basis using Demec gauges. The location of these gauges are shown in Figure 3. There are four different positions for the expansion measurements (A = top, B = side up, C = side down and D = bottom of the beam).

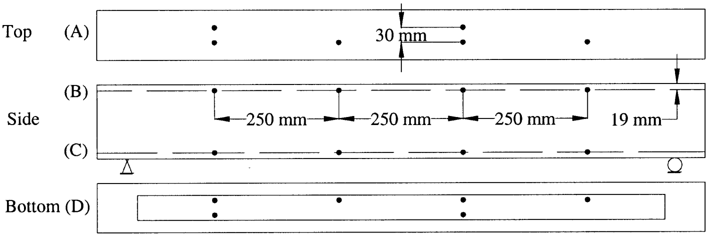

Figure 3. Positions of Demec gauges

Deformation of the steel rebars were measured using electric strain gauges on six beams on a monthly basis, to establish correlations with the expansion measurements taken with the Demec gauges at the same level on the concrete surface. Moreover, these strain gauge measurements were taken during the flexural tests of the beams.

After completion of the exposure periods, all beams were tested under a four-point bending static load up to failure as shown in Figure 1. In addition, electric strain gauges were used to measure strain on the external CFRP reinforcement for eight beams. Deflections of all 38 beams under loading were recorded with a Linear Variable Differential Transducer (LVDT) located at mid-span.

PRELIMINARY RESULTS

Expansion of the beams

After 12 months of exposure, general observations can be made for the overall expansions. Longitudinal expansions were measured between Demec gauges spaced at 250 mm as shown in Figure 3. Transversal expansions were measured between gauges spaced at 112 mm, on the side faces of the beams, and at 30 mm on the top and the bottom faces of the beams.

In view of the considerable number of expansion data, a statistical study is required to reach accurate conclusions. The statistical models used are the complete 2^3 factorial designs, and designs with both nested and factorial factors [4]. With the complete 2^3 factorial designs, we analyze results from an experiment with three different factors (composite reinforcement, expansion position and longitudinal steel ratio or type of concrete) and with two levels for each factor.

Preliminary results after five months of exposure were presented at the Third International Conference on Advanced Composite Materials in Bridges and Structures [5]. The most recent results, from the statistical analysis of the RC-beams submitted to 12 months of exposure, are presented here :

- The average expansion for the beams without CFRPs and with reactive concrete is about 0.098%;
- The expansion of beams without CFRPs is practically the same at the four measurement locations on the beam;
- The expansion of the RC-beams with 4 mm rebars is about 17.4% less than for the 6 mm rebars;

- The expansion of the RC-beams with 6 mm rebars and the one for the reactive concrete beams are not influenced in a very significant way by CFRPs;
- The expansion of the RC-beams with 4 mm and CFRPs is 17.1% less than that for the beams with 4 mm rebars only;
- The expansion on the top of the beams with CFRPs is 7.5% higher than for the beams without CFRPs;
- The expansion on the bottom of the beams with CFRPs is 9.6% less than for the beams without CFRPs;
- The beams with CFRPs tend to have an upward bending and beams without CFRPs tend to have either a downward or upward bending, in this case, much less important;
- The bending of the beams with moderately reactive concrete does not seem to be affected by CFRPs;
- For the same longitudinal steel ratio, the moderately reactive concrete RC-beams showed 31.4% less expansion than the reactive RC-beams;
- For the beams with moderately reactive concrete, the expansion of those with CFRPs is 13.8% less than for those without CFRPs.

Bending tests

The flexural strengths of the 38 beams tested are presented in Table 3. Figure 4 shows their theoretical resisting moment versus their experimental resisting moment. The theoretical resisting moment was calculated with the assumption that the failure will occur with steel yielding followed by tensile failure of CFRP. Moreover, the theoretical resisting moment was calculated with the composite material properties obtained from our laboratory tests on CFRP coupons.

We observe that the CFRP layers have increased the flexural strength of the beams by approximately 119%. The points which lie below the 45° line in Figure 4 correspond to debonding failure.

The duration of exposure of the CFRPs has a significant impact on the increase of flexural strength that can be reached by the beams. For instance, the average increase in flexural strength for all beams reaches 153% when the CFRPs are installed just prior to testing. However, when the testing is performed after a long contact between CFRPs and the AAR-affected beams, the increase in flexural strength is less important. After six-month exposure, it reaches 108%, and after twelve months, it attains 91%. While these values remain quite impressive, this is a clear indication that the AARs do affect the bond between the CFRPs and the concrete surface. Figure 5 illustrates typical load-deflexion curves of beams with 6 mm longitudinal steel.

Table 3. Flexural strengths of the 38 beams tested

	Theoretical Mr (kN.m)		Experimental Mr (kN.m)		Maximum deflexion (mm)	
Rebars	4 mm	6 mm	4 mm	6 mm	4 mm	6 mm
Reactive concrete						
Without CFRPs						
Test after 28 days	2.72	4.70	2.84	5.08	12.96	8.98
	-	-	2.83	4.97	8.96	9.75
Without CFRPs						
Test after 6 months	2.74	4.75	3.45	6.21	30.38	29.95
	-	-	3.15	6.28	42.99	14.05
Without CFRPs						
Test after 12 months	2.74	4.74	3.54	5.96	29.97	29.90
	-	-	3.46	6.22	25.53	28.20
CFRPs installed after curing						
Test after 6 months	12.50	13.07	7.50	8.71	23.40	10.00
	-	-	9.33	11.05	25.70	22.88
CFRPs installed after curing						
Test after 12 months	11.75	12.37	7.62	9.80	23.32	40.15
	-	-	8.08	10.92	25.01	26.58
CFRPs installed after 6 months						
Test after 6 months	13.05	13.75	10.61	11.67	21.93	21.91
	-	-	10.77	13.26	21.14	25.00
CFRPs installed after 6 months						
Test after 12 months	11.83	12.44	8.80	11.04	22.01	24.81
	-	-	9.06	11.50	31.63	35.38
CFRPs installed after 12 months						
Test after 12 months	11.73	12.35	9.96	12.18	22.29	18.59
	-	-	10.12	12.36	21.32	19.98
Moderately reactive concrete						
Without CFRPs						
Test after 12 months	-	4.76	-	5.84	-	25.52
	-	-	-	5.84	-	37.21
CFRPs installed after curing						
Test after 12 months	-	12.83	-	10.26	-	20.23
	-	-	-	10.48	-	25.43
CFRPs installed after 6 months						
Test after 12 months	-	12.91	-	10.98	-	32.53
	-	-	-	11.00	-	30.30

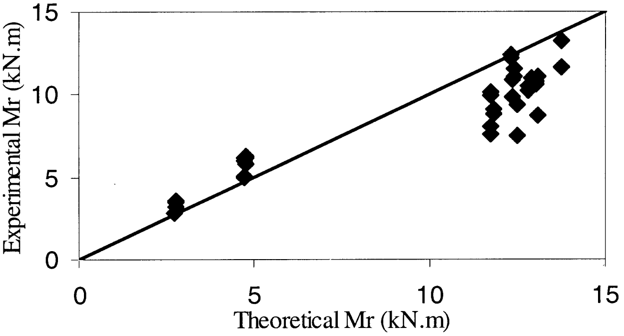

Figure 4. Flexural strength of the beams

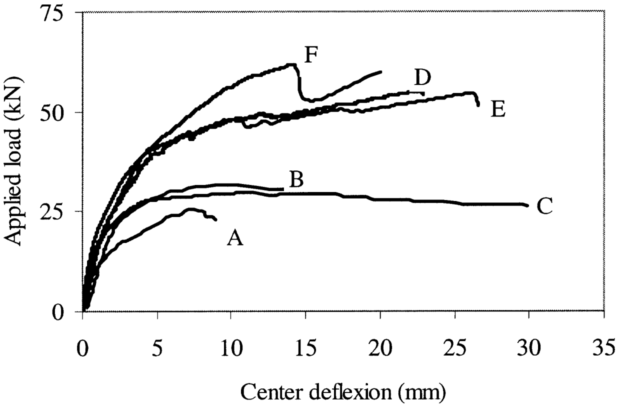

Figure 5. Typical load-deflexion curves of beams with 6 mm rebars

Legend:
A = Beam without CFRPs, tested after 28 days
B = Beam without CFRPs, tested after six months of exposure
C = Beam without CFRPs, tested after 12 months of exposure
D = Beam with CFRPs installed after the curing of the concrete, tested after six months of exposure
E = Beam with CFRPs installed after the curing of the concrete, tested after 12 months of exposure
F = Beam with CFRPs installed after 12 months, tested after 12 months of exposure

CONCLUSION

The main purpose of this research was to evaluate the contribution of the FRPs in reducing the expansion of the beams due to AARs, and also to assess the increase in their flexural strength due to the FRP strengthening. The concrete mix design and the exposure conditions have been selected to rapidly develop AARs.

Even though Table 2 shows that the concrete properties had not changed significantly after 12 months of exposure, the results of the expansion measurements already indicated preliminary signs of AARs in the beams.

The moderately reactive concrete beams showed less expansion than the more reactive concrete beams. The tendency towards an upward bending for the beams with external composite reinforcement suggests that the composite contributes to limiting the expansion at the bottom face of the beams. These expansion results were obtained with only the bottom face of the beams reinforced with CFRPs. It could be interesting to study the behaviour of columns entirely confined with FRPs or beams with all sides wrapped with FRPs.

The CFRPs have increased the flexural strength of the beams by approximately 119%. As shown in Table 3 and Figure 4, debonding failure seems to be caused by the exposure conditions. More investigations need to be undertaken to understand this problem.

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