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Complete List of Authors:	Ghazy, A. ; City of Winnipeg, Public Works Department Bassuoni, Mohamed; University of Manitoba, Civil Engineering Shehata, E. ; Tetra Tech Burmey, D.; City of Winnipeg, Public Works Department
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Comparison of Different Approaches for Determining the Residual Post-Cracking Strength Index of Fiber Reinforced Concrete for Bridges

A. Ghazy¹, M. T. Bassuoni^{2*}, E. Shehata³ and D. Burmeyer⁴

¹Research and Standards Engineer, Public Works Department, City of Winnipeg, MB, Canada and Department of Civil Engineering, Alexandria University, Alexandria, Egypt

^{2*}Associate Professor, Department of Civil Engineering, University of Manitoba, Winnipeg, MB, Canada (corresponding author: mohamed.bassuoni@umanitoba.ca)

³Vice President, Tetra Tech, Winnipeg, MB, Canada

⁴Bridge Planning & Operations Engineer, Public Works Department, City of Winnipeg, MB, Canada

Abstract

In Canada, there are different approaches to evaluate the performance of fiber reinforced concrete (FRC) for bridges based on the residual post-cracking strength index (R_i). They involve different combinations of test methods ASTM C78, ASTM C1399, and ASTM C1609. The aims of this study were to assess all possible (existing and new) methods to determine the R_i values, and capture the major differences between the current Canadian Highway Bridge Design Code (CHBDC S6-14) and City of Winnipeg (COW) specification's approaches, as a case study. Flexural tests [ASTM C78, ASTM C1609 and ASTM C1399] were performed on 60 FRC beams (100×100×350 mm) prepared from concrete provided by four ready-mix concrete suppliers according to COW bridge deck specifications for a project built in Winnipeg. The results showed that all the methods implemented herein for calculating the R_i of FRC gave comparable results. However, by using Method V, all required parameters (first peak load and residual loads at specified deflections) could be directly extracted from one load-deflection curve obtained from ASTM C1609. In addition, when using this method, the R_i can be calculated for each specimen, which enables quantifying the magnitude of variation from average values. Since this approach also requires less number of specimens, reducing time and cost of testing, it has been adopted by COW in bridge specifications for FRC.

29 **Keywords:** Fiber reinforced concrete, Bridges, Residual post-cracking strength index, CHBDC.

30 1. Introduction

31 Fiber reinforced concrete (FRC) is a special type of concrete comprising a volume fraction,
32 typically ranging between 0.1 to 4%, of discrete and randomly distributed metallic (e.g. steel) or
33 non-metallic (e.g. polypropylene or polyolefin) fibers, which may eliminate the need for
34 conventional crack control reinforcement and also improves the early-age and consequently
35 long-term performance of reinforced concrete structures. For example, the City of Winnipeg uses
36 FRC in bridges in deck slabs, barriers and overlays to control cracking from plastic shrinkage,
37 thermal stresses, drying shrinkage, and mechanical loading.

38 Currently, there are different approaches to evaluate the performance of FRC for bridges
39 in Canada. The latest and previous versions of the Canadian Highway Bridge Design Code
40 (CHBDC) [CSA S6 2000, 2006, and 2014] stipulate that the appropriate fiber volume in FRC
41 shall be based on the residual post-cracking strength index (R_i) such that it meets or exceeds
42 specific values ranging between 0 to 0.30 depending on the particular application and the number
43 of directions (meshes) of conventional cracking-control reinforcement. In the 2000 version of the
44 CHBDC, no reference to the number of meshes of conventional reinforcement was given and R_i
45 of 0.30 was required. In the 2006 version of CHBDC, the code required R_i of 0.1 for deck slabs
46 with one crack-control mesh. This value was increased to 0.25 in the 2014 version. For deck
47 slabs with two crack-control meshes, no fibers are required in concrete for crack control in the
48 2006 and 2014 versions of CHBDC. Details of the use and development of R_i for FRC were
49 described in Banthia and Dubey [1999 and 2000] and Banthia and Mindess [2004 and 2011].

As an example of a Canadian transportation agency, the City of Winnipeg (COW) has specified the use of FRC for the construction of superstructure elements of bridges since 2002 and has found it to be beneficial in the control of early-age plastic and drying shrinkage cracking. The COW uses FRC with two meshes of conventional reinforcement. Currently, R_i of 0.15 at seven days [COW Bid Opportunity No.478-2015] is used and field experience has shown that this value coincides with a reasonable dosage of synthetic fibers allowing for workable concrete and in turn feasible placement and finishing operations. According to CHBDC [2014], the R_i is calculated through the combined use of ASTM C78 and ASTM C1399 by:

$$R_i = ASR/R \tag{Eq. 1}$$

where:

ASR = mean value of the average residual strength (MPa) in the reloading curve at deflections of 0.50, 0.75, 1.00, and 1.25 mm according to ASTM C1399 [2015] on at least five FRC beam specimens, and

R = mean value of the modulus of rupture (MPa) determined by performing ASTM C78 test [2018] on at least five FRC concrete specimens.

The COW originally followed the 2000 version of the CHBDC but had difficulties in some projects (high variations of calculated R_i), resulting in the combined use of ASTM C1399 and ASTM 1609 utilizing closed loop equipment. Currently, the COW uses a comparable approach to CHBDC to determine the R_i of FRC for bridge elements, but with some differences in the terms of the equation:

$$R_i = P_{pcr}/P_p \tag{Eq. 2}$$

where:

P_{pcr} = the highest peak load (kN) during the reloading curve using the ASTM C1399 [2015] on five FRC beam specimens, which is slightly different from ASR defined in Eq. 1, and

P_p = mean value of the peak (cracking) loads (kN) by performing ASTM C1609 [2012] on five FRC concrete specimens up to failure.

The major difference between CHBDC (Eq. 1) and COW (Eq. 2) is that the COW requires the determination of the peak/cracking load of FRC via a more sophisticated technique described by ASTM C1609 [2012], which requires special instrumentation and configuration (a closed loop testing machine). Also, there has been no technical or research studies comparing among these or other approaches, to rule out differences in the calculated R_i . Since the R_i is an important parameter for the evaluation of FRC in concrete bridges according to CHBDC, the main objective of this study was to conduct a comparative study on all possible (existing and new) approaches to determine the R_i of FRC to capture differences, if any. For this purpose, ASTM flexural test methods (commonly used in Canada) were conducted on numerous test specimens prepared from concrete mixtures supplied by different ready-mix plants, meeting the COW construction specifications for bridges' superstructure as a Canadian case study.

2. Methodology

This study consisted of testing 60 FRC beams (100×100×350 mm) prepared from concrete provided by four ready-mix concrete suppliers. Fifteen FRC beams were cast under field conditions (26°C and 65% RH) during the construction of a bridge project in Winnipeg. Supplier I provided this concrete according to COW bridge performance specifications [Bid Opportunity No.478-2015], following the guidelines of “performance” in Annex J of CSA A23.1 [2014]. After 24 h, the beams were transferred to the laboratory for standard curing (20°C and more than 95% RH) and testing at 7 days. The other 45 FRC beams were cast under laboratory conditions and cured similar to the previous ones. The beams were prepared from concrete provided by Suppliers II, III, and IV (15 beams each) designed according to the same COW bridge

specifications. In these performance specifications, FRC should meet a class of exposure C-1, according to CSA A23.1/A23.2 [2014] and achieve a minimum compressive strength of 35 MPa at 28 days and R_i of 0.15 at 7 days. The tests described below were performed on FRC.

Fresh Properties

The properties of the fresh concrete (consistency and air content) were evaluated for all the FRC mixtures. The slump was determined according to ASTM C143 [2015]. In addition, the fresh air content of the mixtures was measured according to ASTM C231 [2017].

Mechanical properties

For each batch, triplicate 100×200 mm concrete cylinders were prepared for the compressive strength test according to ASTM C39 [2018], which were performed at different ages (7 and 28 days). Also, sixty 100×100×350 mm FRC beams were prepared from concrete mixtures supplied by ready-mix plants according to COW bridge specifications [Bid Opportunity No.478, 2015] to perform the three flexural tests: ASTM C78 [2018], ASTM C1399 [2015], and ASTM C1609 [2012] (five prisms for each flexural test). Five approaches were used to determine the R_i of FRC as described below. Approaches I and III exist in the current practice, whereas approaches II, IV and V are new/proposed.

I. COW approach: R_i was calculated from the ratio between the average of the highest peak loads during the reloading curves using ASTM C1399 [2015] on five beams, divided by the mean value of the peak (cracking) loads by performing ASTM C1609 [2012] on five beams.

II. Modified COW approach: R_i was calculated from the ratio between the average load in the reloading curve at deflections of 0.50, 0.75, 1.00, and 1.25 mm according to ASTM

C1399 [2015] on five beams, divided by the mean value of the peak (cracking) loads by performing ASTM C1609 [2012] on five beams.

III. Canadian Highway Bridge Design Code (CSA S6 2014) approach: R_i was calculated from the ratio between the average load in the reloading curve at deflections of 0.50, 0.75, 1.00, and 1.25 mm according to ASTM C1399 [2015] on five beams, divided by the mean value of the modulus of rupture determined by performing ASTM C78 [2018] on five beams.

IV. Modified CHBDC approach: R_i was calculated from the ratio between the average load at deflections of 0.50, 0.75, 1.00, and 1.25 mm using ASTM C1609 [2012] on five beams, divided by the mean value of the modulus of rupture determined by performing ASTM C78 [2018] on five beams.

V. ASTM C1609 only: R_i was calculated for each beam, by performing ASTM C1609 [2012], as the ratio between the average load at deflections of 0.50, 0.75, 1.00, and 1.25 mm divided by the peak (cracking) load in the same load-deflection curve. This was repeated for five beams to calculate the average R_i .

3. Results

Table 1 shows the properties of the fresh and hardened FRC for all mixtures. Also, Figures 1, 2, and 3 show the summarized results for the FRC beams tested according to ASTM C78 [2018], ASTM C1399 [2015] and ASTM C1609 [2012], respectively.

4. Analysis

The R_i from all the approaches were calculated and the results are shown in Table 2, along with the average R_i from the five methods and the coefficient of variation among them.

The results were also statistically analyzed by the analysis of variance (ANOVA) method at a significance level $\alpha = 0.05$. ANOVA is a statistical model used to analyze the differences between group means and their variation among and between groups [Montgomery 2014]. According to ANOVA, exceeding the critical value of an F -distribution density function reflects that the tested variable significantly affects the mean of results. Also, the p -value is the probability of obtaining a result as extreme as, or more extreme than, the result actually obtained when the null hypothesis is true.

Generally, all the methods implemented herein for calculating the R_i of FRC produced comparable results without statistical significance within the results of each supplier, as the coefficient of variation was small within the range of 1.9 to 6.3%. Also, the F value, among the five methods, was 0.52 (p -value of 0.72) which is less than the F_{cr} of 3.26. The COW approach (Method I, using the highest peak [P_{max}] on the reloading curve from ASTM C1399 [2015]) for determining the R_i of FRC yielded comparable (average of 3% higher) results compared to the CHBDC approach (Method III). Also, using the average of post-cracking loads at specific deflections as stipulated by ASTM C1399 [2015] test (Method II, Modified COW approach) yielded comparable or slightly lower (maximum of 5%) results compared to the COW approach (using P_{max} on the reloading curve). On the other hand, the modified CHBDC approach (Method IV, using ASTM C1609 [2012] instead of ASTM C1399 [2015]) had comparable ($\pm 2\%$) results to the CHBDC approach.

Using ASTM C1609 [2012] alone in Method V for determining the R_i of FRC yielded a marginal variation (within $\pm 9\%$) compared to all the other approaches. However, by using this approach, all the parameters (first peak load and residual loads at specified deflections) could be

extracted from one load-deflection curve. In addition, the R_i was calculated for each replicate beam, which enabled quantifying the magnitude of variation or dispersion of the data by calculating the standard deviation from the mean R_i values of each supplier [Table 2], which was not possible by the other approaches. This ensured that no single beam had R_i less than the required threshold of 0.15.

5. Concluding Remarks

- All the five methods implemented herein for calculating the R_i of FRC gave comparable results, without statistical significance. However, only ASTM C1399 and ASTM C1609 tests are explicitly prescribed for determining the flexural behavior of FRC.
- The specified COW approach (Method I, combination of ASTM C1399 on five beams and ASTM C1609 on additional five beams) for determining the R_i of FRC yielded comparable (average of 3% higher) results to the CHBDC approach (Method III, combination of ASTM C1399 on five beams and ASTM C78 on additional five beams), without statistical significance among the population of data analyzed (60 FRC beams).
- Using ASTM C1609 alone and the proposed approach described in Method V for determining the R_i of FRC yielded close (within $\pm 9\%$) results relative to the other approaches implemented herein without statistical significance within the data of each supplier. In addition, the R_i was calculated for each beam based on data from one load-deflection curve, which enabled quantifying the magnitude of variation of the mean values from the required threshold. Also, this approach requires less number of prisms (five beams), which will shorten the time of testing and associated costs. Therefore, it has

been adopted by the COW for determining the R_i of FRC in new bridge specifications, and it may be worth considering by other Canadian jurisdictions and CHBDC.

- Concerted efforts are still needed among Canadian jurisdictions and code committees using other performance or perspective specifications to further verify the generality of Method V for calculating the R_i of FRC, which is recommended for future research.

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236 **Table 1.** Properties of fresh and hardened FRC mixtures

237 **Table 2.** Summary of R_i values

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239 **Figure 1.** ASTM C78 results (Note: error bars in this figure represent standard deviation).

240 **Figure 2.** ASTM C1399 results (Note: the values between brackets are the standard deviation).

241 **Figure 3.** ASTM C1609 results (Note: the values between brackets are the standard deviation).

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	Fresh properties		Hardened properties	
	Slump (mm)	Fresh air-content %	Compressive strength (MPa) at 7 days	Compressive strength (MPa) at 28 days
Target values according to COW specifications	--	5 – 8 %	--	≥ 35
Supplier I	125	7	29.3 [0.5]	39.3 [0.6]
Supplier II	140	7	32.6 [0.7]	38.6 [0.3]
Supplier III	120	5	48.9 [0.3]	61.5 [0.5]
Supplier IV	110	6	26.9 [0.9]	35.1 [0.6]

*The values between brackets are the standard deviation for the compressive strength results.

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Supplier	Approach					Average	Coefficient of Variation (%)
	I- COW	II- Modified COW	III- CHBDC	IV- Modified CHBDC	V- ASTM C1609		
I	0.22	0.19	0.22	0.21	0.20 [0.03]	0.21	6.3
II	0.22	0.22	0.22	0.20	0.22 [0.07]	0.22	4.1
III	0.23	0.23	0.23	0.23	0.24 [0.06]	0.23	1.9
IV	0.38	0.38	0.38	0.39	0.36 [0.04]	0.38	2.9

*The values between brackets are the standard deviation for the R_i values.

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