Cement & Concrete Composites 31 (2009) 555–563

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Durability of recycled aggregate concrete designed with equivalent mortar volume method

Abdelgadir Abbas [a], Gholamreza Fathifazl [b], O. Burkan Isgor [c,*], A. Ghani Razaqpur [d], Benoit Fournier [e], Simon Foo [f]

[a] Amec Americas, Calgary, Alberta, Canada
[b] Adjeleian Allen Rubeli Consulting Structural Engineers, Ottawa, ON, Canada
[c] Carleton University, Department of Civil and Environmental Engineering, 1125 Colonel By Drive Ottawa, ON, Canada KIS 5B6
[d] McMaster University, Department of Civil Engineering, Hamilton, ON, Canada
[e] Laval University, Department of Geology and Geological Engineering, Québec, QC, Canada
[f] Public Works and Government Services Canada, Gatineau, Quebec, Canada

ARTICLE INFO

Article history:
Received 10 September 2008
Received in revised form 9 February 2009
Accepted 11 February 2009
Available online 25 February 2009

Keywords:
Recycled concrete aggregate (RCA)
RCA-concrete
Mix design
Chloride penetration
Carbonation
Freeze-and-thaw action

ABSTRACT

Results of a comprehensive investigation about the durability of structural-grade concrete made with recycled concrete aggregate (RCA) are presented. The RCA-concrete mixes were proportioned using a new concrete mix design method, termed the equivalent mortar volume (EMV) method. The EMV method is based on the hypothesis that RCA is a composite material comprising mortar and natural aggregate; therefore, when proportioning a concrete mixture containing RCA, one must account for the relative amount and properties of each the two components and adjust both the fresh coarse aggregate and fresh paste content of the mix accordingly. Tests were conducted to study the freeze–thaw, chloride penetration and carbonation resistances of the mixes proportioned by the EMV method and by the conventional method. Results of the test showed that RCA-concrete mixes proportioned by the EMV method have higher resistance to freeze–thaw action, chloride penetration and carbonation than those designed with the conventional method, and they satisfy the current requirements for concrete exposed to severe environments.

1. Introduction

As the supply of suitable fresh aggregates in some locations is rapidly dwindling and such aggregates need to be transported from remote locations [1], there are economic and environmental benefits to the use of recycled concrete aggregate (RCA) in making structural-grade concrete [2]. The recycled aggregate concrete – termed RCA-concrete – must, however, satisfy certain mechanical and durability requirements before it can be used as a structural material. The unique circumstances imposed on concrete structures by harsh environmental conditions in some localities (e.g. the extensive use of de-icing salts or freeze-and-thaw cycles) require a comprehensive investigation of the durability of RCA-concrete for application under those conditions.

So far in the literature, the conventional mix proportioning methods for normal concrete, with some adjustments such as using larger quantities of cement, have been used for proportioning recycled aggregate concrete mixes without paying attention to the residual mortar content of RCA [3–8]. Although equal or higher compressive strength has been achieved by adjusting the mix proportions [2,9], these adjustments have usually resulted in RCA-concrete suffering from lower elastic modulus and less resistance to freeze-and-thaw action than similar conventional concrete. The concrete proportioned by the conventional methods has higher total mortar content, which in turn results in it being vulnerable to attack by severe environmental conditions and exposure to chemicals. To overcome this problem, a new mix proportioning method was developed by the authors of this paper [10]. The method is based on the hypothesis that RCA is a two-phase material comprising residual mortar and original virgin aggregate; therefore, when proportioning a concrete mixture containing RCA, the volume and properties of each phase must be taken into account. In other words, it cannot be assumed, as is currently customary, that RCA simply replaces natural aggregate in the mix because it also changes the overall mortar content of the mix due to presence of the attached residual mortar in RCA. The main feature of the proposed method, dubbed equivalent mortar volume (EMV) method, is treating residual mortar in RCA as part of total mortar volume of concrete. The total mortar volume is considered as the sum of residual and fresh mortar volumes in concrete made with recycled aggregate, and termed RCA-concrete for the sake of brevity.

* Corresponding author. Tel.: +1 613 520 2600x2984; fax: +1 613 5203951.
E-mail address: burkan_isgor@carleton.ca (O.B. Isgor).

0958-9465/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconcomp.2009.02.012

Since the RCA-concrete mixes proportioned by the EMV method do not suffer from the aforementioned shortcomings of concrete proportioned by the conventional methods, it is expected that the former mixes will provide better resistance to severe environmental conditions and chemical actions. To verify this, an extensive experimental study was carried out to investigate the resistance of RCA-concrete mixes proportioned by the EMV method to freeze-and-thaw action, chloride penetration, and carbonation. It is acknowledged that that the durability problems associated with concrete are not limited to these three; however, harsh environmental conditions that are present in northern climates bring these three issues to the forefront of the possible durability problems that would be encountered by RCA-concrete. The concrete mixes in the present study involved mixes (1) containing coarse RCA and proportioned by either the conventional mix design method or the EMV method and (2) containing coarse natural aggregate of similar properties to the original virgin aggregate of coarse RCA proportioned by the conventional mix design method. The latter are control mixes and are used as reference for assessing the performance of the RCA-concrete mixes. Before the presentation of the experimental program, a brief description of the EMV method is presented in the following section.

2. Equivalent mortar volume (EMV) method

The total volume of mortar in concrete produced with RCA is made of residual mortar and new mortar. When conventional mix design is used, the RCA is considered as part of the coarse aggregate, and no consideration is given to the volume of attached residual mortar. Because of this, concrete produced with RCA has larger volume of total mortar (residual and new) than that of a mix designed using the same method but containing natural aggregate only. The EMV method involves the determination of the appropriate amount of RCA to be used in the mix in relation to the amount of coarse natural aggregate that would be used in a conventional concrete mix with the same specified properties. This approach guarantees that the volume of total mortar (residual and new) in concrete produced with RCA be equivalent to that in the conventional concrete. Alternatively, the EMV method ensures that the total volume of coarse natural aggregate (partly from RCA and partly from new fresh aggregate added to the batch) in RCA-concrete is equal to the volume of natural aggregate in conventional concrete with the same specified properties. The derivation of the equations for the EMV method will not be presented here; however, it can be found in Ref. [10].

The method commences by using current mixture proportioning methods to determine the proportions of the ingredients of a conventional concrete mix with the same specified properties as the target RCA-concrete. For generality, the target RCA-concrete mix is assumed to be made with a blend of fresh coarse natural aggregate and RCA, with the proportion of each aggregate type determined by the mix designer. For this purpose, a parameter R is defined as the ratio of the fresh natural aggregate content of RCA-concrete to the fresh natural aggregate content of the companion conventional mix. According to the EMV method the required volume of RCA to guarantee equivalent total natural aggregate content in RCA-concrete as the companion conventional concrete with the same specified properties can be calculated using:

$$V_{\mathrm{RCA}}^{\mathrm{RCA\text{-}concrete}} = \frac{V_{\mathrm{NA}}^{\mathrm{NAC}} \times (1 - R)}{(1 - \mathrm{RMC}) \times \frac{SG_b^{\mathrm{RCA}}}{SG_b^{\mathrm{OVA}}}} \tag{1}$$

where $V_{\mathrm{RCA}}^{\mathrm{RCA\text{-}concrete}}$ is the volume fraction of coarse RCA in RCA-concrete, $V_{\mathrm{NA}}^{\mathrm{NAC}}$ is the volume fraction of fresh natural aggregate in the companion conventional concrete, RMC is the residual mortar content of the RCA, SG_b^{RCA} and SG_b^{OVA} are the experimentally determined bulk specific gravity values of RCA and original virgin aggregate, respectively, and R is the volume ratio of the fresh natural aggregate content of RCA-concrete to the fresh natural aggregate content of the companion conventional mix. The residual mortar content (RMC) of RCA can be experimentally determined by a method developed by the authors as detailed in [11]. After calculating the required volume of RCA, the proportions of fine aggregate, cement, and water in RCA-concrete are determined.

It is noteworthy that in the proposed EMV method, by assuming different R values, many alternatives RCA-concrete mixtures with the same total mortar and total natural aggregate volumes, but with different residual mortar/fresh mortar volume ratios, can be designed. In other words, contrary to the conventional mix proportioning methods, adoption of different R values in the EMV method does not result in overall higher mortar volume in RCA-concrete compared to the companion natural aggregate concrete. In this study, to have the same total mortar volumes for the RCA-concrete mixes and the control normal concrete mixes, the fresh natural aggregate volume of the RCA-concrete was increased by an amount equal to the volume of the residual mortar of RCA. Accordingly, the RCA content, as percentage of the total coarse aggregate volume, were determined to be 63.5% and 74.3%, for the mixes made with RCA from Montreal (RCA-MO) and Vancouver (RCA-VA), respectively.

3. Experimental program

3.1. Material characterization of RCA

The recycling plants that provided the RCA for the present study receive concrete from various demolition projects, and the material that they produce incorporates a blend of virgin aggregates from different sources. The first batch of RCA was obtained from a recycled aggregate processing plant located in Montreal, Québec (RCA-MO), and the second was from a plant in Vancouver, British Columbia (RCA-VA). RCA-MO was obtained from concrete in which the natural aggregates were crushed limestone, and RCA-VA was obtained from demolition concrete made predominantly with well-rounded river gravel. Since the RCA from both sources were received unscreened and ungraded, before starting the material characterization testing, they were mechanically screened to remove the impurities and fines and to separate the RCA into different particle sizes using sieves with openings of 4.75, 9.5, 12.7, 19, and 25 mm. To avoid damage to the RCA, the sieving time was fixed to 30 s per batch, and after sieving the RCA was washed, air dried, and stored in drums for later use in the material characterization tests.

Petrographic examination of the RCA-MO showed that the original virgin aggregates essentially consisted of manufactured (crushed) fine-grained, dark-grey limestone. On the other hand, the original virgin aggregates in RCA-VA consisted of well-rounded polygenic gravel, which is mainly composed of various volcanic and intrusive (~granitic) rock types, with some (lower proportions) particles of quartzite, chert, sandstone and limestone. In general, particle size distribution of the original virgin aggregates in RCA-MO and RCA-VA were within the typical range used in "conventional" concrete, i.e. 5–25 mm.

Further examination of residual mortar was performed under the petrographic microscope (reflected light) and the scanning electron microscope (SEM) to identify additional micro-textural and compositional characteristics that could help in understanding of the performance of the RCA in the various tests performed in the laboratory. The origin of the concrete from which the two types of

Table 1
Average physical properties for coarse and fine aggregates.

Aggregate	Porosity (%)	Absorption capacity (%)	Specific gravity			RMC (%)
			Bulk	SSD	Apparent	
RCA-MO	12.3	5.4	2.31	2.42	2.64	41
RCA-VA	8.1	3.3	2.42	2.50	2.64	23
Limestone	0.9	0.34	2.70	2.71	2.73	0
River gravel	2.4	0.89	2.72	2.74	2.79	0
River sand[a]	–	0.54	2.70	2.72	2.76	–

[a] Sand with fineness modulus of 2.60.

RCA were derived is unknown; however, it was found that the residual mortar of RCA-MO generally contained more air voids than that the mortar of RCA-VA [12]. In accordance with National Standards in Canada [13], concrete exposed to the elements to incorporate between 4% and 9% of entrained air for frost resistance. Although the exposure conditions in the Vancouver area are milder than those in Montreal, nevertheless, exposed concrete in both regions are expected to be normally air entrained. The other main observation made on residual mortar under the SEM was the presence of fly ash particles in the residual mortar of the RCA-VA [12]. For the past 30 years, it has been common practice in the greater Vancouver area to replace 20–25% of cement by mass with fly ash; the fly ash is classified as a CSA type CI, i.e. with an intermediate (~10–15%) calcium oxide content [14].

The material characterization involved the determination of the absorption capacity, specific gravity, porosity and the residual mortar content (RMC) for RCA-MO, RCA-VA and natural aggregates used to produce the concrete specimens. The weighted average values of these properties are given in Table 1. The specific gravity and absorption capacity tests were performed as per ASTM C 127-88 [15]. The RMC of each RCA type was determined based on a new method developed by Abbas et al. [11] which involved immersion of RCA in sodium sulphate solution and its subjection to several freeze-and-thaw cycles. RMC is the percentage of the residual mortar by weight in the RCA, and it can be observed in Table 1 that RCA-MO has a larger RMC than RCA-VA (41% vs. 23%). Further details of materials characterization testing of RCA can be obtained from Ref. [16].

3.2. Sample preparation

The present study focuses on the durability properties of RCA-concrete involving RCA-MO and RCA-VA with the mixes proportioned by the EMV method. The experimental study was designed to eliminate the effects of water–cement ratio and compressive strength of concrete by keeping these parameters constant ($w/c = 0.45$ and $f'c = 35–40$ MPa). However, the effect of the binder type, involving supplementary cementitious materials such as fly ash and ground granulated blast furnace slag, bfs, on the durability properties were investigated. The replacement ratio based on weight of cement, and expressed as percentage, was 25% for fly ash and 35% for bfs. The fly ash was CSA CI type with average specific gravity of 2.01, and the bfs was Grade 80 with average specific gravity of 2.99. In addition, all mixes were prepared as air entrained (targeting 6% air content) to eliminate the effect of air content on the durability properties of RCA-concrete.

The mixture proportions are presented in Table 2 in which the mix designations are based on the following notation: (1) E or C (for mix design method): mixes proportioned by the EMV (E) or the conventional (C) method, (2) M, V, L or G denote mixes whose coarse aggregate include RCA-MO (M), RCA-VA (V), natural limestone only (L) or natural gravel only (G), and (3) C, F or B signify the binder type in the mix, i.e. mixes containing ordinary portland cement only (C), ordinary portland cement plus 25% fly ash (F), or ordinary portland cement plus 35% bfs (B). For example, CM-B represents a mix proportioned by the conventional method, made with RCA-MO and incorporating bfs.

It is important to mention that the EMV method decreases the cement requirement of the mix because it requires less fresh mortar than required by the conventional method. The lower cement requirement makes the RCA-concrete proportioned by EMV method more environmentally friendly. As it can be seen from Table 2, the cement content of the mixes without RCA proportioned by the conventional method is above 400 kg/m^3. When a companion RCA-concrete mix, with a total mortar volume equal to the corresponding conventional mix is designed by the EMV method, the cement content drops to 335 kg/m^3 and 358 kg/m^3 for the mixes made with RCA-MO and RCA-VA, respectively.

After the mixing process, the concrete was cast and cured for 24 h following the procedures described in ASTM C 192/C 192 M-00 [15]. For each concrete mix, three 75 × 100 × 400 mm prisms were prepared for freeze-and-thaw tests in compliance with ASTM C666-97 [15] requirements. Similarly, for each mix three 100 × 100 × 406 mm prisms were prepared for the accelerated carbonation tests. For the chloride penetration tests, for each mix, three cylindrical specimens with 100 mm diameter and 200 mm length were cast. In addition, for each mixture, three cylinders with diameter of 150 mm and length of 300 mm were cast to determine the 28-day compressive strength. For the mixes containing fly ash or bfs, an additional two cylinders were cast to

Table 2
Mix design proportions of mixes.

Mix ID	RCA content (%)	Mix proportions (kg/m^3)							WRA[a] (ml)	AE[a] (ml)
		w	c	Fly ash	BFS	Sand	Coarse aggregate			
							RCA	NA[a]		
CM-C	100	156	349	0	0	888	792	0	1396	35
CM-F	100	157	262	87	0	888	792	0	None	209
CM-B	100	155	227	0	122	888	792	0	523	35
EM-C	63.5	151	335	0	0	630	720	414	1005	33
EM-F	63.5	151	251	84	0	630	720	414	606	201
EM-B	63.5	149	218	0	117	630	720	414	1339	33
CL-C	0	193	430	0	0	808	0	835	None	86
CV-C	100	156	349	0	0	857	867	0	1047	35
CV-F	100	157	262	87	0	857	867	0	None	209
CV-B	100	155	227	0	122	857	867	0	1047	35
EV-C	74.3	161	358	0	0	645	813	281	1075	36
EV-F	74.3	161	269	90	0	645	813	281	None	215
EV-B	74.3	160	233	0	125	645	813	281	1792	36
CG-C	0	191	424	0	0	763	0	900	None	85

[a] NA: natural coarse aggregate; WRA: water reducing agent and AE: air entraining agent.

determine their 56-day compressive strength. Specimens were stored for 28-days in a moist room in accordance with the requirements of ASTM C 511–98 [15].

3.3. Fresh and hardened properties of concrete samples

It is generally accepted that there is a correlation between some of the fresh and hardened properties of concrete and its durability. In general, concrete with proper air entrainment, slump, and compressive strength, cast without segregation or bleeding, is expected to be durable. Therefore, the objective of this study was to produce workable RCA-concrete with comparable compressive strength and air content as conventional concrete. It is acknowledged that the compressive strength of concrete may not always be an indicator of its durability, especially when supplementary cementitious materials are used; however, for structural-grade concrete, high strength is a major design parameter. Table 3 presents the measured fresh and hardened properties of the concrete mixes.

With reference to the table, all RCA-concrete mixes designed with the conventional mix design method and the EMV method were found to be workable, with their slump ranging between 55 mm (CM-B) and 150 mm (EV-B). It can also be observed that the air content for all concrete mixes varied from 5.5% (EV-F) to 7.4% (CM-F and CV-C). These results are in line with the targeted air content of 6% and are within the range of 5–8% specified by CSA 23.2-04 [13] for severe exposure conditions. The fresh density values of RCA-concrete mixes designed by EMV method are higher than the corresponding mixes designed by the conventional method. This can be attributed to the lower total mortar volume of the mixes designed by the EMV method compared to the corresponding mixes designed by the conventional method. The hardened density of the specimens ranged from 2217 kg/m^3 (CM-F) to 2325 kg/m^3 (EV-B), which is within the expected range for normal density concrete.

The 28-day compressive strength of the mixes varied from 34 MPa (CM-F) to 42.0 MPa (CM-B and EM-B), which is within the range of the target strength. The 56-day compressive strength of the specimens containing supplementary cementitious materials was 40 MPa or higher. It is important to note that the compressive strengths of specimens made of mixes designed by the EMV method are higher than those made of mixes designed by the conventional method. Although this difference is not significant (2–5 MPa), it demonstrates that RCA-concrete mixes designed by the EMV method could have higher strength than companion concrete mixes without RCA despite the lower cement content of the former mixes.

Table 3
Fresh and hardened properties of the mixes.

Mix ID	Fresh property			Hardened property		
	Slump (mm)	Air entrained (%)	Density (kg/m^3)	f'_c (MPa)	Density (kg/m^3)	$f'c^{56}$ (MPa)
CM-C	70	6.9	2262	41.8	2264	–
CM-F	130	7.4	2226	34.0	2217	38.5
CM-B	55	6.0	2281	42.0	2269	44.8
EM-C	105	6.0	2305	39.2	2295	–
EM-F	120	5.7	2291	34.2	2293	40.9
EM-B	80	5.7	2306	41.8	2319	46.3
CL-C	175	6.3	2332	36.9	2300	–
CV-C	70	7.4	2306	39.7	2285	–
CV-F	90	6.0	2291	35.0	2281	40.8
CV-B	110	7.1	2286	39.3	2289	41.3
EV-C	140	6.0	2328	40.0	2321	–
EV-F	140	5.5	2321	35.2	2304	42.3
EV-B	150	6.8	2316	40.0	2325	42.3
CG-C	210	6.3	2339	35.6	2315	–

$f'c^{56}$: 56-day compressive strength, two specimens were tested and averaged.

3.4. Durability investigation

After sample preparation, the durability properties of RCA-concrete mixes designed by the EMV method were investigated. Among these properties, the resistance to freeze-and-thaw action, chloride penetration and carbonation were considered to be of particular importance since these properties are significantly affected by the quality and the quantity of the mortar, properties that are different in RCA-concrete compared to conventional concrete.

3.4.1. Freeze-and-thaw resistance

The freeze-and-thaw tests were carried out using rapid freezing and thawing in water as specified in Procedure A of ASTM C 666-97 [15]. The freeze-and-thaw damage was monitored by measuring the relative dynamic modulus of the test prisms for a maximum of 300 cycles. The relative dynamic modulus is determined by measuring the transverse frequency of the specimens. The performance of concrete against freeze-and-thaw action was represented by the durability factor, which can be calculates as

$$DF = \frac{P_N N}{M} \tag{2}$$

where DF is the durability factor of the test specimen; P_N (%) is the relative dynamic modulus of elasticity after the Nth freeze–thaw cycle; N is the number of cycles at which the relative dynamic modulus of elasticity reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be terminated, whichever is less; and M is the specified number of cycles at which the exposure is to be terminated

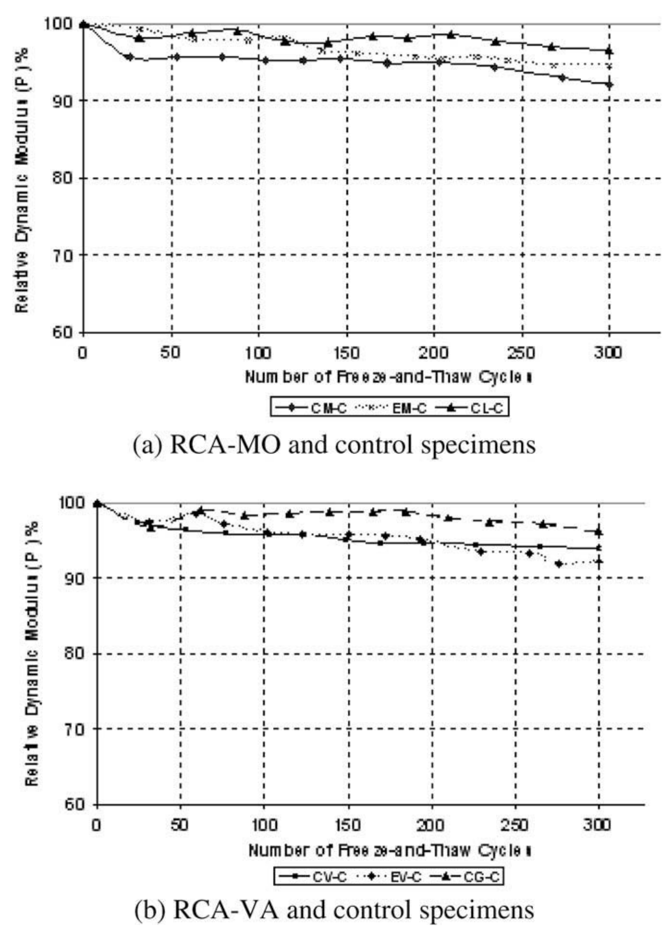


Fig. 1. Relative dynamic modulus of specimens without supplementary cementations materials.

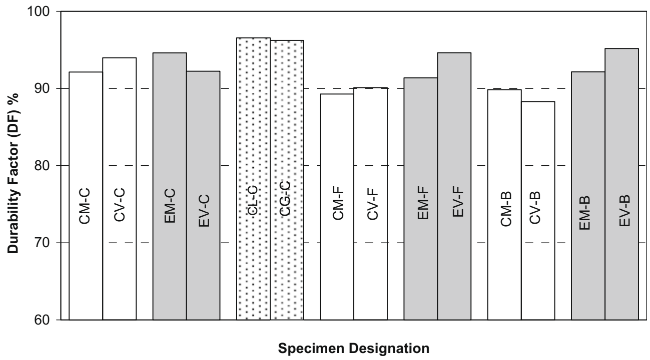


Fig. 2. Summary of the DF measurements of the freeze-and-thaw specimens.

(300 cycles for this study). Conventional air entrained concrete is considered satisfactory if it can withstand 300 cycles with respect to the specified minimum value of the relative dynamic modulus.

Fig. 1 illustrates the variation of the relative dynamic modulus with the number of freeze–thaw cycles for RCA-MO and RCA-VA specimens without supplementary cementitious materials. In general, for all MO and VA specimens, the relative dynamic modulus is in a range from 90% to 100%, which demonstrates that all the specimens performed well against freeze–thaw action. However, the relative dynamic moduli for CL-C specimens (i.e. conventional concrete with limestone) were around 2% higher than those for the EM-C specimens. Similarly, the relative dynamic moduli of the CG-C specimens (i.e. conventional concrete with river gravel) were around 4% higher than those of the EV-C specimens. This difference might be attributed to the difference between the qualities of the residual mortar attached to the RCA of the fresh mortar used in conventional concrete.

A summary of the durability factors (DF) of the test specimens is shown in Fig. 2. A comparison of the DF values in this figure, with consideration of the mix design method, namely EMV (E) vs. conventional method (C), shows that the former mixes performed better than the latter when RCA is used: The DF for mixes with EMV method are slightly (~2–7%) higher than those designed with the conventional method using RCA-MO and RCA-VA. This difference may be attributed to the lower amount of total mortar in the mixes designed by the EMV method. It can be observed from the same figure that the DF of most of the RCA-concrete specimens with fly ash (F) is around 4% lower than that of the companion mixes without supplementary cementitious material. Hence, the freeze–thaw resistance of RCA-concrete is not improved by partially replacing cement with fly ash. However, it should also be noted that these tests were carried out at 28-days, and it is expected that the properties of the mixes with fly ash would improve as the curing period is increased. Similar observations can be made in Fig. 2 with respect to the addition of bfs (B): There seems to be a 3% decrease in the DF of the specimens prepared with bfs; however, this difference may be attributed to the fact that the tests were conducted after 28-days of curing. Further curing of the specimens with bfs is expected to produce better results. It is important to emphasize that lower readings observed in specimens with supplementary cementitious materials does not mean that these specimens are vulnerable to freeze–thaw attack. As discussed before, all the test specimens showed high relative dynamic modulus (and durability factor) and can be used in severe environments according to the present Canadian specifications.

3.4.2. Chloride penetration

The chloride penetration of RCA-concrete was investigated by conducting the acid soluble bulk diffusion test as per ASTM C 1556-04 [15]. This test method covers the laboratory determination of the apparent chloride diffusion coefficient for cementitious mixtures by measuring the acid soluble (total) chloride content. To have better confidence in the results, in this study, two repeat samples were used for the determining the bulk diffusion coefficient of RCA-concrete specimens. These specimens were made by cutting 75 mm thick disks from the ends of the 200 mm long cylinders described earlier. From the remaining part of the cylinder specimen, a 20 mm thick disk was cut to determine the initial chloride ion content, C_0. The 75 mm thick disks were coated with epoxy resin on all surfaces except for the finished surface constituting the end of the original cylinder. The samples were placed in plastic containers and fully immersed in a 15.1% (by weight) sodium chloride solution. All containers were sealed with plastic lids to prevent evaporation. The test specimens were removed from the sodium chloride solution after 60-days. From each sample, approximately 20 g concrete powder was extracted at eight different depths from the exposed face; namely, at approximately 1, 2, 4, 6, 9, 12, 15, and 18 mm, by grinding the surface at the specified depth. The collected powder was used to determine the acid soluble chloride content (total chloride) as specified by ASTM C 1152-90 [15]. The total chloride concentration at the specified depths was determined by the potentiometric titration of chloride with silver nitrate as described in ASTM C-114-03 [15].

In compliance with ASTM C 1152-90 [15], the value of the surface chloride concentration, C_s, and apparent chloride diffusion coefficient, D_a, were calculated by fitting Eq. (3) to the measured total chloride ion content at different depths by means of a nonlinear regression analysis:

$$C_t(x,t) = C_s - (C_s - C_0)erf\left(\frac{x}{\sqrt{4D_a t}}\right) \quad (3)$$

where C_t (% by mass of concrete) is the total concentration of chloride ions at time t (s) and depth x (m), C_s (% by mass of concrete) is the chloride concentration on the exposed surface, C_0 (% by mass of concrete) is the initial chloride concentration, erf is the error function and D_a is the apparent diffusion coefficient (m^2/s). The initial acid soluble chloride concentration, C_0, was measured using the 20 mm thick disks described earlier.

Table 4 presents the measured acid soluble initial chloride content, the surface chloride concentration, and the apparent diffusion coefficient of all test specimens. It should be noted that all concentration measurements are presented as percentage of mass of concrete. In general, from Table 4, it can be observed that the acid soluble initial chloride concentration for RCA-MO and RCA-VA specimens ranged from 0.006% to 0.023%. For RCA-MO specimens, the acid soluble initial chloride concentration ranged from 0.018% (CM-C, EM-B) to 0.023% (CM-B) while for the RCA-VA specimens it varied from 0.006% (EV-C) to 0.011% (EV-B, CV-B). It is clear that

Table 4
Results of the acid soluble chloride content determination test.

Mix ID	C_0 (%)	C_s (%)	$D_a \times 10^{-12}$ (m^2/s)
CM-C	0.018	1.238	4.45
CM-F	0.019	1.490	3.83
CM-B	0.023	1.553	2.15
EM-C	0.022	1.209	4.87
EM-F	0.019	1.576	2.21
EM-B	0.018	1.710	1.80
CL-C	0.008	0.996	5.58
CV-C	0.008	1.120	3.84
CV-F	0.006	1.432	2.62
CV-B	0.011	1.374	1.95
EV-C	0.006	1.703	4.26
EV-F	0.008	1.646	2.56
EV-B	0.011	1.344	1.85
CG-C	0.007	1.183	5.00

the acid soluble initial chloride concentration values of RCA-MO specimens are 2–3 times higher than those of RCA-VA specimens. Although the exact origin of the concrete material from which the RCA were extracted is not known, the higher values observed for RCA-MO specimens may be attributed to the higher degree of salt contamination of the residual mortar attached to RCA-MO. De-icing salts are widely used in the area of Montréal during winter months while in the Vancouver area de-icing salts are rarely used. It is also important to observe that the acid soluble initial chloride concentrations for CL-C and CG-C specimens (i.e. no RCA addition) are 0.008% and 0.007%, respectively. These small quantities are in the range of the expected values, that are observed in conventional concrete with no pre-contamination [18].

The limit of the acid soluble chloride concentration from the mixture ingredients specified by ACI 222R-96 [17] is 0.2% by weight of cement. The maximum acid soluble chloride concentration measured for specimens made with concrete proportioned by the EMV method is 0.022% (EM-C). The percentage of cement by mass of concrete for all specimens with RCA-MO and RCA-VA was around 15–16%. Hence, the maximum acid soluble initial chloride concentration by mass of cement can be calculated as $(0.022 \times 100)/15 = 0.15\%$, which is lower than the 0.2% specified by ACI 222R-96. However, it is important to mention that the residual mortar contains additional cement that is not included in the total amount of cement in RCA-concrete. This means that the 0.15% maximum acid soluble initial chloride by mass of cement is conservative. Hence, it is recommended that for RCA-concrete the limit of chloride content be specified in terms of the mass of concrete rather than the mass of cement.

The apparent chloride diffusion coefficient for all specimens ranged from 1.8×10^{-12} m^2/s (EM-B) to 5.58×10^{-12} m^2/s (CL-C). In general, the apparent chloride diffusion of all RCA-concrete specimens is in the same order of magnitude ($\sim 10^{-12}$ m^2/s) as the conventional concrete [18]. Fig. 3 illustrates the apparent chloride diffusion coefficients of concrete specimens made with RCA-MO and RCA-VA. It can be observed from Fig. 3 that the apparent chloride diffusion coefficients for RCA-concrete specimens (with no supplementary cementitious materials) designed by the EMV method is higher (by around 8% for RCA-MO and by around 10% for RCA-VA) than the mixes proportioned by the conventional method. However, it is also obvious from Fig. 3 that the apparent diffusion coefficients of conventional concrete specimens (with no RCA replacement) are higher than those of RCA-concrete specimens designed by the EMV method. There is also a general trend that the apparent diffusion coefficient for specimens produced with RCA-MO are higher by 10–30% than those of specimens produced with RCA-VA. This may also be attributed to higher level of salt contamination of the residual mortar attached to RCA-MO.

Fig. 3 also illustrates the effect of the supplementary cementitious materials on the apparent diffusion coefficient of concrete specimens produced with RCA-MO and RCA-VA. It can be observed from Fig. 3a that the apparent diffusion coefficients of EM-C specimens designed by the EMV method (with no supplementary cementitious materials) are almost 2.5*x* as large as those of the EM-F specimens. Similarly, it can be observed in Fig. 3b that the apparent diffusion coefficients of EV-C specimens designed by the EMV method (with no supplementary cementitious materials) are approximately 1.5*x* as large as those of EV-C. It can be stated that the chloride penetration in RCA-concrete is significantly improved by using fly ash as partial replacement for cement. Similar observation can be made with regard to the addition of bfs. Actually, the use of bfs reduces the apparent diffusion coefficient of all mixes designed by the EMV method, and the reduction ranges from 1.2 to 2 times more than the reduction achieved by the addition of fly ash. These observations are in line with the findings for conventional concrete produced with natural aggregate [19].

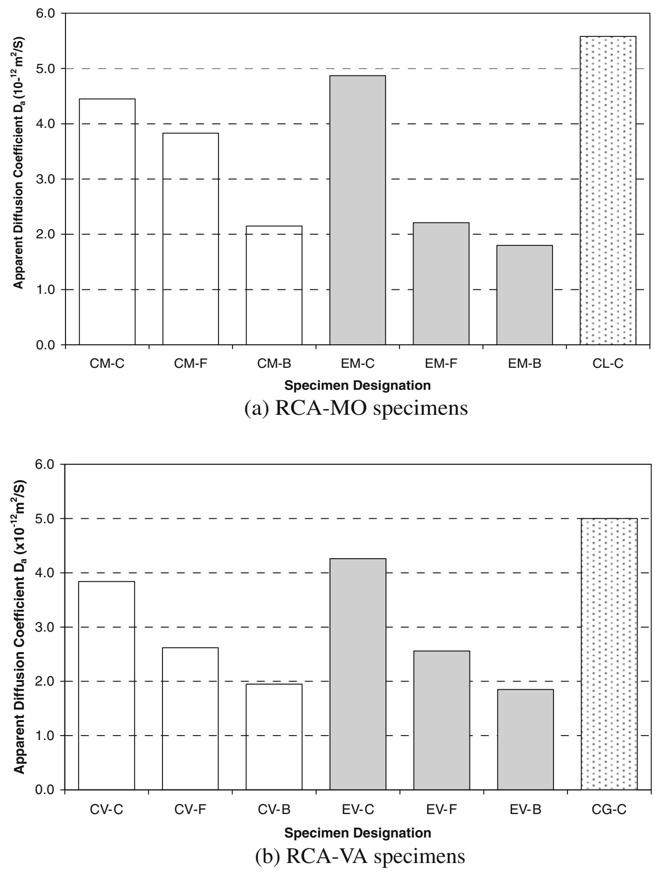


Fig. 3. Apparent chloride diffusion coefficient for RCA-MO and RCA-VA specimens.

3.4.3. Carbonation

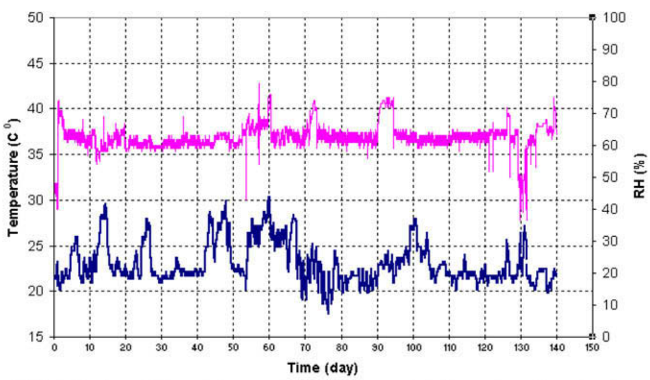
The carbonation test was carried out using a setup based on RILEM recommendations [20]. For this purpose, after the 28-day curing period, the $100 \times 100 \times 406$ mm test prisms, comprising three repeat samples per concrete mix, were placed in a carbonation chamber, as shown in Fig. 4a. The chamber atmosphere was made of a mixture of 3% carbon dioxide and 97% air by volume and its temperature and humidity levels were maintained at 60 ± 5% and 23 ± 1.7 °C, respectively.

Fig. 4b shows the relative humidity and temperature variations during the 140-days of testing. In order to retrieve samples for periodic measurement of the carbonation depth, CO_2 exposure was interrupted seven times at 7, 21, 35, 56, 84, 112 and 140-days after the initial exposure. The peaks and valleys noticed in the latter figure are due to the forgoing interruptions. After the retrieval of each specimen from the chamber, 50 mm thick slices were cut from its ends, and the remaining piece was returned to the chamber for further exposure to carbonation. The freshly cut surface of each slice was cleaned and sprayed with 1 g phenolphthalein indicator solution in 70% ethanol, which resulted in the un-carbonated concrete surface turning pinkish red and the carbonated concrete retaining its original color. The carbonation depth was measured normal to the four sides of each slice immediately and the corresponding carbonation coefficient, D_c, was calculated by inserting the measured carbonation depths corresponding times into the following equation [18]:

$$d = D_c\sqrt{t'} \tag{4}$$

where d is the depth of carbonation front (mm), t' is the time (days) and D_c is the carbonation coefficient ($mm/day^{0.5}$).

(a) Carbonation chamber



(b) Relative humidity and temperature measurement in the carbonation chamber.

Fig. 4. Carbonation test apparatus and process.

The carbonation depths obtained from this accelerated test are expected to be higher than those under the normal exposure conditions (i.e. lower CO_2 concentrations) for concrete specimens with similar initial conditions and material properties. It is therefore important to know the expected depth under similar conditions for conventional concrete so that the current results for the RCA-concrete specimens could be properly analyzed. Bouzoubaa [21] reported that for structural-grade conventional concrete with no supplementary cementitious materials, the depth of carbonation is expected to be in the range of 0–7 mm after 140-days of exposure, the greater depths belonging to concrete with high w/c ratio. The range for structural-grade conventional concrete with fly ash is expected to be around 10–15 mm at 140-days while for concrete containing bfs the expected range is in between the above two ranges.

Fig. 5 illustrates the variation of carbonation depth of the specimens with length of exposure time for the specimens with and without supplementary cementitious materials. It can be observed from this figure, as expected, specimens without supplementary cementitious materials exhibit the smallest carbonation depth, followed by the specimens with bfs. Mixes with fly ash had the largest greatest carbonation depth throughout the 140-days of exposure. This behaviour can be attributed to the pozzolanic action of the supplementary cementitious materials, which consume $Ca(OH)_2$ and consequently lower the alkalinity of the concrete [22].

Fig. 6 shows the carbonation coefficient of the test specimens. Similar to the observations made in Fig. 5, the carbonation coefficients of specimens with fly ash were the largest (from 0.97 mm/day$^{0.5}$ for CV-F to 1.13 mm/day$^{0.5}$ for CM-F), and were almost twice the values of specimens without supplementary cementitious materials (ranging from 0.51 mm/day$^{0.5}$ for CL-C to 0.63 mm/day$^{0.5}$ for EM-C). The coefficients for the specimens containing bfs varied from 0.65 mm/day$^{0.5}$ for EV-B to 0.73 mm/day$^{0.5}$ for EM-B, which lie between the values for the other two types of mixes.

As can be noticed in Fig. 6, the carbonation coefficient 0.52 mm/day$^{0.5}$ for CM-C specimens, which were made of a concrete mix designed by the conventional mix design method, was about 17% lower than the carbonation coefficient of 0.63 mm/day$^{0.5}$ for the EM-C specimens which were made of a concrete mix designed by the EMV method. This may be attributed to the lower cement content of the latter mix than that of the former. Hence, RCA-MO specimens with no supplementary cementitious materials and designed by the conventional mix design method had higher alkalinity in comparison with the corresponding specimens designed by the EMV method. This difference between the carbonation coefficients of the test specimens caused by the concrete mix design method can also be observed for the mixes containing bfs (~10% difference). However, for specimens containing fly ash, the carbonation coefficient for the mixes designed by the EMV method is lower than that of mixes designed by the conventional method. On the other hand, as illustrated in Fig. 6, the carbonation coefficient for

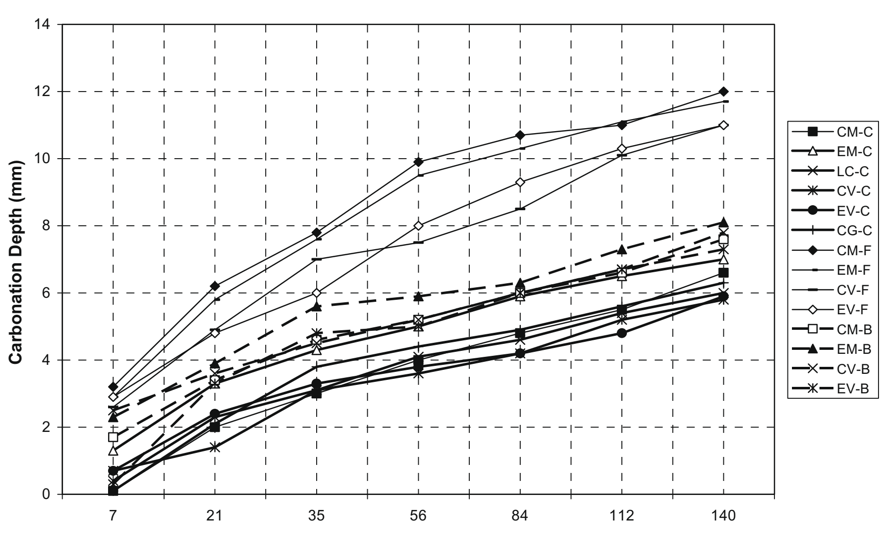


Fig. 5. Variation of the carbonation depth with exposure time.

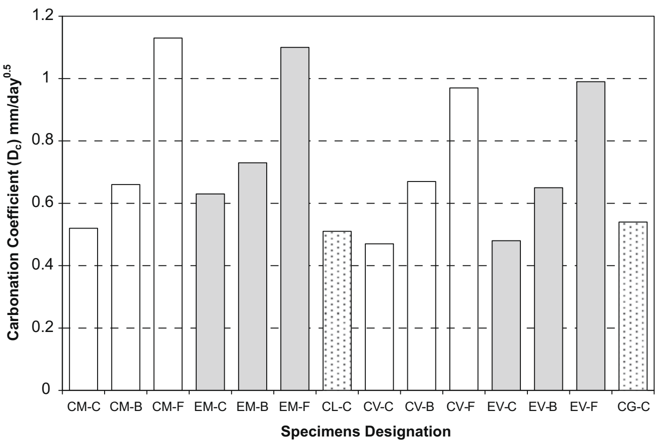


Fig. 6. Carbonation coefficient of test specimens.

RCA-VA specimens which were designed by the EMV method, were almost the same as the carbonation coefficient of specimens designed by the conventional mix design method for all the mixes, with or without supplementary cementitious materials.

Since the total volume of mortar in the RCA-concrete mixes designed by the EMV method and that of the companion mixes without RCA are the same, the carbonation coefficients of groups of specimens made of these mixes will be compared. From Fig. 6, it can be observed that the carbonation coefficient for EM-C specimens is 0.63 mm/day$^{0.5}$ while those of the CL-C specimens are 0.51 mm/day$^{0.5}$. Since these two mixes had the same total mortar volume, the above difference may be attributed to the lower cement content of the EM-C mix compared to the CL-C mix, which were 335 kg/m^3 and 430 kg/m^3, respectively. Hence, the reserve alkalinity in the EM-C mix is lower than that of the CL-C mix. In contrast, as Fig. 6 indicates the carbonation coefficient for the EV-C specimens is 0.51 mm/day$^{0.5}$ and that for the CG-C specimens is 0.54 mm/day$^{0.5}$, despite the fact that cement content of the EV-C specimens are lower than that of the CG-C specimens. Although reserve alkalinity from the cement is lower in the specimens designed with the EMV method, the presence of fly ash in RCA-VA, as identified in the material characterization study, compensates for the difference resulting in very similar carbonation coefficients for both mixes.

4. Conclusions

The general conclusion of this research is that RCA-concrete mixtures designed by the EMV method have strong resistance against freeze-and-thaw action, chloride penetration and carbonation as required for structural-grade concrete in severe environment. Based on the results of the presented investigation, the following specific conclusions are drawn:

- The application of EMV mix proportioning method resulted in an RCA-concrete with comparable or higher compressive strength and higher fresh and hardened density compared to the RCA-concrete proportioned with conventional method. The workability of RCA-concrete was comparable within conventional and EMV methods.
- Using the durability factor as a performance indicator, RCA-concrete mixes proportioned by the conventional mix design method (100% RCA content) or by the EMV method (63.5% and 74.3% RCA content for RCA-concrete made with RCA-MO and RCA-VA, respectively) has strong resistance against freeze-and-thaw action. However, since lower total mortar content in RCA-concrete can be achieved using the EMV method, this method produces concrete with stronger resistance against freeze-and-thaw action compared to RCA-concrete proportioned by conventional mix design method.
- The measured acid soluble initial chloride concentration of the RCA-concrete proportioned by the EMV method was found to be lower than the limits specified by the current standards. However, since the estimation of the total cement content of RCA-concrete mixes is difficult due to the fact that the cement content in the residual mortar cannot be accurately known, for RCA-concrete it is recommended that all limits for chloride content be specified in terms of the mass of concrete rather than the mass of cement.
- The apparent chloride diffusion coefficients for all RCA-concrete specimens made of mixtures proportioned by the EMV method were found to be of the same order of magnitude as the specimens made of conventional structural-grade concrete (i.e. 10^{-12} m^2/s). In fact, the apparent chloride diffusion coefficients for the RCA-concrete specimens without supplementary cementitious materials and proportioned by the EMV method were lower than those of the specimens made of mixture proportioned by conventional method.
- The resistance to chloride penetration of RCA-concrete specimens made of mixtures proportioned by the EMV method was improved by the addition of supplementary cementitious materials (fly ash or bfs) as partial replacement for ordinary portland cement. The addition of bfs reduced the apparent diffusion coefficient of RCA-concrete mixes designed by the EMV method by 120–200% compared to the reduction achieved by the addition of fly ash. The application of the EMV method in conjunction with the addition of supplementary cementitious materials yields concrete with high resistance to chloride penetration.
- The carbonation depths of RCA-concrete with and without supplementary cementitious materials fall in the expected range for structural-grade conventional concrete. RCA-concrete specimens without supplementary cementitious materials showed the lowest level of carbonation, followed by specimens containing bfs and fly ash, respectively.
- The specimens made with concrete proportioned by the EMV method showed that the main factor affecting the carbonation of RCA-concrete is the reserve alkalinity of its binder. Specimens with high cement content were found to have high resistance to carbonation. However, for specimens with fly ash, the carbonation coefficient for mixes designed by the EMV method was lower or equal to those of mixes designed by the conventional method.

Acknowledgements

The authors wish to express their gratitude to Public Works and Government Services Canada and to CANMET-MTL for their support of this research and to the RichVan Holdings Ltd of British Columbia and Groupe Beauval of Quebec for providing the RCA used in this study. The financial support of the Natural Sciences and Engineering Research Council of Canada is also gratefully acknowledged.

References

[1] Stueck WBC. Company's hunt finds its quarry: complicated plan to ship crushed stone and sand to the gravel-starved state of California. Globe and Mail 2006.
[2] Abbas A, Fathifazl G, Isgor OB, Razaqpur AG, Fouriner B, Foo S. Environmental benefits of green concrete. In: Climate change conference; 2006.
[3] Dhir RK, Limbachiya MC, Leelawat T. Suitability of recycled concrete aggregate for use in BS 5328 designated mixes. Proc Instit Civ Eng Struct Build 1999;134(3):257–74.

[4] Limbachiya MC, Leelawat T, Dhir RK. Use of recycled concrete aggregate in high-strength concrete. Mater Struct 2000;33(233):574–80.
[5] Mandal S, Chakarborty S, Gupta A. Some studies on durability of recycled aggregate concrete. Indian Concr J 2002;76(6):385–8.
[6] Gomez-Soberon JMV. Shrinkage of Concrete with Replacement of Aggregate with Recycled Concrete Aggregate. ACI Special Publications 2002;209: 475–96.
[7] Gomez Soberon JMV. Creep of Concrete with Substitution of Normal Aggregate by Recycled Concrete Aggregate. ACI Special Publications 2002;209:461–74.
[8] Gomez-Soberon JMV. Porosity of recycled concrete with substitution of recycled concrete aggregate: an experimental study. Cem Concr Res 2002;32(8):1301–11.
[9] Ray SP, Venkateswarlu B. Recycled aggregate concrete. J Struct Eng 1991;18(2):67–75.
[10] Fathifazl G. Structural performance of steel reinforced recycled concrete members. PhD dissertation, Carleton University, Ottawa, Canada; 2008.
[11] Abbas A, Fathifazl G, Isgor OB, Razaqpur AG, Fournier B, Foo S. Proposed method for determining the residual mortar content of recycled concrete aggregates. J ASTM Int 2007;5(1).
[12] Abbas A, Fathifazl G, Fournier B, Isgor OB, Zavadil R, Razaqpur AG, Foo S. Quantification of the residual mortar content in recycled concrete aggregates by image analysis. Mat charac J, in press.
[13] Canadian Standard Association (CSA). Concrete materials and methods of concrete construction. CSA standards A23.2, Toronto; 2004.
[14] Bouzoubaa N, Fournier B. Current situation with the production and use of supplementary cementing materials (SCMs) in concrete construction in Canada. Can J Civ Eng 2004;32(1):129–43.
[15] ASTM. Concrete and concrete aggregates. Annual book of American society for testing and materials, vol. 4.02. Philadelphia: ASTM; 2003.
[16] Abbas, A. Durability of green concrete as a structural material. PhD thesis, Department of Civil and Environmental Engineering, Carleton University, Ottawa, Canada; 2007.
[17] ACI Committee 222. Corrosion of metal in concrete. Report ACI 222R-96. Farmington Hills (Michigan), American Concrete Institute; 1996.
[18] Neville AM. Properties of concrete. 2nd ed. Essex (UK): Longman Group Ltd.; 1995.
[19] Thomas MDA, Bamforth PB. Modelling chloride diffusion in concrete: effect of fly ash and slag. Cem Concr Res 1999;29:487–95.
[20] RILEM recommendation CPC 18. Measurement of hardened concrete carbonation depth. Mater Struct 1988;21(126):435.
[21] Bouzoubaa N. Private communication, Natural Resources. CANMET, Ottawa, Canada; 2007.
[22] Thomas MDA, Matthews JD. Carbonation of fly ash concrete. Mag Concr Res 1992;44(158):217–28.