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Assessment of additional ASR damage resulting from residual expansion tests using the DRI and SDT test methods

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ABSTRACT

Currently, ASR damage evaluation of concrete road infrastructure can be done following FHWA protocol (Fournier et al., 2010) [1]. The current level of ASR damage (diagnosis) is evaluated using the Damage Rating Index (DRI) and the Stiffness Damage Test (SDT), and future potential of damage (prognosis) is assessed using residual expansion tests, in humid air (> 95 % RH and T = 38 ± 3 °C) and alkaline solution (NaOH 1 N, 38 ± 3 °C). While accelerated expansion tests on cores have been used for decades, they provide only limited insights into ASR severity, without providing information on the ASR damage mechanisms, nor allowing extrapolation to the structural level. The aim was to identify correlations between pre- and post-expansion test results and additional expansion generated by assessing the actual extent and mechanisms of extra ASR damage caused by these tests. Results of the expansion tests in humid air were inconclusive, making the test procedure questionable. On the other hand, residual expansion tests in alkaline solution proved to be more relevant for assessing potential future damage to concrete. No new damage mechanism related to the added alkalis could be identified. The results indicated a comparable progression of ASR damage between the NaOH solution and in situ conditions. A cracking pattern in concrete at high expansion levels due to ASR was identified based on petrographic examination of test specimens following residual expansion testing in 1 N NaOH solution.

1. Introduction

The evaluation and management of concrete infrastructures damaged by alkali-silica reaction (ASR) poses a major challenge for civil engineers. ASR can indeed compromise their durability and structural integrity by causing internal expansion that leads to cracking in the concrete, as well as significant volume changes that may modify the geometry of the affected structural members and generate operational issues. In recent years, the assessment of the current level of ASR damage (*diagnosis*) has increasingly relied on two specific tests, the Damage Rating Index (DRI) and the Stiffness Damage Test (SDT), both conducted on cores extracted from the affected structure [2–4]. Simultaneously, it is crucial to anticipate the potential future damage to the structure, a process often referred to as *prognosis*. Other than using extrapolation from in situ monitoring data, this step is generally based on residual expansion tests conducted both on cores stored in humid air (RH > 95 % and T = 38 ± 3 °C) and in alkaline solution (NaOH 1 N, 38 ± 3 °C), as well as on soluble alkalis determination. Diagnosis and prognosis investigations are key components of the ASR management protocol proposed by Fournier et al. [1]. However, improvements to those approaches are required as their interpretation is not trivial, notably the extrapolation of the data to the structure level.

1.1. Damage Rating Index (DRI)

The DRI method was developed in the 1990s by Grattan-Bellew and colleagues [5–7], based on the work of Sims et al. [8]. It involves a semi-quantitative analysis of the petrographic damage features observed on a polished concrete section using a stereomicroscope with 15 × magnification. Before examination, a grid with 1 × 1 cm square units is drawn on the concrete section, and the recommended magnification allows a detailed observation of each unit one at a time. The examined surface area must normally be at least 200 cm^2.

The ASR-related damage features inventoried on the surface, in the original method proposed by Grattan-Bellew and colleagues [5,6] are closed cracks in the aggregates, open cracks in the aggregates with or

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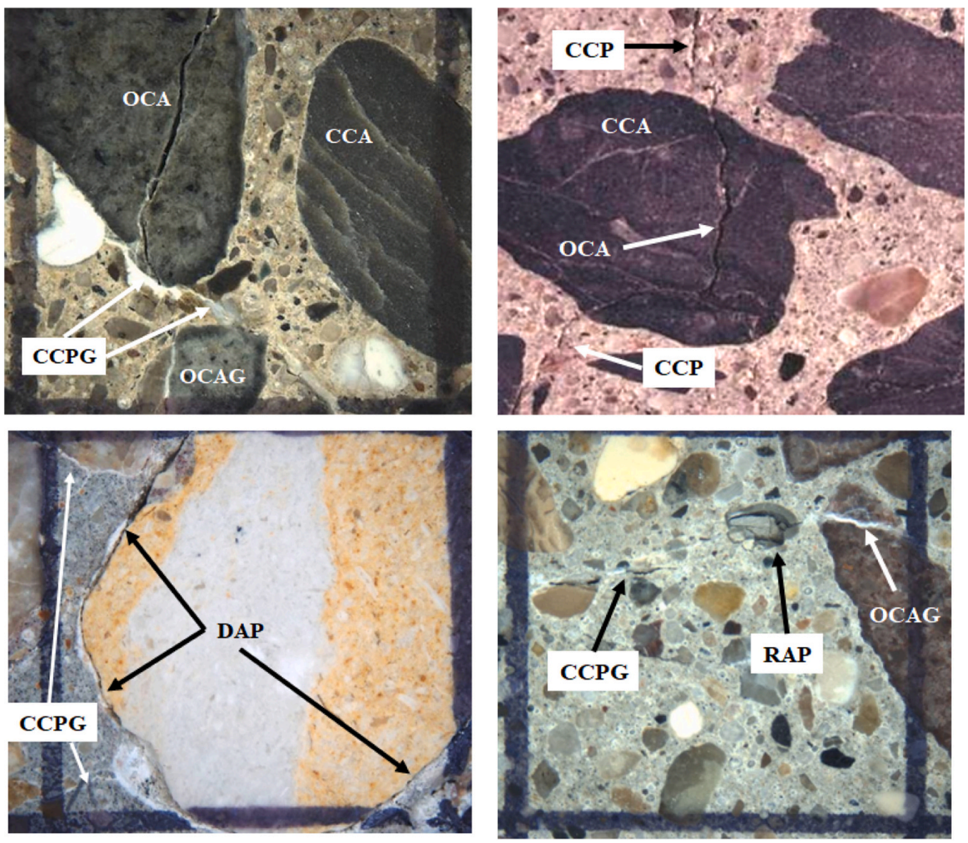
without reaction products, loss of bond between the aggregate and the cement paste, the presence of reaction rims, cracks in the cement paste with or without reaction products, and air voids filled with gel. For every inventoried feature, the number of occurrences in each square of the grid drawn on the examined concrete polished section is determined, and the cumulative count is multiplied by a weighting coefficient. The weighting coefficients are assigned on the basis of the assumed significance of the different features in the overall ASR damage. They have evolved since they were first introduced by Grattan-Bellew [5,6], but the set of values suggested by Villeneuve et al. [9], which was found to reduce the variability of the DRI test (between operators), has become a common reference in the scientific community (Fig. 1). The weighted sum of counts of all defects is then reported to an area of 100 cm^2 to normalize the results, and the obtained result is the DRI value.

Sanchez et al. [10] recently tested a range of concretes (and aggregates), subjecting the specimens in the laboratory to conditions promoting the development of ASR (38 ± 3 °C and 100 % RH) and assessing their condition with the DRI method at different expansion levels. They found a linear correlation between expansion and DRI, with the most notable correlation observed for 35 MPa concretes prepared with reactive aggregates from the Quebec City area, likely matching the average design compressive strength of the concrete used to cast the structural elements investigated in the present study (Section 3).

1.2. Stiffness Damage Test (SDT)

Walsh [11] previously reported a good correlation between crack density and loading/unloading cycles (stress/strain relationship) of rock specimens. Crouch et al. [12] adapted the method to concrete and subsequently proposed a new cyclic compression loading test of concrete samples, referred to as the *Stiffness Damage Test*. Starting in the early 1990s, Crisp et al. [13,14] used this method for damage assessment in



Petrographic features			Weighting factors
Cracks in the aggregate particle	Closed (without reaction products)	CCA	0.25
	Opened or in a fine network (without reaction products)	OCA	2
	Opened or in a fine network (with reaction products)	OCAG	2
Cracks in the cement paste	Without reaction products	CCP	3
	With reaction products	CCPG	3
Debonded aggregate particle		DAP	3
Reacted aggregate particle		RAP	2

Fig. 1. Petrographic features of ASR inventoried during the DRI determination and their corresponding weighting factors [9].

concrete due to ASR. After analyzing the stress-strain response of a large number of cores extracted from damaged concrete structures, they proposed the Young's modulus reduction, dissipated energy (hysteresis area), and the non-linearity index (NLI) [13] as diagnostic parameters of the extent of ASR damage in a specimen. Since then, different investigators proposed modifications in the assessment of these parameters or introduced new ones [15–17].

While meaningful, all of these parameters are influenced by the concrete properties, such as strength, often making interpretation challenging, since the results depend on more than just crack density within the specimens investigated. In response, Sanchez et al. [18] introduced new evaluation parameters from the SDT: the Stiffness Damage Index (SDI) and the Plastic Deformation Index (PDI), two indexes related to the energy dissipated during the loading cycles, making them independent of the undamaged concrete properties.

Similar to their work on DRI, Sanchez et al. [10] established a correlation between SDT output parameters and the expansion levels of laboratory concrete test specimens stored under controlled conditions (100 % RH, 38 $\pm$3 °C). Again, a strong correlation was found for 35 MPa concrete mixtures incorporating reactive aggregates from the Quebec City area. The authors found a good correlation between expansion and SDI/PDI output parameters, which nevertheless reached a plateau when an expansion of the order of 0.2 % was reached. They explained this plateau by referencing the proposed cracking pattern for concrete affected by ASR [19]. They noticed that cracking in the aggregates, measured at the DRI magnification level, predominates until the test specimens reach approximately 0.2 % expansion, at which point cracking in the cement paste has developed significantly. Since energy dissipation – and consequently the SDI and PDI – is primarily influenced by cracks in the aggregates [10], these parameters show minimal increase when cracking in the cement paste becomes the dominant factor.

1.3. Residual expansion tests

Prognosis can be evaluated using soluble alkali determination and residual expansion tests or, in some cases, in situ monitoring. The latter is considered the most reliable approach as it reflects the actual conditions of the concrete in service. It includes tracking the expansion of structural elements, relative movements and deformations, and measuring temperature and humidity/moisture content within the concrete [4,20]. While in situ monitoring provides the most accurate data, it is demanding and it often necessitates a significant amount of time to yield enough data for a prediction the future behavior. Conversely, laboratory tests are conducted over shorter time frames, with fewer instruments.

Laboratory tests involve imposing accelerated conditioning in the laboratory to cores extracted from selected location(s) within the structure to monitor their expansion over a period of at least one year, typically. Various laboratory test methods have been employed worldwide to gather information on the residual expansion potential of concrete due to ASR [21]. The methods used in this study have been implemented at Laval University [16,22,23]. There are two main test procedures for residual expansion: (1) the humid air test (> 95 % RH) at 38 °C, and (2) the immersion test in 1 N NaOH (alkaline) solution at 38 °C [24]. Concrete specimens are placed in sealed containers that provide either humid air or NaOH immersion conditions and that are kept in a conditioning chamber at 38 °C. These methods are simple and allow to quantify the potential for residual ASR expansion.

Additionally, laboratory-measured expansion is unrestricted and does not account for the effects of existing constraints within the concrete structure, which can significantly affect the expansion process [25]. Studies have also been conducted to analyze the effect of restraint, although they focused more specifically on delayed ettringite formation [26–28]. Expansion is influenced by confinement (from external loads or reinforcement), making concrete expansion anisotropic and less significant in directions where confinement is present. Another issue with these methods is the observed anisotropy between longitudinal and diametral expansion [16,25,29–31].

The total measured expansion in a residual expansion test conducted on sampled specimens includes deformations associated with potentially three phenomena: the hygroscopic expansion of concrete, the potential expansion of pre-existing gel during the test, and the additional (residual) expansion caused by ASR. When exposed to a humid environment or in contact with water, concrete absorbs moisture and expands, the resulting volume change being called hygroscopic expansion [32,33]. This expansion can be evaluated through moisture reconditioning conducted prior to the residual expansion tests, which intends to restore the moisture condition that was prevailing inside the concrete at the time of sampling. Additionally, the expansion of the pre-existing gel can be triggered in the presence of water by an osmotic phenomenon causing water transfer through a semi-permeable membrane [34–36]. Since silica gel is hygroscopic [37], it adsorbs water leading to its swelling. As the water content increases in the test specimen, the existing gel can swell further, which does not necessarily reflect the natural conditions of structures on-site. This hypothesis, however, has to be questioned, as recent research demonstrated that the expansion mechanism within reactive aggregates, prior to affecting the cement paste, is neither due to gel swelling nor osmotic phenomena [38]. The authors found that the pressure is generated by the precipitation of non-crystalline ASR products, which can be described as a solidification pressure. This pressure arises from the electrostatic repulsion between negatively charged precipitates, dissolved silica, and aggregate surfaces.

Despite these considerations, the humid air test is often considered the closest to the potential residual expansion of concrete, because no additional alkalis or hydroxides are introduced during the experiment [24].

In normal circumstances, the alkalis in the concrete pore solution are expected to be recycled within the concrete, through ionic exchanges between calcium-bearing hydrates and the alkali-rich gel when it reaches the cement paste around reactive aggregates [39]. This likely maintain conditions in concrete specimens prone to ASR expansion for extended periods of time. However, Grattan-Bellew [5] suggested that expansion tests on concrete specimens tend to underestimate residual expansion potential. In fact, test specimens are subject to alkali leaching due to the runoff of condensed water droplets on their surface, which reduces the concentration of alkalis and hydroxides in the concrete pore solution. The use of cores with larger diameters has been proposed to reduce the deleterious impact of alkali leaching on residual expansion measurements [1,23]. As a result, expansion may reach an early plateau, not necessarily due to the consumption of reactive silica and alkalis by the reaction [40], which are limiting factors for expansion in bulk ASR-affected concrete [41]. It has been shown that alkali leaching depends mainly on concrete permeability (dependent on the w/cm ratio) and the size of the tested samples [42], in addition to the moisture exposure conditions. Therefore, sample size should be considered when interpreting results. In order to reduce the deleterious effect of alkali leaching, it is thus recommended to use cores with a diameter of at least 150 mm [1].

When attempting to assess residual expansion of ASR-affected concrete, a complementary test is often performed with specimens immersed in an alkaline solution to yield additional data. This test is considered to evaluate the absolute reactivity of aggregates containing reactive silica by providing external alkalis and hydroxide ions to the concrete pore solution, thus increasing the actual amount of alkalis available for the reaction [19]. Still, during the test, significant amounts of silica gel may be released in the storage NaOH solution rather than generating expansion within the test specimens, thus resulting in lower ultimate expansion [43]. Furthermore, although expansion is primarily controlled by aggregate reactivity, other parameters such as alkali content [44], core size [45], and concrete w/cm ratio influence the rate magnitude of expansion in alkaline immersion test conditions. The use of cores with a diameter of the order of 100 mm, smaller than those used for humid air exposure, was found to be appropriate to ensure that the alkaline solution can effectively penetrate the entire specimen, while ensuring a concrete volume large enough for representativeness [1]. Usual expansion test methods conducted under accelerated laboratory conditions provide estimates of the reactive potential of concrete, but none truly reflects the reality. That often results in significant challenges in interpreting and extending the results of residual expansion testing to issue a reliable prognosis for concrete structures affected by ASR. Although accelerated expansion tests on laboratory cores have been utilized for decades, they provide semi-quantitative results reflecting the severity of ASR, but without offering values that translate directly to the future in-situ expansion nor precise insights on the subsequent deterioration.

These methods are often applied without a thorough understanding of the underlying expansion and deterioration processes taking place during testing, in comparison to those having occurred previously in field conditions. Consequently, using the results from these tests for establishing a prognosis carries a significant degree of uncertainty.

Opportunities have arisen to study these tests using cores drilled from two ASR-affected bridge structures: the Original Champlain Bridge and its upstream jetty, both located in the Montreal area and spanning the St. Lawrence River. A t the time of its decommissioning in 2019, the Original Champlain Bridge was the busiest motor vehicle bridge in Canada. The jetty (referred to as *Estacade*) was designed to prevent ice from drifting towards the Original Champlain Bridge and to shield the artificial downstream islands against erosion.

2. Scope of work and objective

This study involves an experimental program using cores incorporating similar reactive siliceous limestone aggregates and extracted from the Original Champlain Bridge and its jetty. The cores were subjected to diagnosis and prognosis tests according to the protocol proposed by Fournier et al. [1], with additional DRI and SDT tests conducted on cores following residual expansion tests.

The primary aim is to explore potential correlations between existing damage in sampled ASR-affected concrete and the damage further incurred during residual expansion testing. The relationships between the output parameters of the DRI and SDT tests will be examined in connection with the expansion observed during residual expansion tests. Additionally, the study will explore how these parameters relate before and after the residual expansion tests. This investigation seeks to enhance understanding of the mechanisms involved under accelerated laboratory conditioning, both in humid air and alkaline solution immersion, and to accurately determine the extent of additional damage generated during the so-called residual expansion experiments. A cracking pattern that represents the progression of damage in cores subjected to alkaline solutions expansion test will be proposed. Furthermore, the study will examine the relationship between the increase in ASR symptoms and total expansion and establish links between laboratory test results and the actual behavior of ASR-affected concrete in service. The findings are expected to contribute to updating and improving ASR management protocols, by offering a basis for practical recommendations towards a more reliable assessment of the potential for future damage in ASR-affected concrete structures and improved maintenance practices. Yet, it is important to stress the limited scope of the study, as only one type of reactive aggregate and a limited number of cores were tested.

3. Materials and methods

3.1. Structural elements investigated

In this project, cores were extracted from structural elements of the *Original Champlain Bridge* and its *jetty*, two bridges located side by side spanning the St. Lawrence River in the Montreal area. In 2019, The Jacques Cartier and Original Champlain Bridges Incorporated (JCCBI) initiated an R&D program linked to the deconstruction of the Original Champlain Bridge. Research teams were given access to sections of the structural elements of the bridge upon its deconstruction, which could then be tested to assess their condition after 57 years in service, in particularly severe exposure conditions. Located next to the river, the structural elements were subjected to repeated cycles of freezing-thawing, wetting-drying, and windy conditions. In addition, large quantities of de-icing salts were applied to the bridge. However, the drainage system was ineffective, leading to significant saline infiltration through the joints, which greatly contributed to the corrosion of the tendons in the longitudinal beams.

The elements involved in the experimental study reported herein are two pier sections and five pier cap sections from the approach spans (on land). Sections were extracted from the central portion and overhanging elements of the pier cap (Fig. 2).

It should be mentioned that the pier cap had been repaired with a 200 mm thick reinforced concrete jacket 15 years before the decommissioning of the bridge. In the study, only the original ASR-affected core concrete was investigated.

In the jetty, cores were extracted from the footings of the piers (underwater) during sampling campaigns carried out in 2014 and 2017 (Fig. 3). The footings are typically about 5 m in width, 17 m in length and could range from 2 to 8.5 m in height/thickness. The concrete footings are enclosed in steel caissons, some of which were found to be not waterproof anymore according to field surveys.

3.2. Testing methods

Both bridge elements studied contained the same reactive limestone aggregate and non-reactive granitic sand. Diagnosis tests were first conducted on different core specimens after extraction to assess the existing concrete condition in the bridge elements investigated through DRI and SDT tests. Next, residual expansion tests were conducted on 11 core sections stored in humid air (RH $>$ 95 %, 38 $\pm$ 3 °C) and 11 core sections immersed in alkaline solution (NaOH 1 N, **38** $\pm$3 °C). Finally, after completion of the residual expansion tests, the condition of the specimens was re-assessed, with 14 cores tested for DRI (six that were conditioned in humid air and eight by alkaline solution immersion) and eight cores tested for SDT (five that were conditioned in humid air and three by alkaline solution immersion).

By comparing the results of DRI / SDT damage assessment on core specimens tested for residual expansion with those obtained for the as-is core specimens, the additional damage incurred during the expansion tests can be assessed and correlated with the extent of expansion undergone. The comparison is necessarily made between different sets of specimens, but great care was taken to use comparable core sections from close locations, same depths, and presumably similar initial levels of damage (Fig. 4). For the SDT results, comparisons are made exclusively between data from cores drilled in the same direction within the selected structural elements, thereby eliminating the potential impact of preferential crack orientation. In total, 27 DRI tests and 18 SDT tests were conducted.

3.2.1. Damage Rating Index (DRI)

Cores tested for DRI were cut using a concrete saw equipped with a diamond blade. The concrete sections were then polished with a portable polisher, using rubber discs impregnated with progressively finer abrasive particles. The procedure described in Section 1.1 was followed, with DRI values being normalized to a 100 cm^2 surface area. Only particles greater than 2 mm were considered when counting cracks in the aggregates. The weighting coefficients used for DRI follow those established by Villeneuve et al. [9] (see Fig. 1).

3.2.2. Stiffness Damage Test (SDT)

From the time of sampling in the field up to 2 days before testing, the

Fig. 2. Structural elements extracted from the Original Champlain Bridge and used in this study [photos from the study of Fournier et al. 2024 [46]). A. Typical structural element on shore. B. Actual pier selected for coring showing external post-tensioning (repair conducted in 2008); the closest part of the pier cap corresponds to the North side of the structural element. C. Location of sections D7 39.1 (exposed) and D6–35.1 & 35.2 (protected under the bridge deck) in pier cap (North side); sections D7–38.1 and 38.2 in top of pier (north side). D. Location of sections D7 39.2 (exposed) and D6–35.3 (protected under the bridge deck) in pier cap (South side). E. Details of sections D7–38.1 and 38.2 in top of pier after complete removal of the pier cap. F. Coring of sections D7 39.1 (on the left) (exposed; North side) and 39.2 (on the right) (exposed; South side).

Fig. 3. General view of the piers of the Original Champlain Bridge jetty (*Estacade*).

specimens intended for SDT experiments were wrapped in plastic films to maintain their in-situ moisture level. The specimens were immersed in a $Ca(OH)_2$ solution, following the protocol proposed by Smaoui et al. [16].

Test specimens were first installed in a special test frame equipped with three displacement transducers 120° apart to measure the longitudinal deformations of the concrete specimen under load. After securing the setup in the hydraulic testing machine (loading capacity: 1000 kN; load cell used: 250 kN), five loading/unloading cycles were applied up to a fixed compressive load. This loading protocol yields the data to determine the Stiffness Damage Index (SDI) and the Plastic Damage Index (PDI), in accordance with the procedure proposed by Sanchez et al. [18]. The load was applied at a rate of 0.10 MPa/s, up to 40 % of the selected reference concrete compressive strength value. Cores tested after residual expansion testing were also loaded up to the same fixed compressive load. A uniform maximum load, corresponding to a compressive stress of 9.85 MPa, was chosen to allow comparisons between the results of the different SDT tests.

3.2.3. *Residual expansion tests*

Whether conditioning was conducted in humid air or in a 1 N NaOH solution, length change measurements were taken on the core specimens at regular intervals, as described by Bérubé et al. [22]. The residual expansion data reported here corresponds to expansion values after a one year storage period in the above conditions, i.e. following a first significant break in the (steep) residual expansion rate due to moisture re-saturation of the test specimens prior to a steady regime of ASR-related expansion [4,47]. Re-saturation took on average seven days for cores immersed in 1 N NaOH solution and 42 days for those exposed to humid air.

Cores from the bridge elements that were tested in humid air had nominal diameters of 100 or 140 mm, while all those tested in alkaline solution had a nominal diameter of 100 mm. Larger diameter cores were

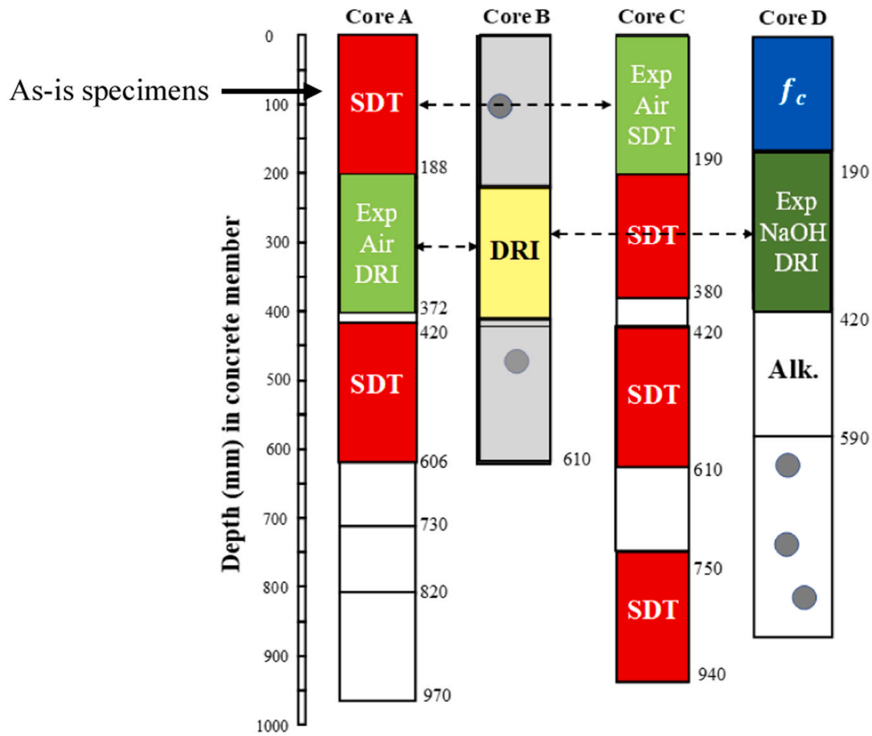


Fig. 4. Comparison of damage assessment testing conducted on specimens obtained from parallel cores extracted within the same structural element and at similar depths – Fournier et al., 2024 [46]. "Exp air DRI" refers to a specimen subjected to a residual expansion test in humid air, followed by DRI testing. "Exp NaOH DRI" refers to a specimen tested in a residual expansion test in a 1 N NaOH alkaline solution, followed by DRI testing. "SDT/DRI" refers to an as-is specimen tested with SDT/DRI without undergoing a residual expansion test. The grey points indicate reinforcing bars embedded in the concrete.

used in humid air to minimize alkali leaching and thus prevent the premature plateauing of expansion.

4. Results

Tables 1 and 2 summarize the results of the laboratory tests conducted in this study. It includes the results of DRI and SDT experiments conducted on as-is core specimens after sampling, the residual expansion values (at 52 weeks) from testing conducted both in humid air and in 1 N NaOH solution at 38 °C, and the results of DRI and SDT experiments conducted on specimens tested for residual expansion. For comparison purposes, the estimated expansion level reached by the concrete in the as-is samples was calculated based on an empirical relationship between expansion values reached by concrete specimens stored in humid air at 38 °C at a given moment and the corresponding DRI values (Tables 1 and 2) for concrete mixtures incorporating the same type of reactive aggregate (siliceous limestone), as proposed by Sanchez et al. [10]. That relationship will be presented and discussed in a subsequent discussion.

The identification codes assigned to the concrete specimens from the Original Champlain Bridge follow a specific format: **A-X-BY-SZ** for pile sections and **B-X-BY-SZ / C-X-BY-SZ** for unexposed and exposed pier cap

Table 1
Test results for core specimens stored for residual expansion testing in humid air (38 °C) and for as-is core specimens not subjected to expansion testing.

Structure	As-is cores not tested for residual expansion testing						Cores tested after residual expansion testing					
	Specimen (equivalent depth in the concrete element)	Core size (mm)	Estimated expansion in humid air [%]	DRI value	SDT		Specimen	Core size (mm)	Residual expansion [%] after 52 weeks	DRI value	SDT	
					SDI	PDI					SDI	PDI
Original Champlain Bridge	B–1-B4-S2	93	0.18	733			B–1-B3-S1	95	0.067	970		
	B–3-B6-S1	93	0.19	766			B–3-B4 (2)-S2	140	0.033	1093		
	A–1-B5-S3	140	0.21	818			A–1-B1-S2	140	0.043	1073		
	A–2-B8-S2–1	140	0.24	918			A–2-B2-S2	140	0.052	1164		
	A–2-B8-S2–1	140	0.24	918			A–2-B4-S2	100	0.091	1135		
	C–1-B11-S4	140	0.20	787			C–1-B14-S4	140	0.033	1123		
	A–1-B1	140			0.23	0.14	A–1-B4 (2)-S1	140	0.034		0.27	0.17
	A–1-B5	140			0.25	0.19	A–1-B4 (2)-S2	140	0.047		0.30	0.22
	C–2-B11	95			0.22	0.14	C–2-B7 (1)-S3	95	0.057		0.26	0.15
	B–3-B5	95			0.21	0.15	B–3-B4 (2)-S1	93	0.025		0.24	0.15
	B–3-B4(2)	93			0.23	0.16	B–3-B3-S1	93	0.021		0.29	0.20

Table 2
Test results for core specimens subjected to residual expansion testing in 1 N NaOH (38 °C) and for as-is core specimens not subjected to expansion testing.

Structure	As-is cores not tested for residual expansion testing						Cores tested after residual expansion testing					
	Specimen (equivalent depth in the concrete element)	Core size (mm)	Estimated expansion in humid air [%]	DRI value	SDT		Specimen	Core size (mm)	Residual expansion [%] after 52 weeks	DRI value	SDT	
					SDI	PDI					SDI	PDI
Original Champlain Bridge	B−2-B5-S2	93	0.24	917			B−2-B7-S1	93	0.112	1379		
	A−1-B2-S1	100	0.17	669			A−1-B3-S1	100	0.171	1140		
	A−2-B8-S1	140	0.20	786			A−2-B6-S1	100	0.197	1349		
	C−2-B6-S1	95	0.12	533			C−2-B3-S1	95	0.144	939		
	A−1-B3	100			0.27	0.17	A−1-B6-S1	100	0.224		0.49	0.31
	A−2-B4	100			0.26	0.19	A−2-B5-S2	100	0.483		0.36	0.30
	C−2-B11	95			0.22	0.14	C−2-B5	95	0.158		0.36	0.25
	B−2-B2	93			0.27	0.20	B−2-B1-S1	93	0.079		0.38	0.22
Jetty	P4F2V	150	0.31	1161			P4F2V	150	0.208	1897		
	P1F1H	150	0.28	1044			P1F1H	150	0.143	1559		
	P6F3V	150	0.41	1476			P6F1H	150	0.248	2344		
	P3F2H	150	0.31	1165			P3F3H	150	0.049	1297		

elements, respectively (see Fig. 1). In this system, A, B, and C correspond to structural elements D7–38, D6–35, and D7–39, respectively. The letter “X” indicates the section number extracted from the respective elements, “BY” represents the borehole number from which the core was extracted, and “SZ” represents the section position, with Z = 1 corresponding to the section nearest to the external surface.

4.1. Residual expansion

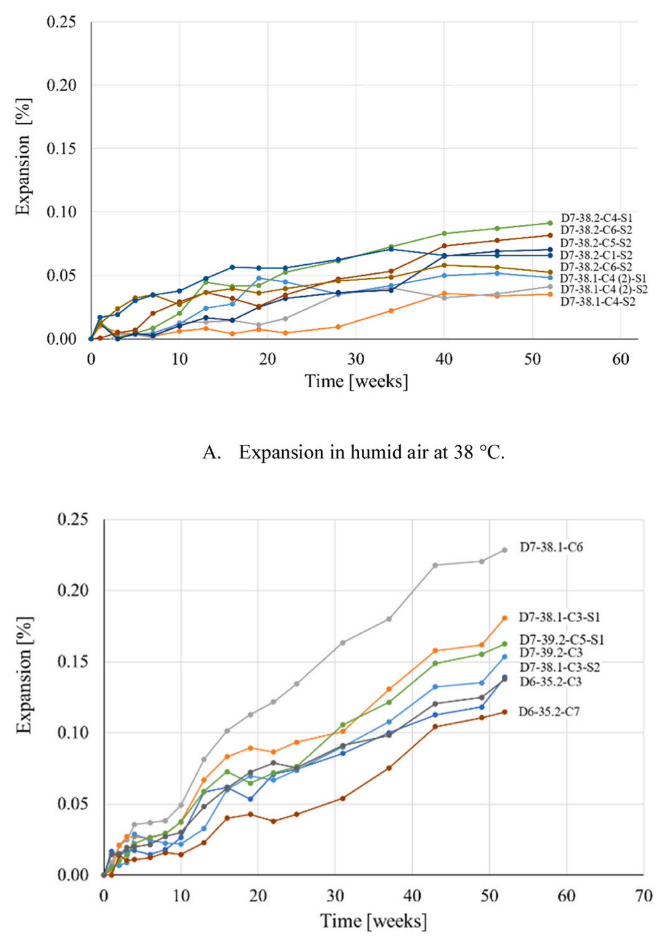
A selection of typical expansion curves is shown for core specimens from the Original Champlain Bridge stored in humid air at 38°C and in alkaline solution at 38 °C (Fig. 5). The expansion data in Tables 1 and 2 were obtained from Khaleghi-Esfahani et al. [4] for Original Champlain Bridge and from Thériault et al. [47] for the jetty.

Expansion at a decreasing rate was recorded for most cores stored in the humid air, resulting in limited measured expansion for all samples (Fig. 5A). In contrast, for the alkaline solution, steadily increasing expansions (Fig. 5B) and much higher final expansion values were recorded (Tables 1 and 2), with no clear plateau observed, indicating that the reaction was still ongoing at the end of the monitoring period.

4.2. DRI results

The DRI values determined for the examined core specimens can be visualized in Figs. 6 and 7. The data include, for each specimen, the relative “weight” of each damage symptom on the final DRI value. Fig. 6 illustrates the DRI results for core specimens after being subjected to expansion in humid air for approximately one year, directly compared to those obtained for as-is sampled specimens from similar locations (Fig. 4). Fig. 7 is constructed in the same way, this time with the results of core sections subjected to expansion in a 1 N NaOH alkaline solution. The comparison between each pair of bars thus highlights the increase in damage for the core sections that were subjected to residual expansion testing and the corresponding “additional” expansion measured during the tests ("After").

For each pair of specimens compared, it can be observed that the DRI values systematically increase after the residual expansion test, whether in humid air or in the alkaline solution. This indicates that the residual expansion tests generate additional internal damage to that already incurred in the field. Also, the increase in ASR symptoms is present in every pair listed in the tables, meaning that ASR is responsible for this



A. Expansion in humid air at 38 °C.

B. Expansion in 1N NaOH solution at 38 °C.

Fig. 5. Results of residual expansion testing conducted on cores from the Original Champlain Bridge [4].

additional damage. In humid air, counts for cracks both in the

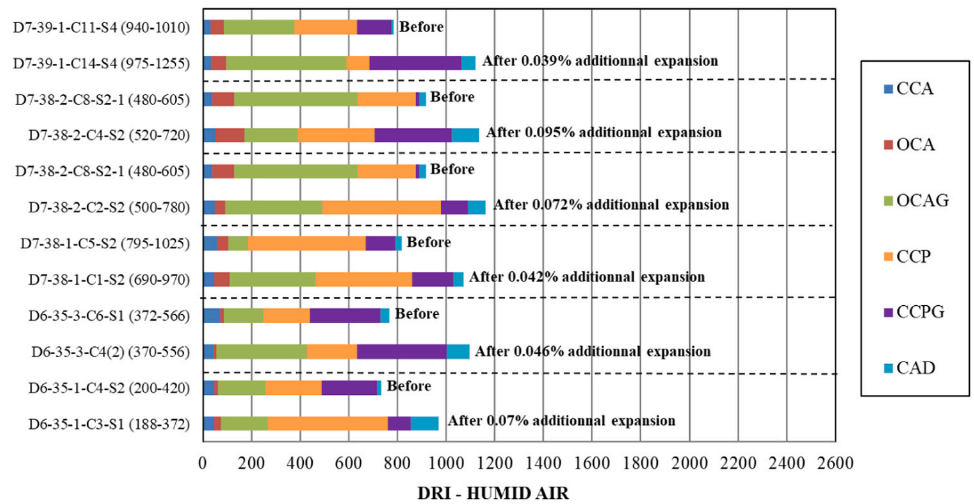


Fig. 6. Details of petrographic symptoms of deterioration in the examined cores – results for as-is sampled cores and cores tested after residual expansion in humid air [WF: weighting factor for DRI calculations; CCA: closed cracks in the aggregate particles (WF = 0.25); OCA: open cracks in the aggregate particles (WF = 2); OCAG: open cracks in the aggregate particles + gel (WF = 2); CCP: cracks in the cement paste (WF = 3); CCPG: cracks in the cement paste + gel (WF = 3); CAD: coarse aggregate debonded (WF = 3)].

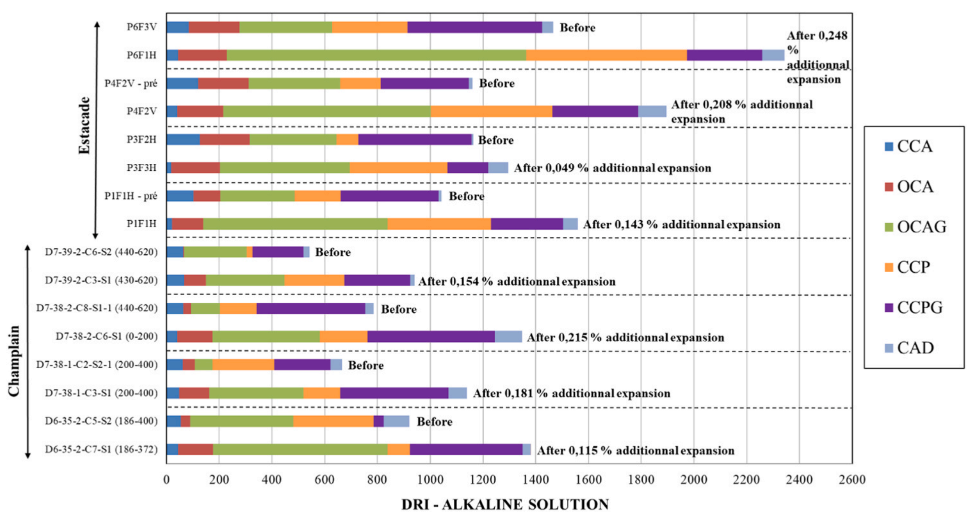


Fig. 7. Details of petrographic symptoms of deterioration in the examined cores – results for as-is sampled cores and cores tested after residual expansion tests in a 1 N NaOH solution.

aggregates and the cement paste generally increase. Although this is true also for the cores immersed in the alkaline solution, the counts for open cracks in the aggregates increase more significantly. It is clear that the additional damage in the alkaline solution immersion is more significant than that observed in the humid air expansion results (Fig. 7).

While the data in Fig. 7 clearly show an increase in the number of open cracks in the aggregates after immersion in 1 N NaOH solution, the increase in cracking within the cement paste is somehow difficult to appreciate. For this reason, it is useful to consider solely the evolution of cracking in the cement paste. Fig. 8 presents the number of cracks observed in the cement paste, with or without reaction products, for core specimens subjected to expansion in a 1 N NaOH alkaline solution, directly compared to those observed in as-is sampled specimens from similar locations (Fig. 4).

It can be observed that the number of cracks in the cement paste does in fact increase for each pair of specimens, indicating that cracking keeps extending in the paste as ASR expansion develops, irrespective of the stage. The evolution of petrographic features as a function of expansion will be further analyzed in a subsequent section. Yet, although an increase is noted, it is clearly less pronounced than the cracking developing in the aggregates. It is important to recall that the DRI method only takes into accounts the number of visible cracks. Parameters such as crack length or width are not considered in the index value calculation. Therefore, a less pronounced increase in crack counts in the cement paste does not necessarily imply that cracking is not evolving. Crack length, for instance, may continue to grow and contribute to ASR damage, which would not be reflected in the results obtained through the DRI method.

4.3. SDT results

Tables 1 and 2 summarize the results of the SDT tests carried out on as-is core samples and core samples subjected to residual expansion tests, respectively. Again, the comparisons are made between two core samples from the same location in the structure and with similar diameters. The output parameters (SDI, PDI) do not vary much within the series of as-is core specimens, which actually reflects a relatively uniform condition of the concrete in the sampled areas of the structure. Both SDI and PDI parameters are higher for all specimens tested for residual expansion in an alkaline solution compared to those tested in

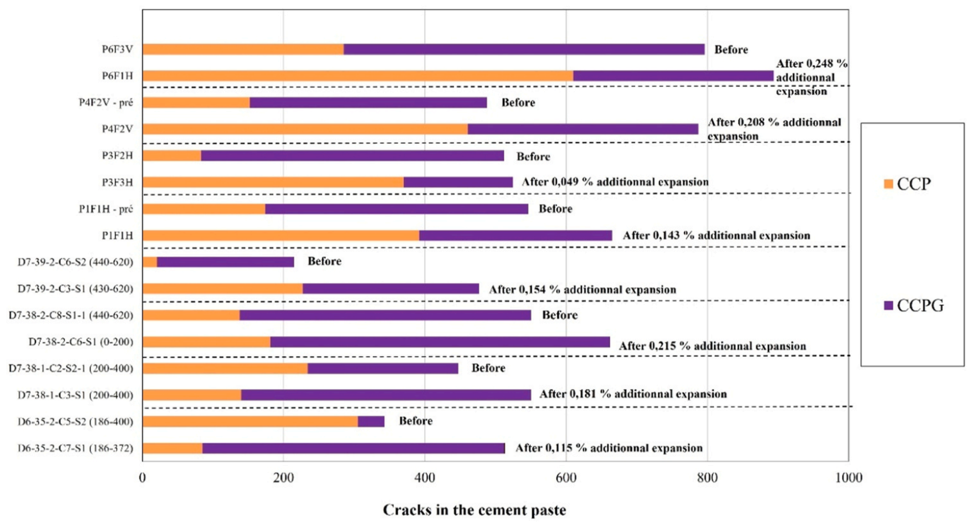


Fig. 8. Details of cracks in the cement paste in the examined cores – comparative results for as-is sampled cores and cores tested after residual expansion tests in a 1 N NaOH solution.

humid air, indicating increased energy dissipation during the test and, in turn, more extensive cracking of the concrete.

5. Discussion

Before discussing the results of the experimental program, their variability is first addressed. For both the DRI and SDT test methods, the measurement uncertainty of the output parameters was estimated.

For the DRI tests, variability is linked to the experience of the petrographers performing the tests, as the accuracy of the method relies on their observations. In order to reduce this source of error, it is important to compare the results of examinations conducted by the same petrographer. To estimate the single-operator variability, a series of four DRI specimens with various damage levels underwent a second examination for comparison. From this, an average variability of 3.9 % was determined [48].

The variability of the SDT output parameters was examined by comparing the results of three as-is core specimens extracted from the same structural element, at the same depth and from parallel cores of similar dimensions (length and diameter). The SDI and PDI parameters were found to have variabilities of 6.9 % and 5.1 %, respectively.

5.1. Interpretation of residual expansion test results using the DRI method

Figs. 6 and 7 illustrate the increase in DRI values in concrete specimens resulting from residual expansion testing at 38 °C, both in humid air and in a 1 N NaOH solution. Fig. 9 further shows the relationship between the increase in DRI values and the deformation measured at the end of the residual expansion tests, for both storage conditions. On this figure, the relationship established by Sanchez et al. [10] for similar reactive siliceous limestone aggregates (Québec) was added for comparison.

First, a notable difference is observed between the results obtained depending on the type of conditioning. The expansion test in humid air caused only slight additional expansion compared to the results from alkaline solution immersion, not exceeding 0.08 %, which resulted in

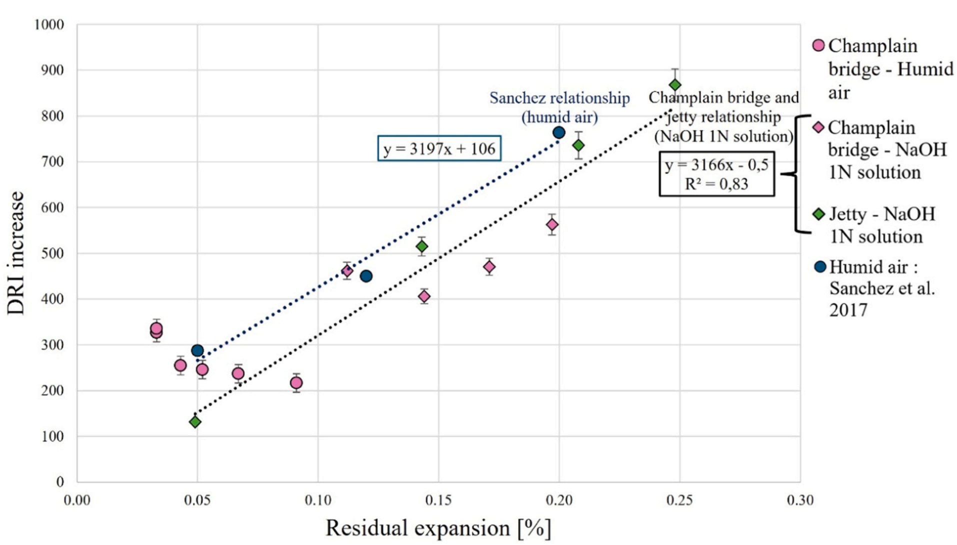


Fig. 9. Relationship between the variation in the DRI value during residual expansion testing and the concrete deformation recorded after 52 weeks of conditioning after hygrometric re-equilibration in different storage conditions. The trend observed for the NaOH 1 N solution is established based on the results from the Original Champlain Bridge cores and the jetty cores. No clear trend could be identified for the data obtained from the Original Champlain Bridge cores that underwent residual expansion under humid air exposure.

limited additional damage in the test specimens (an increase in DRI from 200 to 300). The reason for such results is presumably a somewhat limited "residual" alkali content in the concrete and/or that leaching of alkalis from the specimens reduced the concrete alkali content under the threshold necessary to maintain deleterious ASR activity in the test specimens, as reported by [49,50]. As shown in Fig. 5, over the 52-week testing period, the cores exposed to humid air overall exhibited a constantly decreasing expansion rate, while the expansion in NaOH kept steady. Therefore, using cores with a larger diameter (in the present case, 140 mm) is apparently not sufficient to prevent alkali leaching. Such behavior has also been observed in recent studies [51] for cores tested under humid conditions, where authors reported a tendency to plateau relatively early in the expansion tests, particularly for cores with a diameter of 100 mm.

Given the much higher expansion values recorded in the alkaline solution, where a continuous supply of external alkalis was provided, the hypothesis of alkali leaching in humid air is quite plausible. However, it is also possible that the current alkali content of the concrete is already limited after extraction of the specimens, and that significant expansion could occur only if additional alkalis are introduced into the system. Additionally, the specimens were initially damaged, which further accelerated alkali leaching in humid air, while promoting alkali ingress in 1 N NaOH. This could explain why the recorded expansion rates are much slower compared to those typically experienced in tests conducted on initially intact specimens [10]. Premature cessation of expansion in humid air is observed for all tested specimens, regardless of their diameter, which varied from 93 to 140 mm.

The additional concrete expansion recorded in the alkaline solution appears to be proportional to the increase in the DRI (Fig. 9). The results obtained in the present study can be compared to the relationship reported by Sanchez et al. [10] for similar reactive siliceous limestone aggregates (Québec), based on expansion tests carried out in humid air at 38 °C (also illustrated in Fig. 9). It is noteworthy that both relationships display very similar slopes. This finding is interesting, because it suggests that the cracks generation incurred by the specimens during immersion in the NaOH solution is similar to that observed in test prisms stored in humid air. While the underlying deterioration mechanisms in alkaline solution and humid air cannot be analyzed, their effects appear to lead to a comparable generation of cracks in both the aggregates particles and the cement paste. These assumptions are strengthened by the fact that the results from the bridge and the jetty elements exhibit the same trend, despite probably slight differences in concrete composition and exposure conditions.

Besides, the offset observed in Fig. 9 between the curve from the data generated in this study after NaOH immersion and the one reported by Sanchez et al. [10] can likely be explained by the fact that the latter conducted their experiments on "virgin" laboratory cast specimens. Their test specimens had not undergone ASR prior to the expansion tests, but still embodied intrinsically present defects at the beginning of the expansion tests. The reported DRI values determined for as-is concrete is typically of the order of 100–350 [10].

Based on the data reported by Sanchez et al. [10], the relationship between DRI and expansion in humid air expansion tests showed somewhat similar trends for a range of reactive aggregates, suggesting that the development of internal damage as a function of ASR expansion is comparable among these aggregates. Therefore, the relationship found in the present study for existing concrete could potentially be applicable to different types of aggregates, which would be quite convenient for the evaluation and management of ASR-affected structures.

So far, only the total DRI number has been discussed. However, it could be useful to break down this number in order to get a better insight of how ASR-related symptoms evolve within the concrete during residual expansion testing. The DRI is mainly influenced by cracks in the aggregates and the cement paste (with or without gel). This is shown in Fig. 10, which presents the evolution of the DRI number, as a whole and broken down as a function of single petrographic damage feature, and the *total expansion* likely experienced by the tested concrete specimens. The latter is obtained by adding the *estimated* and *residual* expansion values for the various specimens investigated (Original Champlain Bridge and jetty) in Tables 1 and 2. A quite good linear correlation is observed between the total expansion and the evolution of the various petrographic feature counts in the test specimens, at least from the moment of sampling in the structure.

Fig. 11 further presents the relationship between the total expansion and the evolution of the number of open cracks (normalized to a 100 cm^2 surface), broken down between those found in aggregates and those present in the cement paste, for as-is sampled specimens and core sample specimens subjected to residual expansion testing. In the case of the as-is specimens (i.e. two dashed lines on the left side of the figure), the total expansion was estimated by applying the relationship proposed by Sanchez et al. [10] to the DRI values measured on those specimens

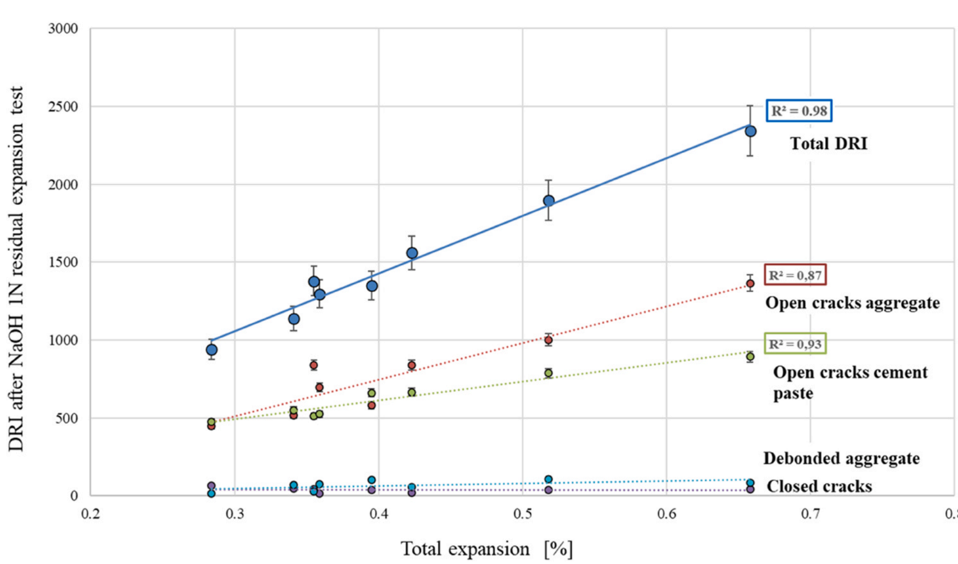


Fig. 10. Evolution of the DRI value, as a whole and broken down as a function of single petrographic damage features in the test specimens subjected to residual expansion testing in the NaOH solution (note: the values for open cracks in the aggregates and in the cement paste do not take into account the presence or absence of ASR gel).

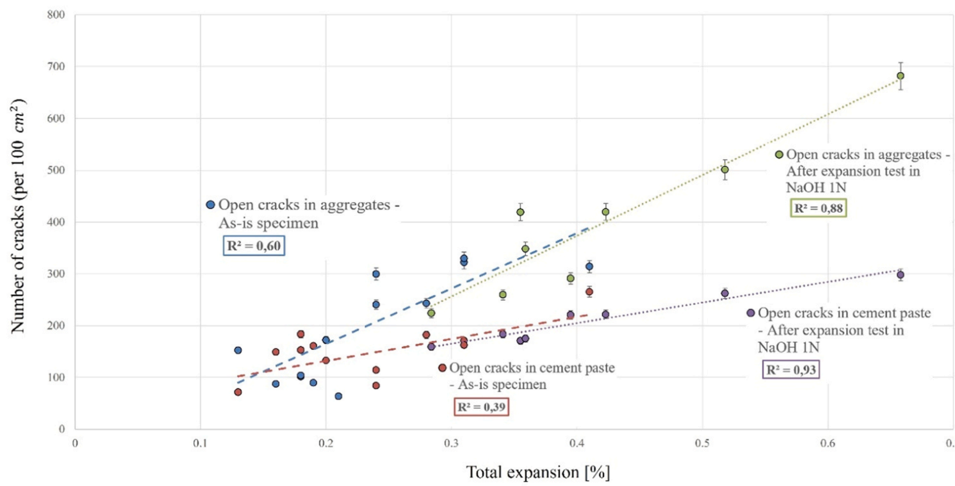


Fig. 11. Total number of cracks (normalized to a 100 cm² surface) in aggregate and in cement paste as a function of expansion, measured on as-is core specimens and core specimens tested in a 1 N NaOH solution.

(Fig. 9). For the specimens subjected to the NaOH expansion (i.e. two dotted lines on the right side of the figure), the total expansion was determined by adding the measured NaOH expansion to the estimated expansion of the corresponding as-is specimens. The focus will be on the consistency observed between the trends of the as-is specimen curves and those of the specimens tested for residual expansion, as the relationship for the as-is specimens is obtained using estimated values from an already existing DRI-expansion relationship.

Cracks in the cement paste can be observed at low expansion levels in the as-in specimens, which is likely linked to the fact that the concrete experienced other on-site pathologies affecting the cement paste. In particular, signs of freeze-thaw deterioration were identified in some cores, especially those taken in areas of elements that were more exposed to environmental conditions.

Regarding the results of expansion testing in the alkaline solution, it is interesting to observe that the trends for increasing numbers of cracks in the aggregate particles and the cement paste as a function of expansion are in direct linear extension to the trends established with the as-is specimens. This indicates that the relationship between the cracking development and the expansion does not change from field exposure to NaOH exposure. Therefore, it might be inferred that even though NaOH accelerates the reaction kinetics, it does not modify the underlying expansion mechanism.

The results clearly suggest that the reserve of reactive silica within the coarse aggregates of the investigated concretes is not yet fully depleted. Cracking within the aggregates continues to increase with expansion at a constant rate, even beyond 0.6 %. This is particularly noteworthy, because the Original Champlain Bridge has been in service for almost 60 years, and yet the concrete still exhibit significant potential to undergo further expansion. This finding underscores the importance of establishing a suitable protocol for evaluating residual expansion.

Based on the above results, it seems relevant to compare the cracking pattern within NaOH test specimens to that proposed by Sanchez et al. [19] for specimens exposed to humid air. These authors suggested that beyond a limit of approximately 0.2 % of expansion, the number of cracks in the aggregates starts to plateau and further damage develops through extensive cracking into the cement paste and connecting reacted aggregate particles. However, this is not the case here, as no plateau in the number of cracks within the aggregates is observed as a function of the expansion recorded, well beyond 0.2 %. It is important to note that the maximum expansion levels affecting the concrete specimens studied by Sanchez et al. [19] was of the order of 0.30 %, likely as a result of the leaching of alkalis from the specimens that caused premature cessation of the reaction. Therefore, the proposed cracking pattern development may not be representative of the actual on-site evolution, where leaching only affects the very superficial section of the structural element according to Courtier [52].

The results of the DRI determination on test specimens subjected to residual expansion testing in NaOH actually allow to determine the potential cracking pattern in concrete at significantly higher expansion levels, which can actually be experienced when the concrete alkali content is maintained beyond the threshold limit for ASR to occur. For expansion levels exceeding 0.3 %, it was indeed observed that cracks keep developing inside of the reactive aggregates through the creation of additional gel veinlets within the aggregates, where reactive silica can be reached by alkalis and dissolved. This is well illustrated in Fig. 12.

Sanchez et al. [19] proposed a model for cracking development both in the aggregate particles and the cement paste of ASR-affected concretes, based on humid air conditioning test data. This model can thus be further enhanced for high expansion levels based on the observations made on slabs cut and polished from specimens immersed in an alkaline solution, as shown in the schematic representation proposed in Fig. 13. As illustrated in Figs. 7 and 13, the development/extent of cracking with reaction products, both in the reactive aggregate particles and in the cement paste, keeps increasing significantly with increasing expansion in the NaOH solution. The so-called “onion-skin” [19] cracking pattern identified by Sanchez et al. for some reactive aggregates was however not observed in the present study and it is therefore not represented. This pattern was indeed seen in samples containing highly reactive volcanic aggregates [19].It is actually not characteristic of the reaction mechanisms in reactive siliceous limestone, which corresponds to the type of aggregate used under study.

At this point, it seems worthwhile to examine the relationship between the DRI values of specimens subjected to residual expansion testing for one year at 38 °C in different exposure conditions (humid air; NaOH immersion) and those recorded on comparable as-is sampled specimens, i.e. extracted from the same structural element, from parallel/adjacent cores, and at equivalent depths. The relationships found experimentally are presented in Fig. 14.

The linear curve-fit has a relatively high coefficient of determination ($R^2 = 0.8$), suggesting a proportional relationship between the DRI values of as-is specimens and the values determined on comparable specimens tested for residual expansion for one year in an alkaline solution. Despite a much lower spread in DRI values for the test specimens subjected to expansion testing in humid air, the figure shows that as the initial DRI increases, the post-expansion DRI continues to rise in a consistent manner. This confirms that reactive silica is still present and

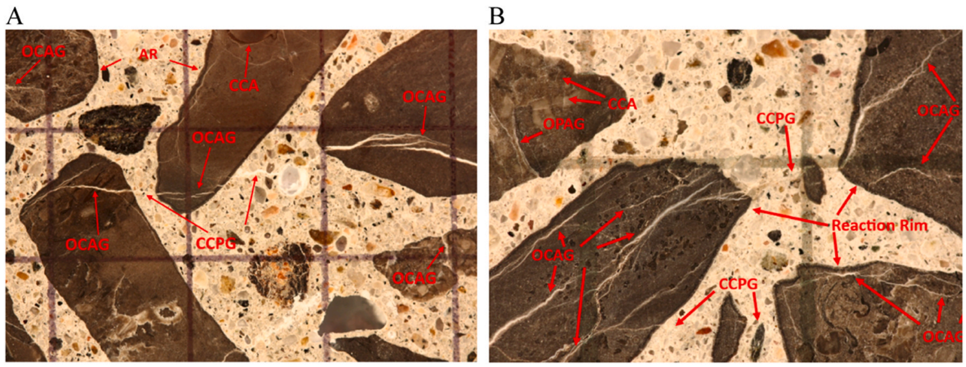


Fig. 12. Micrographs from polished slabs showing the progression of cracking for concretes subjected to a residual expansion test in an alkaline solution (1 N NaOH) – A. total expansion of 0.36 %, presence of a few cracks within the aggregate particles; B. total expansion of 0.66 %, development of much more extensive cracking (with secondary reaction products) within those particles.

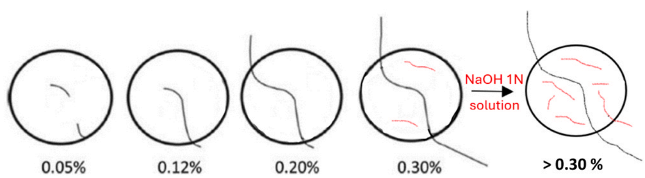


Fig. 13. Cracking pattern in concrete during residual expansion tests in 1 N NaOH, adapted from Sanchez et al. [19].

the reactivity of the specimens has not subsided. In fact, when examining further the relationship, it seems to depart from a linear trend at very high DRI values, i.e. the higher the DRI on as-is cores, the greater the increase in DRI during residual expansion testing. This can be explained by the fact that the higher the initial DRI value, the more extensively cracking has developed in the concrete, resulting in easier migration of alkalis from the immersion solution to the aggregate reactive sites inside the concrete. Therefore, the more damaged (i.e. showing extensive ASR-related cracking) the concrete initially, the higher the expansion rate, which may however be indicative of the particularly severe conditions involved in NaOH immersion testing. It should be stressed however that the number of data is limited, prompting the need for further verification.

Based on the rather homogeneous relationship between expansion and DRI values obtained by Sanchez et al. [10] for a range of reactive aggregates, it is possible that the relationship illustrated in Fig. 14 could apply to concretes incorporating other reactive aggregates, but further testing is required to verify this hypothesis.

5.2. Interpretation of residual expansion tests using the SDT parameters

In the graphs of Fig. 15, the SDI/PDI values are plotted against the residual expansion data obtained both in humid air and in an alkaline solution. The results reported by Sanchez et al. [10] for concrete with comparable compressive strength (35 MPa) and made with a similar

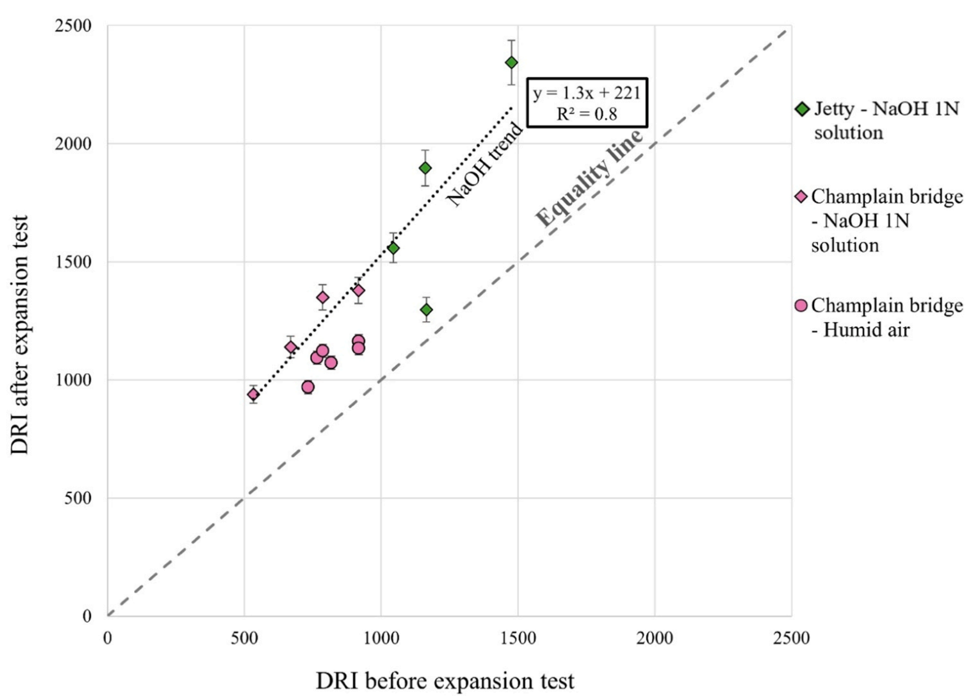
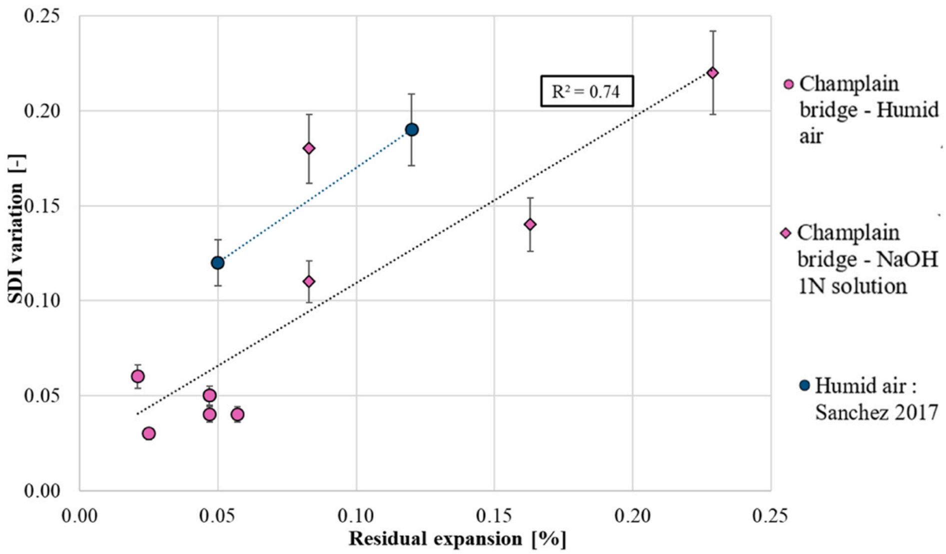
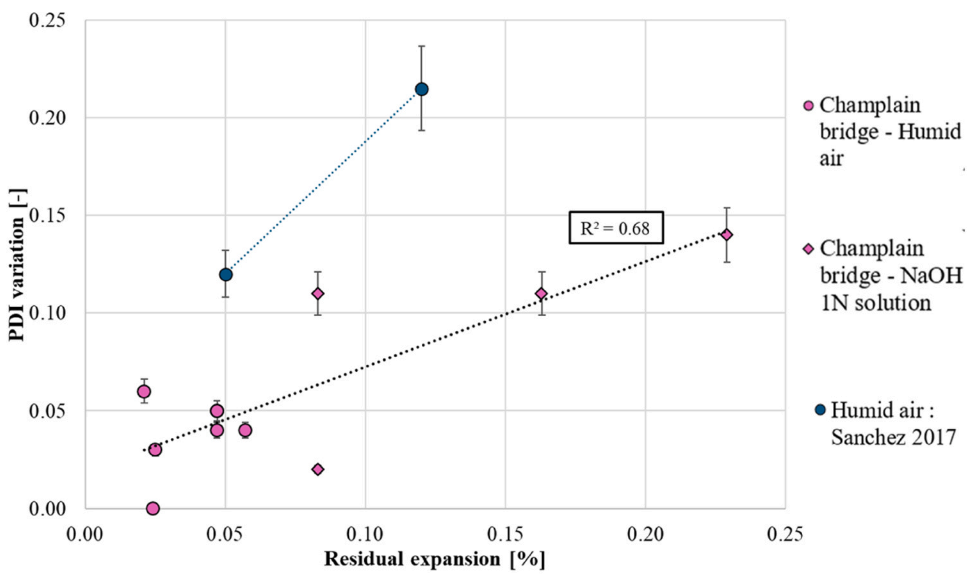


Fig. 14. Relationship between the DRI values of specimens subjected to residual expansion testing and those determined on comparable as-is cores (extracted from the same element, in the same areas and at similar depths). The trend observed for the NaOH 1 N solution is established based on the results from the Original Champlain Bridge cores and the jetty cores. No trend could be identified for the data obtained from the Original Champlain Bridge cores that underwent the residual expansion test under humid air exposure.



A. Relationship between the variation in SDI and residual expansion.



B. Relationship between the variation in PDI and residual expansion.

Fig. 15. Relationship between the variation in the SDT parameters (SDI/PDI) during residual expansion testing and the concrete deformation recorded after 52 weeks *after* hygrometric re-equilibration on specimens immersed in a NaOH solution.

reactive siliceous limestone aggregate (note: before the plateau) have been added for comparison purposes.

At first sight, the SDT results obtained for specimens stored in humid air and in an alkaline solution, respectively, are consistent with the trends observed in the previous section when analyzing the DRI data. In fact, both the SDI or PDI variations are found to increase with the residual expansion recorded at one year, suggesting a grossly linear relationship in first approach, with the test results for the specimens conditioned in the alkaline solution extending in a reasonably continuous fashion from the group of data points corresponding to humid air conditioning. When comparing with the results obtained by Sanchez et al. [10], the curves are somewhat parallel in the case of the SDI parameter (Fig. 15A), although not so much for the PDI (Fig. 15B). However, it is important to note that the available data is quite limited, and the analysis of the established relationship is therefore rather restrained.

Furthermore, no plateau is observed for either parameter within the range of residual expansion recorded. Since the SDI and PDI parameters are primarily affected by cracking in the aggregates [10], this could be expected. Again, consistent with the trends found for the DRI results in the previous section, it tends to confirm that cracking continues to develop with expansion for the test specimens stored in the alkaline solution, thus affecting further the physical integrity and mechanical properties of the concrete.

The complementarity of the petrographic (DRI) and mechanical (SDT) tests and the validity of the results are thus confirmed, as consistent results were obtained with both test methods. The DRI offers petrographic insights into the extent of cracking in the concrete, while the SDT provides quantitative information on how much cracking affects the mechanical properties.

5.3. Recommendations

The following recommendations are provided and could be considered to improve protocols for the management of ASR-affected structures.

Interpretation of data from residual expansion testing performed in humid air should be made with caution. The results may not be representative of the in situ concrete behavior, as they can be significantly affected by alkali leaching. The smaller the size of the test specimen, the ultimate potential expansion recorded is more or less likely to be underestimated. For instance, the FHWA protocol [1] recommends the use of cores with diameters of at least 150 mm to prevent alkali leaching. However, in this study, alkali leaching still occurred despite using cores with a diameter of 140 mm. This suggests that even relatively large specimens do not entirely prevent the phenomenon. It would therefore be interesting to consider additional measures to prevent alkali leaching during residual expansion testing in humid air. Einarsdottir (2017) [53] for example showed that leaching from test prisms (ASTM C1293) can be significantly decreased by loosely covering the upper half of each prism with a plastic bag, leaving the bottom half of the prism open to the moisture in the storage container. Wood (2021) [54] suggested to use wick action of concrete cores sitting in small amount of water (10 g / kg concrete) to maintain sufficient moist conditions within test specimens in residual expansion testing, thus reducing risk of alkali leaching occurring when using conventional consistent conditions of water supply (38 °C and 100 % RH). It should be stated in the FHWA protocol [1] that these results represent a lower bound for the potential residual expansion of the concrete and of the additional damage that may be generated.

Conversely, with an external alkali supply likely to fuel and exacerbate the reaction in comparison with the actual in situ conditions, the results of residual expansion testing conducted in an alkaline solution can be considered to provide an upper bound for the potential residual expansion. Considering that petrographic examination using the DRI method indicates that the NaOH leads to crack generation similar to that in humid air, it is thus proposed to develop a residual expansion method where the test specimens would be immersed in a solution matching the alkali concentration determined in the concrete pore solution, in such a way to avoid both leaching and the supply of external alkalis. A similar approach has been proposed in the past [55]. This would also allow to verify whether tests in humid air and in an alkaline solution actually yield lower and upper bound values for the potential residual expansion due to ASR.

Protocols for the management of ASR-affected structures, such as that proposed by FHWA [1], could be enhanced by performing DRI testing after the residual expansion tests to assess the additional damage induced in the cores. Since the relationship between the DRI value increase and the additional residual expansion appears to be linear, based on the data generated in this study, it may not necessary to carry out the DRI analysis on all specimens after residual expansion tests. Instead, performing DRI on a limited number of cores after residual expansion tests, such as three samples representing the range of expansion values (e.g. the lowest, highest, and intermediate value) may be sufficient to establish a reliable correlation for the concrete tested. This relationship can then be used to estimate the DRI values of the remaining specimens based on their expansion results, without the need to conduct a full petrographic analysis. It becomes particularly useful if a correlation can also be established between DRI and other parameters such as the concrete mechanical properties, especially since expansion data often do not correlate well with the evolution of compressive strength. This is the subject of another study in the long-haul project.

Nevertheless, it is important to emphasize that estimating the DRI value through an empirical relationship does not provide information about the actual damage characteristics. Therefore, if the goal is to investigate the specific cracking patterns or damage mechanisms that occurred during the expansion test, a full petrographic and DRI analysis should still be performed.

Before concluding, it seems important to take a step back and consider the ASR prognosis task in a broader way. While obtaining an estimate of the potential for ultimate expansion of the concrete is of utmost importance, gaining information on how the situation will realistically evolve in the future is just as essential. ASR expansion rate needs to be paid closer attention and studies aiming to correlate the expansion rates recorded in laboratory experiments with those experienced on site are necessary for proper exploitation of the test results and, ultimately, the establishment of reliable diagnoses. In that quest, the development of modeling tools is critical to allow prediction of the future expansive and cracking behavior of concrete in the structure, in different and often time-varying exposure conditions, based upon experimental results obtained for example from small unrestrained specimens subjected to controlled conditions. To address the challenge of simulating the damage induced at the scale of the structure from physicochemical phenomena taking place at the level of the heterogenous concrete microstructure (cement paste porosity, aggregate porosity, reactive silica with the aggregates, alkalis, water), a multiscale or homogenization approach will be necessary. Suitable modeling tools would allow for instance to take into account the specimens geometry and exposure conditions in residual expansion tests and accurately interpret/predict either the plateau associated with alkali leaching or continuous expansion and increase in cracking within aggregates and cement paste when a constant supply of external alkalis is provided. Ideally, a comprehensive model would also allow to take into account the fact that the sampled test specimens have been relaxed from the state of stress that was prevailing inside the structure.

6. Conclusions

The following conclusions can be drawn from the experimental program conducted in this study on series of concrete core specimens extracted from ASR-affected structural members in the field:

- The cores extracted from elements of the Original Champlain Bridge and its jetty showed an increase in expansion for all specimens tested in both residual expansion tests (i.e. specimens stored in humid air at 38 °C or in 1 N NaOH solution at 38 °C) resulting in increased ASR damage. Even after 57 years of service and significant degradation due to ASR in an environment highly favorable to its development, Original Champlain Bridge still had potential for further ASR reaction. Actually, the reactive silica within the aggregates was far from fully consumed. It is believed that in many cases, the timeframe within which the reaction might naturally come to a halt significantly exceeds the typical service life of such structures.
- Typical residual expansion tests conducted in humid air often yield limited expansion and damage generation, due to leaching of alkalis. This raises concerns about the validity and usefulness of the test procedure to predict future damage due to ASR in concrete, as it may not fully capture the damage potential due to the conditioning bias, rendering the results not necessarily representative of the field conditions. The results may be regarded as a lower bound value for the residual expansion potential of ASR-affected concrete.
- Expansion tests conducted in an alkaline solution (1 N NaOH) can theoretically allow to exploit the full reactivity of the aggregates and yield the maximum expansion potential of the concrete specimens. The results of the experiments conducted in the present study showed that albeit the aggressiveness of the immersion solution, it produces damage features similar to those observed in humid air tests. These tests can thus offer a representative assessment of the upper bound value for future expansion of concrete affected by ASR.
- For the tested specimens, it was possible to correlate the additional expansion and damage in an alkaline solution, based on the initial DRI value.
- The findings are pointing towards the need for developing a more realistic test procedure where the in-situ or initial alkali level in the concrete would limit the movement of alkalis through the use of an immersion solution with a concentration in alkalis equal to that of

the concrete pore solution. Comparative analysis with results from humid air and alkaline solution (1 N NaOH) tests is recommended to validate this approach.

- Efforts towards the development of suitable modeling tools are necessary in order to make better use of laboratory test data in the management of ASR-affected concrete structures and issue more accurate and thorough prognosis.

CRediT authorship contribution statement

E. Baret: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, **B. Fournier**: Writing – review & editing, Validation, Supervision, Resources,Project administration, Methodology, Funding acquisition, Conceptualization, **B. Bissonnette**: Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, **M. Khaleghi**: Writing – review & editing, Visualization, Data curation, **L. Courard**: Writing – review & editing, Supervision, Funding acquisitiona, **M. Ranger**: Writing – review & editing, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available on request.

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