EVALUATION OF THE DEGREE OF DAMAGE CAUSED BY ALKALI-SILICA REACTION IN A HIGHWAY PAVEMENT: A CASE STUDY

Anthony Allard[1*], Benoît Fournier[1], Josée Bastien[1], Benoît Bissonnette[1], Léandro Sanchez[2], Josée Duchesne[1]

[1]Université Laval, Québec, QC, CANADA

[2]University of Ottawa, Ottawa, ON, CANADA

Abstract

The evaluation of the current condition and cause of deterioration is a key element for elaborating remedial actions in aging concrete structures. Several tests, such as the *Stiffness Damage Test* (SDT) and the *Damage Rating Index* (DRI), were developed over the years and optimized to propose a protocol for reliably evaluating the condition of concretes affected by alkali-silica reaction (ASR).

Near Bécancour, QC, Canada, a highway concrete pavement never opened to traffic and affected by ASR presents an interesting case for the application of the proposed protocol for the evaluation of the damage caused by ASR. Four sections of highway, showing varying degrees of visual deterioration, were cored and multiple tests were carried out, such as the SDT, the DRI, the gas pressure tensile test, splitting-tensile strength and direct tension test. Statistical analyses of the test results were performed in order to verify whether the proposed protocol is applicable.

Keywords: Alkali-Silica Reaction, Stiffness Damage Test, Damage Rating Index, pavement, damage

1 INTRODUCTION

A boom in construction occurred in North America in the 1950's to 1970's, period during which multiple road infrastructures were built. While they were designed according to the accepted standards of the time, the conditions to which they are subjected have changed significantly over the years, especially regarding traffic loads and material's quality control. Moreover, a large proportion of those concrete structures have developed different pathologies, such as corrosion, frost damage or alkali-silica reaction (ASR) that have seriously affected their durability and service life expectations.

ASR is a chemical reaction between the aggregate's reactive siliceous phases and the strongly alkaline pore solution of the concrete, which forms a secondary alkali-silica gel. This gel absorbs the available water of the pore solution and surrounding environment, thus causing swelling, internal stresses and cracking of the affected concrete element.

Cracking affects the mechanical properties of the concrete to different extents, as shown in Figures 1A and 1B. Indeed, they demonstrate that compressive strength is the least affected property by ASR, at least until large expansions are reached. This can be explained by the fact that two phenomenon oppose each other. First, the long term hydration of the concrete causes higher compressive strength that mitigates the negative aspect of ASR. Second, the "failure" of concrete in compression takes place in multiple stages, and contrarily to tensile "failure" that is dominated by the development of a small number of cracks, compressive failure happens when a large number of cracks connect with each other [1]. A large number of cracks are thus needed in order to affect the compressive strength, which only happens at a late stage of ASR. It explains why the compressive strength is not typically seen as a reliable indicator of the advancement of ASR in concrete.

On the other hand, ASR affects the tensile strength of concrete very rapidly (Figure 1B); however, the extent of tensile strength's reduction depends on the type of test performed. Indeed, direct tension and gas pressure tensile tests will normally present higher losses in strength while the splitting cylinder test will present a more gradual loss in tension. ASR-affected concrete will also present a rapid loss of rigidity (modulus of elasticity) caused by the rapid appearance of cracking in the aggregate particles [2,3].

When selecting the best approach for repairing ASR-affected concrete infrastructures, it is important to assess their state of deterioration to get a complete view of the situation. For that purpose, Sanchez [2] recently proposed a step-by-step approach based on the evaluation of the

* Correspondence to: anthony.allard.1@ulaval.ca

reduction in mechanical properties coupled with the analysis of the development of microstructural features of ASR distress using the *Stiffness Damage Test* (SDT) and the *Damage Rating Index* (DRI) carried out on cores extracted from various components of the structure under evaluation. Those two tests have shown through various studies a very interesting potential to assess the state of deterioration [4–7]. The approach proposed was developed on the results of a large laboratory investigation, which needs to be validated on real cases of ASR-affected concrete infrastructures.

The highway pavement studied in this paper is located in the Bécancour greater area and was built in the 1970's. The concrete slabs are around 15 meters long and linked by dowel bars. A steel grid 6 x 6 inches is present at mid-depth within the slabs and complicated the coring process. The coarse aggregate used in the concrete formulation of the pavement is a highly reactive siliceous limestone from the Saint-Lawrence lowlands [8].

2 MATERIALS AND METHODS

2.1 Location and type of field specimens

For this project, cores were extracted from four sections of the pavement, two of them being visually classified as heavily damaged (E1 and E2; figures 2A & 2B), and one as moderately damaged (ME; Figure 2C), i.e. showing respectively extensive and moderate levels of cracking. Section E2 was actually located besides a destroyed slab joints (Figure 2D). The last section was considered undamaged (NE) or to present minimal signs of deterioration (Figure 2E), as it was located under an overpass and was shielded from direct rain or snow fall. Four sets of cores were extracted from each of the above sections in order to perform the different tests planned in the investigation program, i.e. compression strength, tensile strength (gas pressure, splitting cylinder, and direct tension), SDT and DRI. Immediately after extraction, the cores, 90 to 100 mm in diameter x 200-225 mm long (i.e. full pavement depth), were cleaned up with a dry towel and wrapped in several layers of plastic film.

2.2 Testing of specimens

The protocol proposed by Sanchez [2] suggests determining the reduction in concrete's mechanical properties (compressive strength, tensile strength and stiffness) due to ASR. As such, concrete from the undamaged or least damaged zone was used as the baseline for further testing.

Three to six steel-free cores were used for stiffness damage testing, and one for semi-quantitative petrographic analysis (DRI). Three tests were used to determine the tensile strength of the concrete pavement.

The splitting cylinder tensile test determines indirectly and generally overestimates the tensile strength of the concrete through the application of a compressive load over the length of the core [9], as specified in ASTM C496 [10]. The direct tension test consists in applying a tensile load to a concrete cylinder through the use of steel plates epoxied to the cylinder's end portions, and that are connected to the load cell with the help of steel chains. This test method does not predefine the failure plane, so the rupture occurs on the weakest plane. One of the difficulties of this test is to maintain the parallelism between the specimen's length and the direction of applied loading, thus ensuring a true tensile stress on the test specimen. The gas pressure tension test was developed in the 1970's by Clayton & Grimer [11]. The concrete cylinder is inserted into a metal jacket. A pressure is then exerted on the cylindrical surface of the specimen by the introduction of a gas (nitrogen) into the confining cell where the extremities of the specimen are free. The increase of the pressure leads to a compressive axisymmetric loading on the curved surface of the cylinder, which results in tensile stresses in the longitudinal direction. Eventually, a tension failure occurs along the weakest plane. The pressure of the gas at the moment of failure is then considered to be the indirect tensile strength of the concrete.

The *Stiffness Damage Test* (SDT) is a cyclical compression test where a concrete cylinder/core undergoes five cycles of loading-unloading at a rate of 0.1 MPa/sec. A metallic cage (Figure 3A) equipped with linear variable differential transformers (LVDT) linked to an acquisition data system registers the deformations during the cycles. After an extensive investigation carried out on laboratory specimens incorporating a variety of reactive aggregates and affected to various degrees by ASR, Sanchez [2] proposed to use a maximum load corresponding to 40% of the compressive strength of the undamaged concrete. The author also introduced the *Stiffness Damage Index* (SDI) and the *Plastic Deformation Index* (PDI). The SDI corresponds to the ratio between the dissipated energy and the total energy used during the test, while the PDI represents the ratio of the plastic deformation over the sum of the plastic and elastic deformation (Figure 3B). These new parameters are particularly interesting since they allow to compare damage in concretes of different formulations and strengths.

The *Damage Rating Index* (DRI) consists in performing a petrographic analysis of a polished concrete slab to quantify the presence of petrographic features of ASR. The concrete specimen is first cut in half and one of the surface thus obtained is finely polished. A grid of 1 cm x 1 cm is then traced on a minimal surface of 150 cm² in order to provide a representative surface. Each square is then examined under a stereobinocular microscope at a magnification of about 15X. The sum of the counts of the various deterioration features are multiplied by selected weighing factors and the total sum is normalized for a surface area of 100 cm² [12]. The number thus obtained represents the *Damage Rating Index*. The petrographic features and their corresponding weighing factors used in this case study are those proposed by Villeneuve [12] and also used by Sanchez et al. [13] (Table 1).

3 RESULTS

3.1 Compressive strength determination

The average compressive strengths ranged from 44.5 (E2) to 62.9 MPa (ME), with a value of 57.7 MPa being obtained for the undamaged zone under the bridge deck (NE) (Table 2). Despite similar visual aspects, the cores extracted from zone E1 showed significantly lower strengths than those of zone E2 (averages of 44.5 vs 61.0 MPa); this was somewhat unexpected considering that the latter was obtained close to a heavily damaged joint and that the concrete strength was actually similar to that of the visually undamaged and moderately damaged concretes.

While no records of the specified 28-day compressive strength were available, the general Ministry of Transportation's guidelines of the time specified a concrete compressive strength of about 31 MPa for this type of infrastructure. All cores from the different extraction zones developed significantly higher compressive strengths, likely through continuous hydration of the concrete. However, it is also possible that the concrete mixture proportion used for this infrastructure was of a higher quality than that found in the specifications.

3.2 Stiffness Damage Testing

Since the *Stiffness Damage Test* is a cyclical loading test applying a stress corresponding to 40% of the design compressive strength, it is possible to extract the modulus of elasticity of the concrete from that test, which is normally a good indicator of the level of damage suffered by the material.

The modulus of elasticity obtained from the various sets of cores (average of the 2nd and 3rd cycles) are presented in Table 2. As for the compressive strength, similar results were obtained for extraction zones NE, ME and E2. Once again, the undamaged zone NE is not the one that developed the highest value, as zone ME and E2 showed higher values of Young's modulus (33.6 vs 35.8 and 33.8 GPa). Also, even though zones E1 and E2 were both visually classified as heavily damaged, the concrete from zone E1 presented a reduction in rigidity of about 27% compared to NE, while the modulus of elasticity of the concrete from zone E2 has not diminished.

The average *Stiffness Damage Indices* (SDI) corresponding to each extraction zones are presented in Table 2. Once again, the results for zones NE, ME and E2 are similar (values ranging from 0.12 to 0.14), while zone E1 is different (SDI of 0.20) and likely affected by a greater magnitude of internal cracking.

The average *Plastic Deformation Indices* (PDI) are given in Table 2 for the different zones investigated. The concrete from zones NE, ME and E2 displayed low PDI values, with average values ranging from 0.06 to 0.08 indicating minimal or marginal damage caused by ASR. The higher PDI value of 0.12 obtained for E1 suggests a somewhat higher degree of internal damage than in the other zones.

3.3 Damage Rating Index

The Damage Rating Index (DRI) test was performed on one core from each of the extraction zones. The results are presented in Figure 4. The detailed petrographic features of deterioration are also presented on this figure, while the abbreviations used are defined in Table 1. The DRI indicates that zone E1, with a DRI of 716, presents the highest degree of deterioration, as was established by the other tests. Contrarily to the other results presented before, the DRI test indicates a higher degree of internal damage in zone E2 (DRI of 539) compared to zones NE (DRI of 283) or ME (DRI of 328), but still less than E1. Figure 5 presents typical petrographic features observable on the polished concrete cores.

3.4 Tensile Strength

The results obtained from the three different methods used for tensile strength determination are given in Table 3. The splitting cylinder test produced the highest values (3.5 to 4.3 MPa), followed by the gas pressure tensile test (2.6 to 3.1 MPa), and the direct tensile test (1.9 to 2.8 MPa).

4 DISCUSSION

4.1 Reliability of the condition assessment

Mechanical Testing

The results presented before for the damage assessment correspond to the means of the values obtained on two to six cores for each of the different parameters evaluated; however, it is important to verify if these results are statistically significant. Table 2 presents the statistical data obtained for the SDI, PDI, compressive strength and modulus of elasticity. While the moderately damaged zone (ME) is presented in Table 2, only 2 cores were used for each of the tests and, as such, the results may not be representative of the real concrete condition.

The SDI results show good reproducibility for the undamaged zone NE (CV = 9%) and damaged zone E1 (CV = 8 %), while the results from zones ME and E2 present a high variability with a CV of 22 and 54%. The CV for the PDI ranges from 18 to 33%, if we exclude zone ME, thus suggesting that the variability for this parameter may be too high for its application on field concretes. The compressive strength for each zone has low CVs ranging from 4 to 7%, as does the modulus of elasticity, which presents low CVs for each zones with values ranging from 2 to 3% and a higher value of 11 % for zone ME.

An analysis of variances (ANOVA) was performed on the results from the SDI, PDI, compressive strength, modulus of elasticity and tensile strength tests for the zones where at least 3 cores were available (NE, E1 and E2). The P-values obtained from these statistical analyses are presented in Table 4. These P-values represent the probability of observing a value of the test statistic greater than or equal to the critical value if the null hypothesis is true [14]. This null hypothesis states that there is no difference between the two populations. So, if the P-value is less than 5% (significant level in the ANOVA used), the null hypothesis can be rejected and both populations analysed are statistically different from one another.

The results in Table 4 show that the tests have the ability to differentiate the damage levels between cores from zones NE and E1, as well as between E1 and E2. On the other hand, the results between zones NE and E2 are not considered statistically different. Two assumptions can thus be made, either the concrete from E2 and NE are equally damaged or the variability of the different tests used to assess the degree of damage of the material is too high to differentiate both zones. Also, the PDI seems to present a greater variability or a lesser sensitivity than the other tests/parameters since it does not seem able to differentiate the damaged vs undamaged concrete from the different zones.

The statistical analysis of the results obtained from the different tensile testing series was also performed (not showed here); all analyses were able to reject the null hypothesis, thus confirming that the results are statistically different for the analysed series. Table 3 presents the difference in percentages between the undamaged zone NE and the damaged zone E1. Both splitting tensile and gas pressure tensile tests produced higher values than the direct tensile strength, but the differences between both zones is similar for each test (i.e. about -17%). The sensitivity for the direct tensile test is much greater, with a difference of 32% between both zones, agreeing with common knowledge that the splitting cylinder strength is higher than the direct tensile strength. The gas pressure test measured strengths that are closer to those obtained from the direct tensile method, while showing lower variability of the test results. More work is currently in progress to truly comprehend what can be concluded from the results of those tests in terms of differences in material's properties.

Petrographic examination

The DRI provides an indication of the microstructural condition of the concrete. Based on laboratory investigations, Sanchez et al. [13] showed that the progress in the DRI numbers generally show a strong correlation with increasing expansion due to ASR (see Column DRI in Table 5). The authors also showed that a thorough analysis of the counts of the petrographic features of ASR can provide further insights on the internal concrete damage due to this deleterious mechanism. Such observations were also reported by Fournier [15] through the semi-quantitative petrographic analysis of cores extracted from different piers of a large ASR-affected concrete bridge in Eastern Canada. The authors proposed the following ranges of DRI values based on typical petrography features of deterioration:

- for low DRI's (up to around 250), the concrete is in good condition; no significant signs of deterioration are visible at the macro level (with naked eyes) and a limited number at the micro level (i.e. under the stereomicroscope at a magnification around 15X) that mainly consist in closed cracks within the coarse aggregate particles.
- DRI's between 250 – 400 represent concrete in fair condition but with fine cracking in the aggregate particles with a moderate proportion of those partially filled with ASR gel. Only a limited proportion of the cracks within the aggregate particles extend into the cement paste, at least visible at the 15x magnification used for DRI.
- For DRI's between 400 and 750, signs of ASR are moderate to severe with extensive cracking in the aggregate particles and a good portion of these are filled with ASR gel. Also, cracking in the aggregate particles often extend into the cement and may connect reactive aggregates. Cracking in the cement paste becomes important and some cracks might be filled with reaction products.

It is important to mention that the above observations were found to be very close to those proposed by Sanchez et al. [11], the latter being associated to concrete specimens in free expansion mode under accelerated laboratory conditions.

Based on the above observations, the DRI values and detailed petrographic observations were able to highlight the extent of damage in E2 concrete. The DRI numbers classify the ASR damage as severe in zonesE1 and E2, while zone NE is classified as marginally damaged.

4.2 Analysis of the laboratory investigations for condition assessment

A lot of results were generated during the preliminary phase of this case study, as one of the goals was to evaluate the protocol proposed by Sanchez [2] for evaluating the concrete damage caused by ASR in a concrete pavement. Sanchez's protocol uses the SDI, the DRI and the losses of rigidity, compressive and tensile strength to evaluate the importance of the damage caused by ASR, as is presented in Table 5.

The reduction in mechanical properties, the SDI, DRI and their corresponding ASR damage assessment are presented in Table 6, for each studied zones. Depending upon which parameter issued, the damage assessment caused by ASR can range from negligible to high for the same extraction zone. The values proposed by Sanchez [2] for the classification sometimes overlap for different damage levels, which might explain why the assessment ranges from negligible to high. These overlapping values result from the testing of a wide range of reactive aggregates (coarse and fine) and different concrete formulations (25 to 45 MPa). Moreover, as discussed earlier, it seems that some tests are actually not as "diagnostic" as others for the condition assessment of concrete affected by ASR. It might be that zones E2 and ME were not as internally damaged as the visual inspection seemed to indicate or that the variability for these tests on field concrete is too high. Also, Sanchez [2] reported that the widespread presence of alkali-silica gel in cracks with increasing ASR can result in the SDI and PDI values to level off with increasing expansion due to ASR, thus making this parameter potentially less diagnostic for higher levels of severity.

The DRI seemed to be the test that best correlated with the results of the visual condition assessment of the different pavement sections; however, overall, engineers in charge of the management of ASR-affected structures are not so much interested in the presence of cracks in concrete but more on the impact that those may have on the performance of the concrete member.

A second phase for this case study is in progress. Multiple cores (at least 50) from different damaged zones will be further extracted and most of them will be used to evaluate the variability and the applicability of the *Stiffness Damage Test* on concrete extracted from real infrastructures. It will be interesting to determine whether the variability of the different diagnostic parameters is adequate for the evaluation of ASR damage.

5 CONCLUSIONS

A number of tools are available for assessing the damage caused by ASR in field concrete. A testing protocol was recently proposed that uses reductions in the mechanical properties and the results from the Stiffness Damage Test and the Damage Rating Index for the condition assessment of ASR-affected concrete members. While the tests used for the mechanical properties determination are widely known and recognised, some new tests such as the gas pressure tensile test need more work in order to really understand the results they generate. Also, additional testing is needed to confirm the reliability of various parameters generated through stiffness damage testing for the condition assessment of field concretes.

As of now, the different methods used as part of this case study resulted in different condition assessments of the ASR-affected concrete pavement under study. This might have been caused by a misleading identification of the damage level of section E2 by visual examination, or by an important variability of some of the various test parameters measured by the SDT. It can be concluded from this preliminary case study that only zone E1 can be equally classified as truly damaged by the various tools used in the investigation program, while those tools provided different damage assessments for the other extraction zones. As such, a second phase will be conducted that will involve further sampling of the various zones of the pavement and a complete statistical analysis of the test results to establish the variability of the SDT output parameters.

6 ACKOWLEDGMENTS

The authors would like thank Quebec's Ministry of Transportation for their help and for according us the permission to study this infrastructure, particularly Mr. Alain Hovington and Mrs. Nadia Pouliot. The authors would also like to thank Mr. Cédric Drolet for his gracious help throughout this study.

7 REFERENCES

[1] Popovics, S, Strength and related properties of concrete a quantitative approach, John Wiley & Sons, New York, 1998.

[2] Sanchez, LFM, Contribution to the assessment of damage in aging concrete infrastructures affected by alkali-aggregate reaction, Ph.D. Thesis, Université Laval, 2014.

[3] Mindess, S, Young, J, Darwin, D, Concrete, 2nd ed., Pearson Education Limited, 2003.

[4] Sanchez, LFM, Fournier, B, Jolin, M, Bastien, J, Evaluation of the stiffness damage test (SDT) as a tool for assessing damage in concrete due to ASR: Test loading and output responses for concretes incorporating fine or coarse reactive aggregates, Cement and Concrete Research. 56 (2014) 213–229.

[5] Bérubé, MA, Smaoui, N, Fournier, B, Bissonnette, B, Durand, B, Evaluation of the expansion attained to date by concrete affected by alkali–silica reaction. Part III: Application to existing structures, Canadian Journal of Civil Engineering. 32 (2005) 463–479.

[6] Villeneuve, V, Fournier, B, Duchesne, J, Determination of the damage in concrete affected by ASR - the damage rating index (DRI), in: Conf. Proc. of the 14th ICAAR, 2012.

[7] Rivard, P, Ballivy, G, Assessment of the expansion related to alkali-silica reaction by the Damage Rating Index method, Construction and Building Materials. 19 (2005) 83–90.

[8] Fournier, B, Bérubé, MA, Évaluation du potentiel de réactivité alcaline des granulats à béton produits dans les Basses-Terres du Saint-Laurent du Québec (Canada), Canadian Journal of Civil Engineering.18 (1991) 282–296.

[9] Neville, AM, Properties of Concrete, 5th ed., Pearson Education Limited, London, United Kingdom, 2011.

[10] ASTM C496, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, (2005).

[11] Clayton, N, Grimer, FJ, The Diphase Concept, with particular reference to concrete, in: Developments in Concrete Technol. - 1, Applied Science Publishers LTD, UK, 1979.

[12] Villeneuve, V, Détermination de l'endommagement du béton par méthode pétrographique quantitative, MSc Thesis, Université Laval, 2011.

[13] Sanchez, LFM, Fournier, B, Jolin, M, Duchesne, J, Reliable quantification of AAR damage through assessment of the Damage Rating Index (DRI), Cement and Concrete Research. 67 (2015) 74–92.

[14] Ellison, S, Barwick, V, Duguid Farrant, T, Practical Statistics for the Analytical Scientist: A bench guide, 2nd editio, The Royal Society of Chemistry, Cambridge, UK, 2009.

[15] Fournier, B, Tremblay, S, Frenette, J, Results of the Petrographic and Stiffness Damage Testing of Concrete Cores from the Princess Margaret Bridge, Fredericton, NB. Report submitted to Gemtec - Consulting Engineers and Scientists, 2009.

[16] Fournier, B, Bérubé, MA, Alkali-aggregate reaction in concrete: a review of basic concepts and engineering implications, Canandian Journal of Civil Engineering. 27 (2000) 167–191.

[17] Clayton, N, Currie, RJ, Moss, RM, The effects of alkali-silica reaction on the strength of prestressed concrete beams, The Structural Engineer. 68 (1990) 287–292.

8 TABLES AND FIGURES

TABLE 1: A) Petrographic features identified for the DRI and their corresponding weighing factors. B) Example of petrographic features (modified from Sanchez [13]).

A)

Petrographic features	Weighing Factors
Closed cracks in coarse aggregate (CrCA)	0.25
Opened cracks in coarse aggregate (OCrCA)	2
Cracks in coarse aggregate with reaction product (Cr+RPCA)	2
Coarse aggregate debonded (CAD)	3
Coarse aggregate corroded (CAC)	2
Cracks in cement paste (CrCP)	3
Cracks with reaction product in cement paste (Cr+RPCP)	3

B)

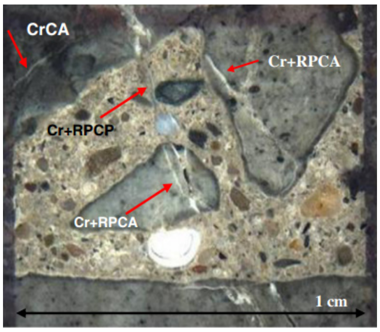

TABLE 2: Average test results and their coefficient of variations for each zones. The number in brackets represents the number of cores tested.

Assessment		NE	ME	E1	E2
SDI	Avg.	0.12 (3)	0.13 (2)	0.20 (6)	0.14 (3)
	CV (%)	9	22	8	54
PDI	Avg.	0.08 (3)	0.06 (2)	0.12 (6)	0.05 (3)
	CV (%)	33	0	18	24
f'_c (MPa)	Avg.	57.7 (3)	62.9 (2)	44.5 (6)	61.0 (6)
	CV (%)	4	5	7	6
E (GPa)	Avg.	33.6 (3)	35.8 (2)	24.5 (6)	33.8 (3)
	CV (%)	3	11	2	3

TABLE 3: Average tensile strengths for zone NE and E1.

Extraction zones	f'_{sp} (Splitting) (MPa)	*Gas pressure* (MPa)	f'_t (Direct) (MPa)
NE	4.3	3.1	2.8
E1	3.5	2.6	1.9
Loss (%) of tensile strength E1 vs NE	-17.6	-16.7	-32.0

TABLE 4: P-values between each set of extraction zones for the different parameters. The shaded zones represent the statistically different families of results.

Parameter	Zone	P-Values		
		NE	E1	E2
SDI	NE		0.002	0.680
	E1			0.110
	E2			
PDI	NE		0.054	0.122
	E1			0.001
	E2			
E	NE		3.3E-07	0.845
	E1			9.1E-08
	E2			
f'_c	NE		7.5E-05	0.106
	E1			2.2E-07
	E2			

TABLE 5: Assessment and classification of ASR damage degree proposed by Sanchez [2].

Classification of ASR damage degree (%)	Reference expansion level (%)[1]	Assessment of ASR				
		Stiffness loss (%)	Compressive strength loss (%)	Tensile strength loss (%)	SDI	DRI
Negligible	0.00 – 0.04	-	-	-	0.06 – 0.16	100 - 155
Marginal	0.05 ± 0.01	5 – 37	(-)10 – 15	15 – 60	0.11 – 0.25	211 - 404
Moderate	0.12 ± 0.01	20 – 50	0 – 20	40 – 65	0.15 – 0.31	330 - 500
High	0.20 ± 0.01	35 – 60	13 – 25	45 – 80	0.19 – 0.32	505 - 765
Very high	0.30 ± 0.01	40 – 67	20 – 35		0.22 – 0.36	606 – 925

TABLE 6: Reduction in mechanical properties, SDI, DRI and the corresponding ASR damage assessment for each zone, this study.

Assessment	Stiffness Reduction (%)	Compressive strength reduction (%)	Tensile strength reduction (%)	SDI	DRI	Supposed expansion level	ASR damage assessment
NE	0	0	0	0.12	283	0.00 - 0.04%	negligible to marginal
ME	-7	-9	-	0.13	328	0.00 - 0.04%	negligible to marginal
E1	27	23	32	0.20	716	0.04 - 0.20%	marginal to high
E2	-1	-6	-	0.14	539	0.00 - 0.20%	negligible to high

A) B)

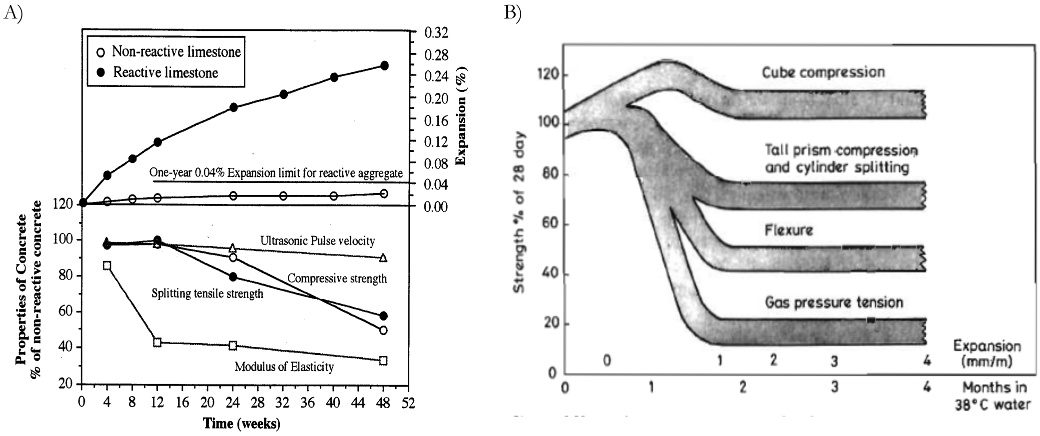

FIGURE 1: Consequences of ASR on the mechanical properties of concrete, expressed as % loss from a companion non-reactive concrete of same age (A from [16]), or from the 28-day strength (B from [17]).

FIGURE 2: Concrete sections investigated. A: Severe map cracking in extraction zone E1. B: Damaged section E2 presenting important signs of deterioration caused by ASR (map cracking and burst slab joint). C: Moderately damaged section (ME). D: Burst slab joint near section E2. E: Undamaged section (NE) presenting minimal ASR signs. F: General view of the pavement.

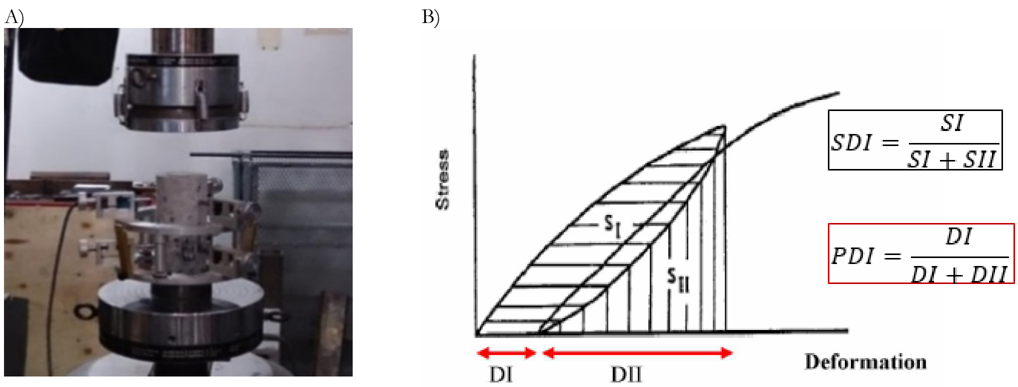

FIGURE 3: Stiffness Damage Test (SDT). A: Experimental set-up used at Université Laval for the test. B: New parameters introduced by Sanchez [2] for the test, i.e. Stiffness Damage Index (SDI) and Plastic Deformation Index (PDI).

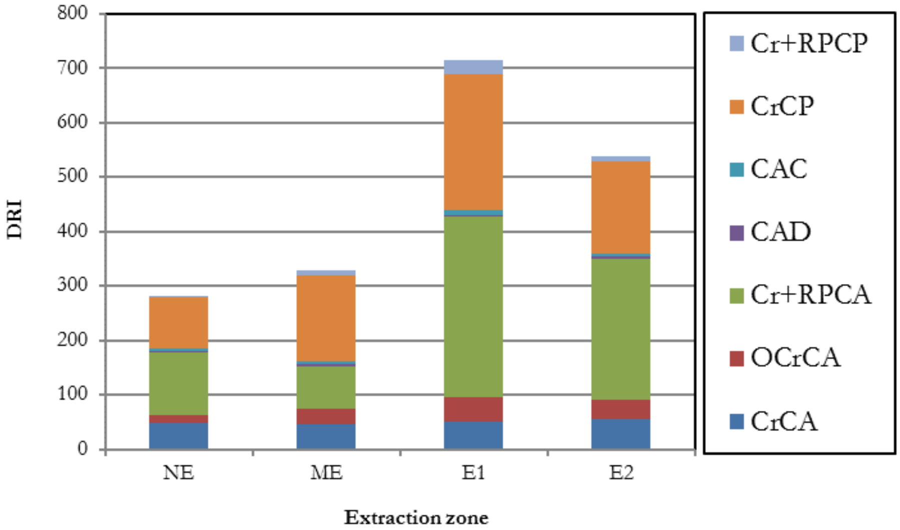

FIGURE 4: DRI for each extraction zone.

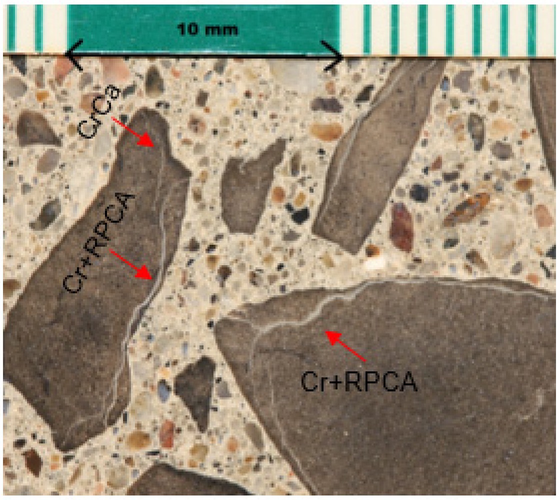

FIGURE 5: Typical petrographic features observable on a polished concrete core from zone E1. Closed cracks within the coarse aggregate as well as cracks in coarse aggregates filled with reaction products are visible.