

**EVALUATION OF THE POTENTIAL OF RESIDUAL EXPANSION OF CONCRETE AFFECTED BY  
ALKALI AGGREGATE REACTION**

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## Abstract

One of the biggest challenges nowadays when dealing with critical AAR-affected infrastructure is to determine the induced expansion and damage attained to date in the different locations of the structure (i.e. diagnosis), to forecast its potential for further distress over time (i.e. prognosis), as well as its potential structural implications. There are a number of prognosis techniques that have been developed in the past decades which are currently being used worldwide. Yet, most of these approaches use residual expansion procedures based on accelerated laboratory tests performed on cores extracted from damaged structures. However, the majority of the results gathered from these tests have been found to be inaccurate when compared to the swelling behavior of the respective structure in the field and several potential issues have been raised with respect to the test setup and alkali leaching. This work aims to evaluate the efficiency of the various commonly used laboratory setups to assess the residual expansion of AAR-affected concrete. Three different setups (i.e. 38°C and 100% RH; 38°C and soaked in 1M NaOH and; 38°C and wrapped in 0.7M NaOH) and two types of reactive aggregates (fine and coarse) were selected for this research. Expansion is monitored over time and four damage degrees (i.e. 0.05%, 0.12%, 0.20% and 0.30%) are selected for further chemical, microscopic (DRI) and non-destructive tests. Results demonstrated that the 1 M NaOH protocol is much more aggressive than the other two setups. Furthermore, it provides the samples with a unique damage pattern that is different from field affected concrete. Finally, the proposed setup shows to be reliable in providing tested samples with similar deterioration mechanisms than expected. Yet, more efficiency in the reaction kinetics and understanding of the alkalis exchange from the system is still required.

**Keywords:** alkali aggregate reaction, reactive aggregate, residual expansion, accelerated laboratory test

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## List of Symbols/Abbreviations

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$f_0$	linear resonance frequency
$f$	resonance frequency at increased excitation amplitude $\acute{\alpha}$
$\acute{\alpha}$	increased excitation amplitude
$E_0$	linear elastic modulus for small deformation
$\beta$	quadratic anharmonicity
$\delta$	cubic anharmonicity
$\epsilon$	strain
$\Delta\epsilon$	strain amplitude
$\acute{\epsilon}$	strain rate
$\alpha$	hysteresis nonlinearity property

# Chapter One: Introduction

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## 1.1. History of Alkali Aggregate Reaction

Travelling through time, concrete has been certified as the most popular and extensively used material in the construction industry due to its interesting mechanical properties and durability; yet there are numbers of damage mechanisms that can affect the long-term performance of concrete. Amongst those, alkali-aggregate reaction (AAR) is one of the most distressful mechanisms affecting the durability and serviceability of concrete infrastructure worldwide.

A revolution sparked in the concrete history in 1940 when an American engineer, Thomas E. Stanton (Stanton, 2008) discovered severe surface cracking on numerous concrete structures for the first time. The investigation started right away after a number of structures were diagnosed with the so-called AAR, a chemical reaction between some mineral phases from the aggregates and the alkalis from the concrete pore solution (Thomas E. Stanton, O. J. Porter, L. C. Meder, 1942). Over the next few decades, thousands of scholars carried out researches and experiments to identify the chemical reaction and the reasons behind it (Maarten A.T.M. Broekmans, 2002). It has been found that the key factors of AAR-induced expansion and damage were the presence of reactive aggregates; high alkali content in the cement along with some external factors such as moisture, temperature, and stress-state conditions (E G Swenson, 1957). Moreover, two forms of AAR were recognized: alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR).

### 1.1.1. Alkali-Silica Reaction (ASR)

Stanton's recognition of AAR opened the door to a new era in the world of concrete durability. Further investigations were conducted by researchers in North America as well as other countries across the world; shockingly this phenomenon was diagnosed in many

important concrete structures and Canada is not an exception to this. Experiments were performed to determine the factors associated with the cracking mechanism, potential for reactivity in the field along with the factors influencing the reaction (Benoit Fournier & Bérubé, 2000; Godart, Bruno; Wood, Jonathan G. M.; de Rooij, 2013; Meissner, 1941).

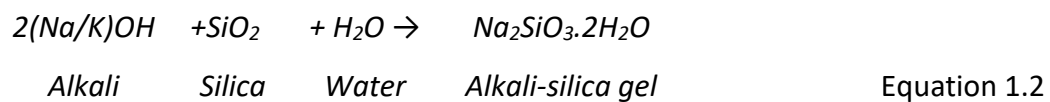
Many authors recognized that prospective mineral phases of reactive fine or coarse aggregates are often poorly crystalline or present metastable silica minerals, sometimes volcanic or artificial glasses and quartz (Benoit Fournier & Bérubé, 2000; Maarten A.T.M. Broekmans, 2002; Meissner, 1941; Edwin George Swenson & Gillott, 1960). These mineral phases may react in alkaline environments and generate a product (i.e. alkali-silica gel), which can lead to further expansion and major crack formation (Stark et al., 1993). Different studies have shown that the average ASR kinetics to develop considerable damage (i.e. expansion, extensive cracking formation, mechanical properties loss, etc.) in the field, can be 10 to 25 years depending on the environmental conditions. ASR is by far the most common type of AAR found worldwide (Bruno Godart, Mario de Rooij, 2013; Fournier & Bérubé, 2000; Stark et al., 1993).

ASR development starts with the break of the siloxane groups ( $\equiv\text{Si-O-Si}\equiv$ ) at the surface of some silica phases ( $\text{SiO}_2$ ), releasing water. At the same time, silanol groups ( $\equiv\text{Si-OH}$ ) may become re-equilibrated, associating themselves with hydroxyl ions [9, 10] and releasing water, as follows (Equation 1.1):



To maintain the electroneutrality, the  $\text{Na}^+$  and  $\text{K}^+$  ions diffuse into the ionized aggregate being adsorbed, and since they tend to attract water, their presence increases the tendency to form a hydrated gel (M. D. A. Thomas et al., 2013; Nixon, P. J; Bollinghaus, 1985). Subsequently, alkali cations (i.e. Na or K) present within the environment are attracted by the  $\text{Si-O}^-$  anions and generate the so-called alkali-silica gel Ca-Na(K)-S-H (M. D. A. Thomas et al., 2013). Moreover, it is widely accepted that  $\text{Ca(OH)}_2$  has an important role

in ASR forming the deleterious calcium-rich ASR gel rim around aggregate particles and changing the properties of the ASR-gel (R.B. Figueira, R. Sousa, L. Coelho, M. Azenha, J.M. de Almeida, P.A.S. Jorge, 2019). Furthermore, within the reactive aggregate particles (poor calcium concentration) the ASR product behaves as a crystalline phase with uniform composition (W. Chen et al., 2017). On the other hand, the amorphous gel found within the bulk cement paste (calcium rich environment) is quite porous and more viscous; which has higher water absorption properties and higher swelling capacity (Blight & Alexander, 2011; Mindess & Francis, 2003). The associated reaction is as follows (Equation 1.2):

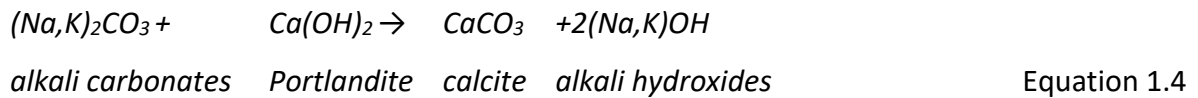
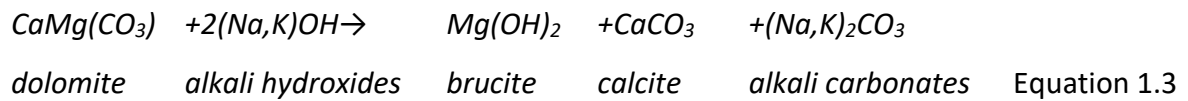


### 1.1.2. Alkali-Carbonate Reaction (ACR)

Alkali Carbonate Reaction (ACR) was first recognized in Canada in late 50's by Swenson at the National Research Council (NRC); this mechanism was found to be much faster and deleterious (although less frequent) than ASR, showing important damage signs in affected structures within 5 years of service. A number of ACR-affected structures were found in North America, especially in southern Ontario (e.g. Kingston and Cornwall), including some areas in the United States (Bérubé et al., 2005).

ACR is only triggered in the presence of carbonate rocks (i.e. argillaceous dolomitic limestones or calcitic dolostones). Its reaction mechanism is still unknown. Yet, a number of studies have verified that the dedolomitization process of the dolomite crystals inside carbonated rocks might be amongst the reasons of the chemical reaction and distress. Different hypotheses were developed by numerous authors to explain ACR. This reaction incorporates migration of surrounding moisture and alkali content through hydraulic pressure into dolomite crystals or active clay minerals may adsorb the surface moisture and alkali content rearranging brucite and calcite. Finally, alkali carbonate reacts with concrete portlandite and alkali hydroxide is reproduced (Fernandes & Broekmans, 2013;

Benoit Fournier & Bérubé, 2000; Edwin George Swenson & Gillott, 1960). The corresponding chemical reaction is expressed as follows (Equation 1.3 and 1.4):



## 1.2. Research Objective

Over the years, several approaches and recommendations, including a variety of laboratory test procedures, have been developed around the world to assess the potential alkali-reactivity of concrete aggregates and the effectiveness of preventive measures (e.g. control of the cement & concrete alkali content, use of supplementary cementing materials, etc.) before their use in the field (A23.2-28A, 2014; CSA A23.1, 2014; CSA A23.2-14A, 2014; Benoit Fournier & Bérubé, 2000). Despite a few issues with some of these test procedures (e.g. long-term duration, alkali leaching, long-term correlation with field structures, evaluation of specific concrete mixtures, etc.) and the constant need of improvement in the different standards/protocols, most of the experts agree that, in general, it is now possible to build new concrete infrastructure with minimum or even calculated/limited risk of AAR (A23.2-28A, 2014; ASSHTO, 2011; ASTM, 2008). However, there is currently no consensus about the most efficient method(s) (e.g. surface treatments for moisture control, chemical treatments, strengthening, stress relief, etc.) that should be implemented, and when, for the rehabilitation of AAR-affected concrete structures/structural members (Benoit Fournier, Marc-André Bérubé, Kevin J. Folliard, 2010; Blight & Alexander, 2011; CSA A23.1, 2014; Benoit Fournier & Bérubé, 2000; Merz & Leemann, 2013; Michael D.A. Thomas et al., 2013). In this context, a number of engineers and researchers around the globe have been trying to develop appraisal techniques and tools that are capable of either halting/mitigating further AAR development in service (Bérubé et al., 2005; M. D. A. Thomas et al., 2013) or at least appraising the current

damage degree (diagnosis) and the potential of future distress (prognosis) of affected aging structures (ASSHTO, 2011; Bérubé et al., 2005; M. D. A. Thomas et al., 2013; Nixon & Sims, 2015; Sanchez et al., 2014; Sanchez, Fournier, Jolin, & Duchesne, 2015; Sanchez, Fournier, Jolin, Bastien, et al., 2016; Wigum et al., 2016) both essential steps in selecting efficient rehabilitation methods and optimum application periods for critical aging infrastructure affected by AAR.

This work deals with the assessment of the current and most common techniques (i.e. residual expansion – RE - tests) used to forecast the potential of further AAR deterioration, so that laboratory outcomes might be better interpreted and applied in the assessment of affected structures in the field. Two test procedures, usually recommended in Canada, were selected for this research for analysis: (1) test in air at > 95% R.H. and 38°C (100°F) and; (2) test in 1M NaOH solution at 38°C (100°F). The first procedure is considered the most reliable method for evaluating the “residual expansion” and the potential for further deterioration of AAR-affected concrete whereas the second technique is recommended for determining the “ultimate expansion” of concrete affected by AAR (ASTM International, 2009; Bérubé et al., 2002; Noël et al., 2018). Moreover, a novel setup is proposed in this research (0.7M NaOH), aiming to improve the reliability and efficiency of residual expansion tests in the laboratory.

### **1.3. Thesis Organization**

This thesis is divided into five chapters. Chapter 1 highlights the concerns related to alkali aggregate reaction (AAR) in concrete. It consists of the following items: introduction, research objectives, and thesis organization.

Chapter 2 presents a detailed literature review on AAR. This section discusses on the following topics: diagnosing and quantifying ASR-induced expansion and damage in concrete through NIRAS test, damage rating index (DRI), stiffness damage test (SDT) and prognosis of the affected concrete using residual expansion methods.

Chapter 3 consists of a journal paper. It evaluates the potential of residual expansion in concrete affected by AAR.

Chapter 4 brings forward the conclusion obtained throughout this project and proposes suggestions for future research in the area.

#### 1.4. References

A23.2-28A, C. (2014). *Standard practice for laboratory testing to demonstrate the effectiveness of supplementary cementing materials and lithium-based admixtures to prevent alkali-silica reaction in concrete.*

AASHTO. (2011). AASHTO Guide Manual for Bridge Element Inspection - 1st Edition - 2011.pdf. In *Bridge Element Inspection Manual.*

ASTM, C. (2008). *1293 Standard test method for determination of length change of concrete due to alkali-silica reaction.* ASTM International.

ASTM Committee C09.65. (2012). ASTM C295-12 Standard Guide for Petrographic Examination of Aggregates for Concrete. In *Annual Book of ASTM Standards Volume 04.02.* [https://doi.org/10.1520/C0295\\_C0295M-12](https://doi.org/10.1520/C0295_C0295M-12)

ASTM International. (2009). ASTM C1293-01: Standard Test Method for Length Change of Concrete Due to Alkali-Carbonate Rock. *Annual Book of ASTM Standards.* <https://doi.org/10.1520/C1105-08A.2>

Benoit Fournier, Marc-André Bérubé, Kevin J. Folliard, M. T. (2010). Report on ASR Mitigation. *Federal Highway Administration Publications FHWA-HRT-04-113 (2004) and Techbrief FHWA-HRT-06-071.*

Bérubé, M. A., Duchesne, J., Dorion, J. F., & Rivest, M. (2002). Laboratory assessment of alkali contribution by aggregates to concrete and application to concrete structures affected by alkali-silica reactivity. *Cement and Concrete Research.* [https://doi.org/10.1016/S0008-8846\(02\)00766-4](https://doi.org/10.1016/S0008-8846(02)00766-4)

Bérubé, M. A., Smaoui, N., Fournier, B., Bissonnette, B., & Durand, B. (2005). 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(3), 463–479. <https://doi.org/10.1139/L04-104>
- Blight, G. E., & Alexander, M. G. (2011). Alkali-Aggregate Reaction and Structural Damage to Concrete. In *Alkali-Aggregate Reaction and Structural Damage to Concrete*. <https://doi.org/10.1201/b10773>
- Bruno Godart, Mario de Rooij, J. G. M. W. (2013). *Guide to Diagnosis and Appraisal of AAR Damage to Concrete in Structures: Part 1 Diagnosis* (J. G. M. W. Bruno, Mario de Rooij (ed.)). Springer Netherlands.
- Buck, O., Morris, W. L., & Richardson, J. M. (1978). Acoustic harmonic generation at unbonded interfaces and fatigue cracks. *Applied Physics Letters*. <https://doi.org/10.1063/1.90399>
- Carles-Gibergues, A., & Cyr, M. (2002). Interpretation of expansion curves of concrete subjected to accelerated alkali-aggregate reaction (AAR) tests. *Cement and Concrete Research*. [https://doi.org/10.1016/S0008-8846\(01\)00747-5](https://doi.org/10.1016/S0008-8846(01)00747-5)
- Chen, J., Jayapalan, A. R., Kim, J. Y., Kurtis, K. E., & Jacobs, L. J. (2010). Rapid evaluation of alkali-silica reactivity of aggregates using a nonlinear resonance spectroscopy technique. *Cement and Concrete Research*. <https://doi.org/10.1016/j.cemconres.2010.01.003>
- Chen, W., Hao, H., Jong, M., Cui, J., Shi, Y., & Chen, L. (2017). Quasi-static and dynamic tensile properties of basalt fibre reinforced polymer Quasi-static and dynamic tensile properties of basalt fibre reinforced polymer. *Composites Part B*, 125(May), 123–133. <https://doi.org/10.1016/j.compositesb.2017.05.069>
- Chen, X. J., Kim, J. Y., Kurtis, K. E., Qu, J., Shen, C. W., & Jacobs, L. J. (2008). Characterization of progressive microcracking in Portland cement mortar using nonlinear ultrasonics. *NDT and E International*. <https://doi.org/10.1016/j.ndteint.2007.08.009>
- Crawford, B., Kasmidi, M., Korompis, F., & Pollnac, R. B. (2006). Factors influencing progress in establishing community-based marine protected areas in Indonesia. *Coastal Management*. <https://doi.org/10.1080/08920750500379300>

- CSA A23.1. (2014). Concrete Materials and Methods of Concrete Construction. In *Canadian Standards Association: Vol. APPENDIX B*.
- CSA A23.2-14A. (2014). *Potential expansivity of aggregates (Procedure for Length Change due to Alkali-Aggregate Reaction in Concrete Prisms at 38°C)*. Canadian Standards Association.
- Den Abeele, K. E. A. V., Carmeliet, J., Ten Cate, J. A., & Johnson, P. A. (2000). Nonlinear elastic wave spectroscopy (NEWS) techniques to discern material damage, Part II: Single-mode nonlinear resonance acoustic spectroscopy. *Research in Nondestructive Evaluation*, 12(1), 31–42. <https://doi.org/10.1080/09349840009409647>
- Den Abeele, K. E. A. V., Johnson, P. A., & Sutin, A. (2000). Nonlinear elastic wave spectroscopy (NEWS) techniques to discern material damage, Part I: Nonlinear wave modulation spectroscopy (NWMS). *Research in Nondestructive Evaluation*. <https://doi.org/10.1080/09349840009409646>
- ElMohandes, F., & Vecchio, F. J. (2013). *VecTor3: A. User's Manual; B. Sample Coupled Thermal and Structural Analysis*. November, 43–119. <https://doi.org/10.1016/B978-0-12-398460-9.00002-0>
- Farny, J. A., & Kerkhoff, B. (2007). Diagnosis and Control of Alkali-Aggregate Reactions in Concrete. *Portland Cement Association*, 1–24. [http://www.cement.org/docs/default-source/fc\\_concrete\\_technology/is413-02---diagnosis-and-control-of-alkali-aggregate-reactions-in-concrete.pdf?sfvrsn=2](http://www.cement.org/docs/default-source/fc_concrete_technology/is413-02---diagnosis-and-control-of-alkali-aggregate-reactions-in-concrete.pdf?sfvrsn=2)
- Fernandes, I., & Broekmans, M. A. T. M. (2013). Alkali-Silica Reactions: An Overview. Part I. *Metallography, Microstructure, and Analysis*, 2(4), 257–267. <https://doi.org/10.1007/s13632-013-0085-5>
- Forster, S. W., Boone, R. L., Hammer, M. S., Lamond, J. F., Lane, D. S., Miller, R. E., Parker, S. E., Pergalsky, A., Pierce, J. S., Robert, M. Q., Schmitt, J. W., & Tobin, R. E. (1998). *State-of-the-Art Report on Alkali-Aggregate Reactivity Reported by ACI Committee 221. 98(Reapproved)*, 1–31.
- Fournier, Benoit, & Bérubé, M.-A. (2000). Alkali–Aggregate Reaction in Concrete: a Review of Basic Concepts and Engineering Implications. *Canadian Journal of Civil Engineering*,

27, 167–191. <https://doi.org/10.1139/l99-072>

- Fournier, Benoît, Bérubé, M., Thomas, M. D. A., Smaoui, N., & Folliard, K. J. (2004). Evaluation and Management of Concrete Structures Affected by Alkali-Silica Reaction – A Review. *Seventh CANMET/ACI International Conference on Recent Advances in Concrete Technology*, 5(Mai), 1–60.
- Gao, X. X., Multon, S., Cyr, M., & Sellier, A. (2011a). Optimising an expansion test for the assessment of alkali-silica reaction in concrete structures. *Materials and Structures/Materiaux et Constructions*, 44(9), 1641–1653. <https://doi.org/10.1617/s11527-011-9724-y>
- Gao, X. X., Multon, S., Cyr, M., & Sellier, A. (2011b). Optimising an expansion test for the assessment of alkali-silica reaction in concrete structures. *Materials and Structures/Materiaux et Constructions*. <https://doi.org/10.1617/s11527-011-9724-y>
- Godart, Bruno; Wood, Jonathan G. M.; de Rooij, M. (2013). *Guide to Diagnosis and Appraisal of AAR Damage to Concrete in Structures* (M. Godart, Bruno; Wood, Jonathan G. M.; de Rooij (ed.)). Springer Netherlands.
- Grattan-Bellew, P.; Danay, A. (1992). Comparison of laboratory and field evaluation of alkali-silica reaction in large dams. *International Conference on Concrete AAR in Hydroelectric Plants and Dams*.
- Kraig Warnemuende, Hwai-Chung Wu. (2004). Actively modulated acoustic nondestructive evaluation of concrete. *Cement and Concrete Research, Volume 34*(Issue 4), Pages 563-570.
- Leśnicki, K. J., Kim, J. Y., Kurtis, K. E., & Jacobs, L. J. (2011). Characterization of ASR damage in concrete using nonlinear impact resonance acoustic spectroscopy technique. *NDT and E International*, 44(8), 721–727. <https://doi.org/10.1016/j.ndteint.2011.07.010>
- M. D. A. Thomas, B. Fournier, & K. J. Folliard. (2013). Alkali-Aggregate Reactivity (AAR) Facts Book. *Book*, 224.
- Maarten A.T.M. Broekmans. (2002). *the Alkali-Silica Reaction : Aspects of Some Dutch Concretes*. 217.
- Meissner, H. S. (1941). Cracking in Concrete Due to Expansive Reaction Between

Aggregate and High-Alkali Cement as Evidenced in Parker Dam. *ACI Journal Proceedings*, 37.

- Merz, C., & Leemann, A. (2013). Assessment of the residual expansion potential of concrete from structures damaged by AAR. *Cement and Concrete Research*, 52(November 2017), 182–189. <https://doi.org/10.1016/j.cemconres.2013.07.001>
- Mindess, A., & Francis, J. (2003). *Concrete* (2nd ed.). Prentice Hall, Pearson Education, Inc. Upper Saddle River, NJ 07458, U.S.A.
- Multon, S. (2004). Evaluation expérimentale et théorique des effets mécaniques de l'alcali-réaction sur des structures modèles. In *Etudes et recherches des Laboratoires des ponts et chaussées. Série Ouvrages d'art*.
- Multon, S., Sellier, A., & Cyr, M. (2009). Chemo-mechanical modeling for prediction of alkali silica reaction (ASR) expansion. *Cement and Concrete Research*, 39(6), 490–500. <https://doi.org/10.1016/j.cemconres.2009.03.007>
- Nixon, P. J.; Bollinghaus, R. (1985). The effect of alkali aggregate reaction on the tensile and compressive strength of concrete. *Durability of Building Materials. 1985, Vol 2, Num 3, Pp 243-248 ; Ref : 5 Ref, Vol 2(Num 3), pp 243-248 ; ref : 5 ref.*
- Nixon, P. J., & Sims, I. (2015). RILEM recommendations for the prevention of damage by alkali-aggregate reactions in new concrete structures: State-of-the-Art report of the RILEM technical committee 219-ACS. In *RILEM Recommendations for the Prevention of Damage by Alkali-Aggregate Reactions in New Concrete Structures: State-of-the-Art Report of the RILEM Technical Committee 219-ACS*. <https://doi.org/10.1007/978-94-017-7252-5>
- Noël, M., Sanchez, L., & Tawil, D. (2018). Structural implications of internal swelling reactions in concrete: Review and research needs. *Magazine of Concrete Research*, 70(20), 1052–1063. <https://doi.org/10.1680/jmacr.17.00383>
- Paul, S. C., Pirskawetz, S., Van Zijl, G. P. A. G., & Schmidt, W. (2015). Acoustic emission for characterising the crack propagation in strain-hardening cement-based composites (SHCC). *Cement and Concrete Research*, 69, 19–24. <https://doi.org/10.1016/j.cemconres.2014.12.003>

- R.B. Figueira, R. Sousa, L. Coelho, M. Azenha, J.M. de Almeida, P.A.S. Jorge, C. J. R. S. (2019). Alkali-silica reaction in concrete: Mechanisms, mitigation and test methods. *Construction and Building Materials*, Volume 222, Pages 903-931. <https://doi.org/https://doi.org/10.1016/j.conbuildmat.2019.07.230>.
- Sanchez, L. F. M., Fournier, B., Jolin, M., & Bastien, J. (2014). 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*. <https://doi.org/10.1016/j.cemconres.2013.11.003>
- Sanchez, L. F. M., Fournier, B., Jolin, M., & Bastien, J. (2015). Evaluation of the Stiffness Damage Test (SDT) as a tool for assessing damage in concrete due to alkali-silica reaction (ASR): Input parameters and variability of the test responses. *Construction and Building Materials*. <https://doi.org/10.1016/j.conbuildmat.2014.11.071>
- Sanchez, L. F. M., Fournier, B., Jolin, M., Bastien, J., & Mitchell, D. (2016). Practical use of the Stiffness Damage Test (SDT) for assessing damage in concrete infrastructure affected by alkali-silica reaction. *Construction and Building Materials*. <https://doi.org/10.1016/j.conbuildmat.2016.08.101>
- Sanchez, L. F. M., Fournier, B., Jolin, M., Bedoya, M. A. B., Bastien, J., & Duchesne, J. (2016a). Use of Damage Rating Index to quantify alkali-silica reaction damage in concrete: Fine versus coarse aggregate. *ACI Materials Journal*, 113(4), 395–407. <https://doi.org/10.14359/51688983>
- Sanchez, L. F. M., Fournier, B., Jolin, M., Bedoya, M. A. B., Bastien, J., & Duchesne, J. (2016b). Use of Damage Rating Index to quantify alkali-silica reaction damage in concrete: Fine versus coarse aggregate. *ACI Materials Journal*. <https://doi.org/10.14359/51688983>
- Sanchez, L. F. M., Fournier, B., Jolin, M., & Duchesne, J. (2015). Reliable quantification of AAR damage through assessment of the Damage Rating Index (DRI). *Cement and Concrete Research*, 67, 74–92. <https://doi.org/10.1016/j.cemconres.2014.08.002>
- Sanchez, L. F. M., Fournier, B., Jolin, M., Mitchell, D., & Bastien, J. (2017a). Overall assessment of Alkali-Aggregate Reaction (AAR) in concretes presenting different

- strengths and incorporating a wide range of reactive aggregate types and natures. *Cement and Concrete Research*, 93, 17–31.  
<https://doi.org/10.1016/j.cemconres.2016.12.001>
- Sanchez, L. F. M., Fournier, B., Jolin, M., Mitchell, D., & Bastien, J. (2017b). Overall assessment of Alkali-Aggregate Reaction (AAR) in concretes presenting different strengths and incorporating a wide range of reactive aggregate types and natures. *Cement and Concrete Research*, 93, 17–31.  
<https://doi.org/http://dx.doi.org/10.1016/j.cemconres.2016.12.001>
- Stanton, T. E. (2008). Expansion of concrete through reaction between cement and aggregate (this article originally appeared in Proceedings of the ASCE, December 1940, v. 66(10), pp. 1781-1811). In *Selected Landmark Paper Collection on Concrete Materials Research*.
- Stark, D., Diamond, S., & Moranville-regourd, M. (n.d.). *Alkali-Silica Reactivity : An Overview of Research*.
- Swenson, E G. (1957). A Reactive aggregate undetected by ASTM tests. *ASTM Bulletin*.
- Swenson, Edwin George, & Gillott, J. E. (1960). Characteristics of Kingston carbonate rock reaction. *Highway Research Board Bulletin*, 275, 18–31.
- Thomas E. Stanton, O. J. Porter, L. C. Meder, and A. N. (1942). California Experience With the Expansion of Concrete Through Reaction Between Cement and Aggregate. *ACI Journal Proceedings*, 38.
- Thomas, M. D.A., & Innis, F. A. (1999). Use of the accelerated mortar bar test for evaluating the efficacy of mineral admixtures for controlling expansion due to alkali-silica reaction. *Cement, Concrete and Aggregates*, 21(2), 157–164.  
<https://doi.org/10.1520/cca10429j>
- Thomas, M., Fournier, B., Folliard, K., Ideker, J., & Shehata, M. (2006). Test methods for evaluating preventive measures for controlling expansion due to alkali-silica reaction in concrete. *Cement and Concrete Research*.  
<https://doi.org/10.1016/j.cemconres.2006.01.014>
- Thomas, Michael D.A., Folliard, K. J., Fournier, B., Rivard, P., Drimalas, T., & Garber, S. I.

- (2013). Methods for Evaluating and Treating ASR-Affected Structures: Results of Field Application and Demonstration Projects. Volume II: Details of Field Applications and Analysis Final Report. *Federal Highway Administration, FHWA-HIF-1*, 338.
- Van Den Abeele, K. E. A., Sutin, A., Carmeliet, J., & Johnson, P. A. (2001). Micro-damage diagnostics using nonlinear elastic wave spectroscopy (NEWS). *NDT and E International*. [https://doi.org/10.1016/S0963-8695\(00\)00064-5](https://doi.org/10.1016/S0963-8695(00)00064-5)
- Villeneuve, V., Fournier, B., & Duchesne, J. (2012). Determination of the damage in concrete affected by ASR- the damage rating index (DRI). *Proceedings of the 14th International Conference on Alkali-Aggregate Reaction in Concrete*.
- Walsh, J. B. (1965). The effect of cracks on the uniaxial elastic compression of rocks. *Journal of Geophysical Research*. <https://doi.org/10.1029/jz070i002p00399>
- Wigum, B. J., Lindgård, J., Sims, I., & Nixon, P. (2016). Rilem activities on alkali-silica reactions: From 1988-2019. *Proceedings of Institution of Civil Engineers: Construction Materials*. <https://doi.org/10.1680/jcoma.15.00070>

## Chapter Two: Background and Literature Review

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### 2.1. Introduction

Alkali aggregate reaction is recognized as one of the most harmful distress mechanisms affecting concrete infrastructure worldwide (Stanton, 2008). Over the years, several approaches and recommendations, including a variety of laboratory tests methods have been developed to assess the potential AAR reactivity of concrete mixtures and the efficiency of preventive measures (e.g. selection of cement type, alkalis loading, use of supplementary cementitious materials, etc.) before their use in the field. Despite some issues with some of these test procedures, the majority of experts agree that, in general, it is now possible to design concrete infrastructure with minimum or calculated AAR risk. However, one of the biggest challenges is the lack of consensus on the most efficient approach to assess an affected structure in terms of diagnosis and prognosis (Farny & Kerkhoff, 2007; Forster et al., 1998; Merz & Leemann, 2013).

It is worth noting that two concepts must be defined in the context of this research, as follows: 1) “diagnosis” in this work means the “cause” and “extent” of damage caused by AAR mechanisms and 2) “damage” is defined as the harmful consequences (measurable ones) of AAR mechanisms on the mechanical properties, physical integrity, and durability of affected concrete. Hence, in practical terms, “damage” is considered here as being part of: 1) stiffness reduction of AAR-affected concrete; 2) mechanical properties reductions of AAR distressed materials and; 3) physical integrity/durability losses (inner cracking extent) of AAR-affected concrete (Sanchez et al., 2017a).

### 2.2. Alkali Aggregate Reaction

The deleterious Alkali Aggregate Reaction (AAR) is a slow chemical process inside concrete commonly takes place in between reactive aggregate containing reactive silica and

existing alkali content of cement in presence of moisture. Reaction products, as a form of AAR gels are produced inducing pressure on concrete. As a result, considerable cracks and deformations are generally noticed after 20-25 years. Yet, the mechanism can be faster in warmer ambience. Therefore, three parameters are considered to be the key factors to induce AAR in a concrete structure (Figure 2.1) (Forster et al., 1998; Benoit Fournier & Bérubé, 2000):

- Presence of reactive aggregate
- High alkali content in pore solution
- Sufficient moisture content

Besides, exposure conditions play a vital role on this mechanism; exterior structural elements manifest more cracks and damage compared to interior elements. Hence, structures subjected to cyclic environment like wetting and drying cycle or seawater, freezing and thawing cycle experience more damage due to AAR. In addition, temperature, water-cement ratio, reinforcement, air-entrainment etc., have a significant impact on AAR-induced development (Farny & Kerkhoff, 2007).

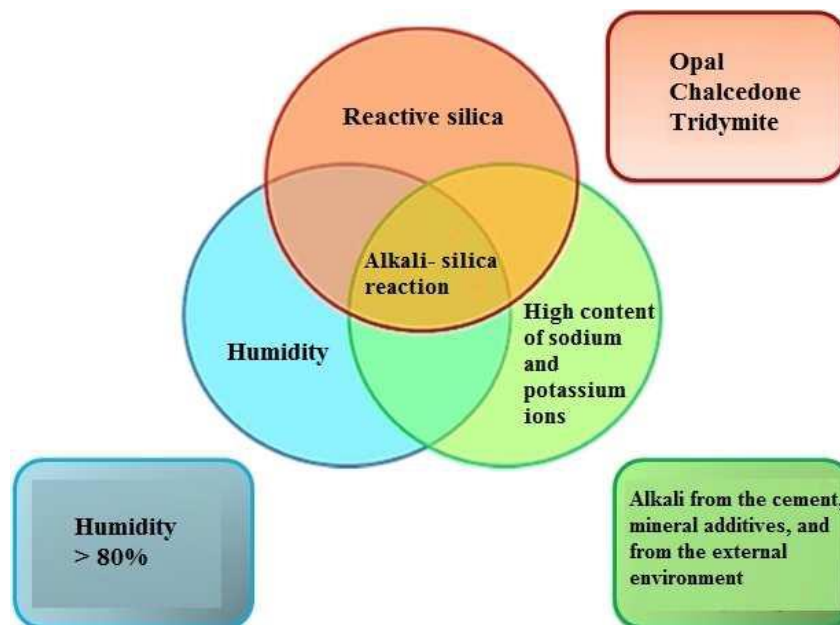


Figure 2.1.: Parameters to induce AAR (Farny & Kerkhoff, 2007)

### **2.3. Diagnosing and quantifying AAR-induced expansion and damage in concrete**

One of the biggest challenges in dealing with AAR damaged aging concrete structures is to establish the correlation between ASR distress "signatures" and the loss/reductions in mechanical properties, physical integrity, durability and performance of the affected material. In order to determine the condition of a structure, the non-destructive methods are needed to carry out a systematic evaluation of the concrete condition (Farny & Kerkhoff, 2007). The measurements can provide critical information on the structure condition. Nevertheless, this information is rather qualitative, and it strongly depends on the experience and skills of the inspectors (Noël et al., 2018).

The preliminary examination gives an idea of unusual features and provides a description of the characteristics of the sample; however, a deeper inspection might be required. The careful and combined use of both the unaided eye and the stereomicroscope is vital, as the former one will often fail to see micro cracks and details until they are observed through the stereomicroscope (ASTM Committee C09.65, 2012; Sanchez, Fournier, Jolin, Bedoya, et al., 2016a). Therefore, the petrographic examination is used to evaluate the overall composition, condition, distress mechanisms, potential future performance and quality of hardened concrete and other cementitious construction materials. A significant number of standard procedures have been developed in recent years for the petrographic evaluation of aggregates (Sanchez et al., 2017a; Sanchez, Fournier, Jolin, & Duchesne, 2015; Sanchez, Fournier, Jolin, Bedoya, et al., 2016a). Moreover, recent studies dealing with the evaluation of the mechanical performance of aging concrete suggest that both the Stiffness Damage Test (SDT) and the Damage Rating Index (DRI) can provide a diagnostic evaluation of the "damage degree" of concrete affected by ASR (Sanchez et al., 2014; Sanchez, Fournier, Jolin, & Bastien, 2015; Sanchez, Fournier, Jolin, Bastien, et al., 2016).

### **2.3.1. Nonlinear Impact Resonance Acoustic Spectroscopy (NIRAS) technique**

Nowadays, nonlinear ultrasonic and acoustics-based testing methods are commonly used non-destructive techniques for concrete specimens affected by AAR. These methods are found responsive to identify micro cracks and damage compared to traditional linear acoustic methods (K. E. A. V. Den Abeele, Johnson, et al., 2000; Leśnicki et al., 2011). Numerous nonlinear resonance techniques such as the nonlinear resonance ultrasound spectroscopy (NRUS) was applied on specimens to understand the thermal damage of concrete; the nonlinear reverberation spectroscopy (NRS) method was applied to assess damage in reinforced concrete; whereas the nonlinear wave modulation spectroscopy (NWMS) procedure identified the initial AAR damage (K. E. A. V. Den Abeele, Johnson, et al., 2000; Leśnicki et al., 2011; K. E. A. Van Den Abeele et al., 2001).

Chen et al. (X. J. Chen et al., 2008) proposed a new technique based on impulse excitation of concrete samples measuring their free vibration responses and named it nonlinear impact resonance acoustic spectroscopy (NIRAS) improving both NRUS and NRS methods and applied on mortar bars to evaluate AAR damage. Samples are excited with a low amplitude impact and vibration signals are captured using an oscilloscope through an accelerometer (Figure 2.2) and finally signals are analyzed using the Fast Fourier Transform (FFT) (J. Chen et al., 2010). The authors explained that concrete is heterogeneous and nonlinear by nature, hence while affected by AAR; NIRAS can recognize the microcracks through the assessment of resonance frequencies. Several authors comply with this idea mentioning the cracks as “imperfect bond system” and demonstrating that this system decreases the mechanical stiffness of the structure together with the resonance frequencies escalating the nonlinear effects (J. Chen et al., 2010; X. J. Chen et al., 2008; ElMohandes & Vecchio, 2013; Leśnicki et al., 2011; Paul et al., 2015). Warnemuende and Wu (Kraig Warnemuende, Hwai-Chung Wu, 2004) applied a nonlinear modulation method to differentiate between various degrees of damage in mortar cylinders subjected to different loading conditions. Chen et al. (X. J. Chen et al., 2008) provided preliminary measurements of ASR damage with a nonlinear modulation

technique. These results suggest the potential of nonlinear acoustic techniques for damage characterization in cementitious materials.

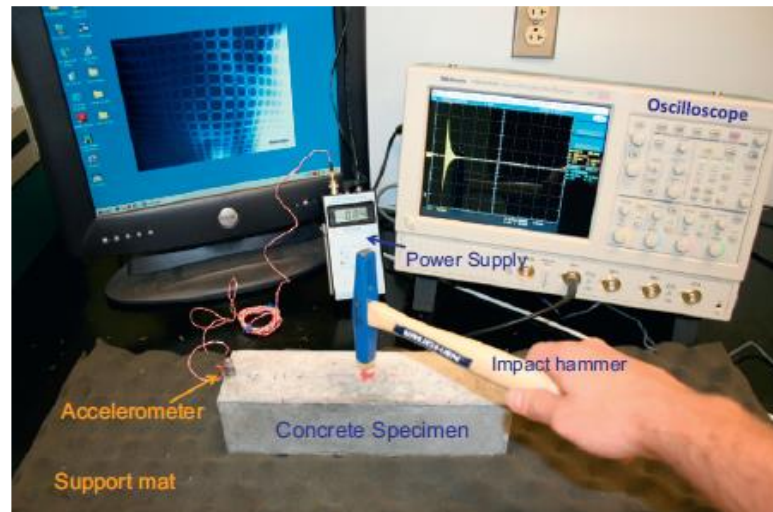


Figure 2.2.: Experimental setup of NIRAS test (X. J. Chen et al., 2008)

Krzysztof et al. performed NIRAS test on AAR affected concrete prisms fabricated with three different types of reactive aggregates subjected to ASTM C1293 method. Each prism was vibrated using a low amplitude hammer and the results were compared. The outcome validates the qualitative assessment of the NIRAS test to distinguish reactive and non-reactive aggregates and AAR damage in terms of nonlinearity parameter (Leśnicki et al., 2011).

### 2.3.2. Damage Rating Index (DRI)

The Damage Rating Index(DRI), which is a microscopic analysis developed by Grattan-Bellow and Danay (Grattan-Bellew, P.; Danay, 1992) is based on the determination by petrographic examination of the internal damage in concrete. The DRI is performed on polished sections of concrete with the use of a stereomicroscope (with magnification approximately 15 to 16X) where damage features are counted through a 1 cm<sup>2</sup> grid drawn on the surface of a polished concrete section, ideally, a surface of at least 200 cm<sup>2</sup>, as

presented in Figure 2.3. However, for comparative purposes, the final DRI value is normalized to a 100 cm<sup>2</sup> area (ASTM Committee C09.65, 2012; Sanchez et al., 2017b; Sanchez, Fournier, Jolin, & Duchesne, 2015; Sanchez, Fournier, Jolin, Bedoya, et al., 2016a).

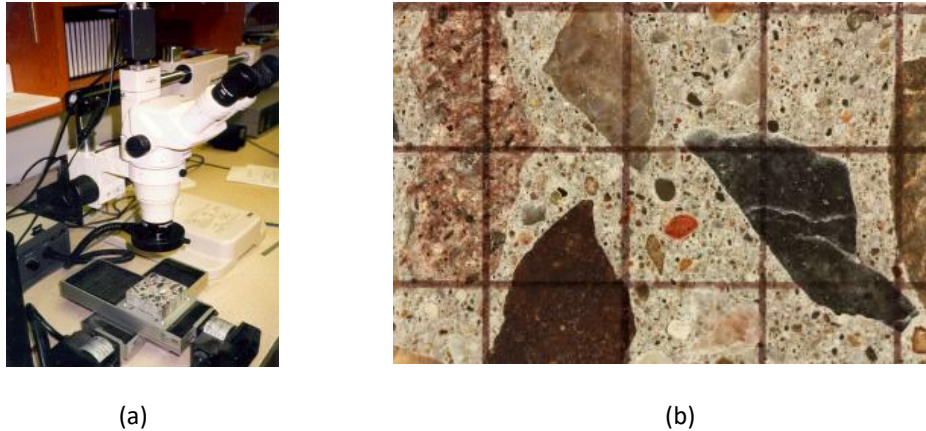


Figure 2.3.: Damage Rating Index: (a) Stereo microscope; (b) 1 cm<sup>2</sup> grid drawn on the surface of the concrete (Sanchez, Fournier, Jolin, Bedoya, et al., 2016a).

The number of counts corresponding to each type of petrographic features is then multiplied by weighing factors, whose purpose is to balance their relative importance towards the mechanism of distress (for instance ASR)(Sanchez et al., 2017a; Sanchez, Fournier, Jolin, & Duchesne, 2015; Sanchez, Fournier, Jolin, Bedoya, et al., 2016a). **Error! Reference source not found.** presents the classification proposed by (Sanchez, Fournier, Jolin, Bedoya, et al., 2016a), the authors tried to reduce the variability between the operators by improving the definition/description of the different damage features and modifying some weighing factors, considering that the factors used in the original method were chosen on a logical basis, but relatively arbitrarily. It is important to mention that the factors used in the method were chosen on a logical basis, but relatively arbitrarily.

Table 2.1.: Weighing factors for petrographic features classification.

<b>Petrographic features</b>	<b>Weighting factors</b>	
Crack in coarse aggregate	CCA	0.25
Opened crack in coarse aggregate	OCA	2
Crack with reaction product in coarse aggregate	OACG	2
Coarse aggregate debonded	CAD	3
Crack in cement paste	CCP	3
Crack with reaction product in cement paste	CCPG	3
Air void lined / filled with gel	AVG	--
Reaction rim around aggregate	RR	--
Disaggregate / corroded aggregate particle	DAP	2

Since the process of damage generation varies through the type/nature of reactive aggregate used (fine vs. coarse aggregate, lithotype, etc.), the DRI should ideally assess the nature and degree of distress features and correlate them with either the expansion attained by the distressed concrete or, ideally, with losses in mechanical properties (Noël et al., 2018; Sanchez et al., 2017a).

### **2.3.2. Stiffness Damage Test (SDT)**

In the early 1990's, Crisp and coworkers proposed to use the Stiffness Damage Test (SDT), developed by Walsh (Walsh, 1965), to quantify the degree of distress in concrete due to AAR. The technique was further developed and modified by different researchers and finally proposed by Crouch et al. as a powerful technique based on cyclic loading in compression of concrete specimens (Sanchez et al., 2014; Sanchez, Fournier, Jolin, & Bastien, 2015; Sanchez, Fournier, Jolin, Bastien, et al., 2016).

Sanchez et al. revised the test procedure and proved to be a reliable diagnostic technique to evaluate the inner quality of concrete structure in terms of serviceability (Sanchez, Fournier, Jolin, & Bastien, 2015). This method incorporates five cycles of uniaxial

loading/unloading on concrete specimens at a controlled rate of 0.10 MPa/s to determine the damage degree. The applied load was suggested to be up to 40% of the concrete's design strength, hence enabling the test as non-destructive to reuse the samples for further analysis as it generates no significant damage (Sanchez et al., 2017a; Sanchez, Fournier, Jolin, & Bastien, 2015; Sanchez, Fournier, Jolin, Bastien, et al., 2016; Sanchez, Fournier, Jolin, Bedoya, et al., 2016b).

The results associated with SDT correspond to Stiffness Damage Index (SDI, as a ratio of  $S_I/S_{I+II}$ ) and Plastic Deformation (PDI, as a ratio of  $D_I/D_{I+II}$ ) parameters (Figure 2.4). For a sound concrete SDI value is found zero whereas the value is equal to 1 for a highly damaged specimen. Thus, the outcome manifests the dissipated energy required to close the cracks over the cyclic compressive loading and finally compared to the PDI to understand the insights of internal damage due to AAR. Modulus of elasticity, hysteresis area and nonlinearity index are suggested as corresponding parameters to evaluate the mechanical properties and stiffness loss of the damaged concrete (Noël et al., 2018; Sanchez et al., 2017a; Sanchez, Fournier, Jolin, Bastien, et al., 2016) and these properties are measured in following ways:

- Modulus of elasticity ( $E_c$ ): average modulus of elasticity value of the second and third cycles;
- Hysteresis area (H): area of the hysteresis loops averaged over the five loading-unloading cycles; hence damaged specimen shows greater energy loss than undamaged samples;
- Nonlinearity index (NLI): represents the ratio of the slope of the stress response at half the maximum load over the secant  $E_c$  which provides information about the damage extent or crack patterns of the specimens.

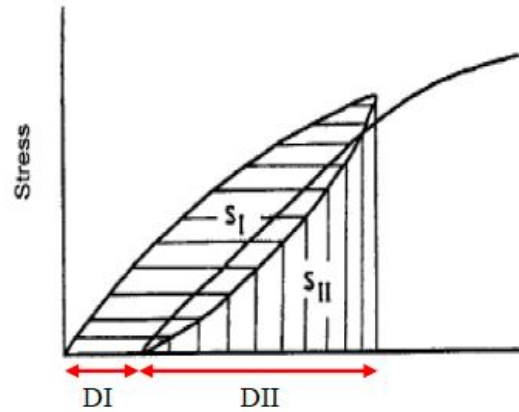


Figure 2.4.: SDI and PDI parameters (Sanchez, Fournier, Jolin, Bastien, et al., 2016).

## 2.4. Forecasting AAR-induced expansion and damage in concrete

To evaluate the structural implications and the potential of further induced damage, the residual expansion (RE) of the concrete plays a significant role. While comparing and monitoring a damaged structure, RE measurements involve a relatively quick assessment of the structure's potential of further expansion and damage.

### 2.4.1. Residual Expansion

In-situ monitoring remains the only reliable method for estimating residual expansion of affected structures. The current rates of deformation are measured periodically or continuously and can be then extrapolated or modelled to forecast future behaviour. However, in situ monitoring is usually quite expensive and often requires the accumulation of several years of measurements before clear distinctions between “permanent” and “cumulative” deformations associated with AAR are made (Bérubé et al., 2005; Merz & Leemann, 2013).

Residual expansion (RE) techniques derive from a generic concept that aims at assessing the “remaining” or “ultimate” expansion that might occur in affected structures in the field. RE tests are normally conducted on cores extracted from AAR-affected structures/structural members and consist of monitoring the “residual” expansion of

these specimens stored in controlled conditions enabling further AAR-induced development; normally, the test outcomes (i.e. expansion over time) are used as input data of numerical tools to predict future mechanical behaviour and performance of AAR-affected infrastructure.

Two test procedures are usually recommended in Canada, where cores extracted from distressed structures/structural members are: (1) tested in air at > 95% R.H. and 38°C (100°F) and; (2) tested in 1M NaOH solution at 38°C (100°F). The first test is considered the most reliable procedure for evaluating the “residual concrete expansion” and the potential for further deterioration of AAR-affected concrete (ASTM International, 2009; Bérubé et al., 2002; Benoît Fournier et al., 2004; Gao et al., 2011a; Multon, 2004; M. D.A. Thomas & Innis, 1999). The concrete is tested with its own (and remaining) alkali content and the test conditions used (temperature and humidity) are similar to those used in the Concrete Prism Test (CPT) as per ASTM C 1293. The second procedure is recommended for determining the “residual aggregate expansion” or even the “ultimate expansion” of concrete affected by AAR and is not intended to correlate necessarily with the potential expansion of affected structures in the field (Bérubé et al., 2002, 2005; Carles-Gibergues & Cyr, 2002; Gao et al., 2011b; Multon, 2004). Although the above procedures seem quite promising, there still is a lack of data regarding the correlation between the tests outcomes and the actual expansion of affected structures/structural members in-service, along with the influence of some test parameters such as alkali leaching on the laboratory test outcomes.

#### **2.4.2. Research gaps in forecasting AAR-induced expansion and damage**

Residual expansion (RE) techniques represent a viable, relatively fast and inexpensive approach to forecast the future behaviour of concrete structures/structural members affected by AAR. Yet, the lack of data correlating the expansion of real affected structures/structural members with the laboratory test outcomes (Bérubé et al., 2002; Gao et al., 2011b; Multon, 2004) along with a deep understanding on how some test parameters such as alkali leaching, confinement conditions, core’s geometry, etc., might

impact on the reliability of RE procedures prevent their standardization and frequent use in the market (Bérubé et al., 2002, 2005; Gao et al., 2011a). Hence, research is still required in this regard so that the validation or denial of the current techniques be performed, which may make some room for improving current RE techniques or even proposing novel laboratory test procedures.

## 2.5. References

- A23.2-28A, C. (2014). *Standard practice for laboratory testing to demonstrate the effectiveness of supplementary cementing materials and lithium-based admixtures to prevent alkali-silica reaction in concrete.*
- ASSHTO. (2011). AASHTO Guide Manual for Bridge Element Inspection - 1st Edition - 2011.pdf. In *Bridge Element Inspection Manual.*
- ASTM, C. (2008). *1293 Standard test method for determination of length change of concrete due to alkali-silica reaction.* ASTM International.
- ASTM Committee C09.65. (2012). ASTM C295-12 Standard Guide for Petrographic Examination of Aggregates for Concrete. In *Annual Book of ASTM Standards Volume 04.02.* [https://doi.org/10.1520/C0295\\_C0295M-12](https://doi.org/10.1520/C0295_C0295M-12)
- Benoit Fournier, Marc-André Bérubé, Kevin J. Folliard, M. T. (2010). Report on ASR Mitigation. *Federal Highway Administration Publications FHWA-HRT-04-113 (2004) and Techbrief FHWA-HRT-06-071.*
- Bérubé, M. A., Duchesne, J., Dorion, J. F., & Rivest, M. (2002). Laboratory assessment of alkali contribution by aggregates to concrete and application to concrete structures affected by alkali-silica reactivity. *Cement and Concrete Research.* [https://doi.org/10.1016/S0008-8846\(02\)00766-4](https://doi.org/10.1016/S0008-8846(02)00766-4)
- Bérubé, M. A., Smaoui, N., Fournier, B., Bissonnette, B., & Durand, B. (2005). 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(3), 463–479. <https://doi.org/10.1139/L04-104>

- Buck, O., Morris, W. L., & Richardson, J. M. (1978). Acoustic harmonic generation at unbonded interfaces and fatigue cracks. *Applied Physics Letters*.  
<https://doi.org/10.1063/1.90399>
- Chen, J., Jayapalan, A. R., Kim, J. Y., Kurtis, K. E., & Jacobs, L. J. (2010). Rapid evaluation of alkali-silica reactivity of aggregates using a nonlinear resonance spectroscopy technique. *Cement and Concrete Research*.  
<https://doi.org/10.1016/j.cemconres.2010.01.003>
- Chen, W., Hao, H., Jong, M., Cui, J., Shi, Y., & Chen, L. (2017). Quasi-static and dynamic tensile properties of basalt fibre reinforced polymer Quasi-static and dynamic tensile properties of basalt fibre reinforced polymer. *Composites Part B*, 125(May), 123–133. <https://doi.org/10.1016/j.compositesb.2017.05.069>
- Chen, X. J., Kim, J. Y., Kurtis, K. E., Qu, J., Shen, C. W., & Jacobs, L. J. (2008). Characterization of progressive microcracking in Portland cement mortar using nonlinear ultrasonics. *NDT and E International*.  
<https://doi.org/10.1016/j.ndteint.2007.08.009>
- Crawford, B., Kasmidi, M., Korompis, F., & Pollnac, R. B. (2006). Factors influencing progress in establishing community-based marine protected areas in Indonesia. *Coastal Management*. <https://doi.org/10.1080/08920750500379300>
- CSA A23.1. (2014). Concrete Materials and Methods of Concrete Construction. In *Canadian Standards Association: Vol. APPENDIX B*.
- CSA A23.2-14A. (2014). *Potential expansivity of aggregates (Procedure for Length Change due to Alkali-Aggregate Reaction in Concrete Prisms at 38°C)*. Canadian Standards Association.
- Den Abeele, K. E. A. V., Carmeliet, J., Ten Cate, J. A., & Johnson, P. A. (2000). Nonlinear elastic wave spectroscopy (NEWS) techniques to discern material damage, Part II: Single-mode nonlinear resonance acoustic spectroscopy. *Research in Nondestructive Evaluation*, 12(1), 31–42. <https://doi.org/10.1080/09349840009409647>
- Den Abeele, K. E. A. V., Johnson, P. A., & Sutin, A. (2000). Nonlinear elastic wave spectroscopy (NEWS) techniques to discern material damage, Part I: Nonlinear wave

- modulation spectroscopy (NWMS). *Research in Nondestructive Evaluation*.  
<https://doi.org/10.1080/09349840009409646>
- Farny, J. A., & Kerkhoff, B. (2007). Diagnosis and Control of Alkali-Aggregate Reactions in Concrete. *Portland Cement Association*, 1–24. [http://www.cement.org/docs/default-source/fc\\_concrete\\_technology/is413-02---diagnosis-and-control-of-alkali-aggregate-reactions-in-concrete.pdf?sfvrsn=2](http://www.cement.org/docs/default-source/fc_concrete_technology/is413-02---diagnosis-and-control-of-alkali-aggregate-reactions-in-concrete.pdf?sfvrsn=2)
- Fernandes, I., & Broekmans, M. A. T. M. (2013). Alkali-Silica Reactions: An Overview. Part I. *Metallography, Microstructure, and Analysis*, 2(4), 257–267.  
<https://doi.org/10.1007/s13632-013-0085-5>
- Forster, S. W., Boone, R. L., Hammer, M. S., Lamond, J. F., Lane, D. S., Miller, R. E., Parker, S. E., Pergalsky, A., Pierce, J. S., Robert, M. Q., Schmitt, J. W., & Tobin, R. E. (1998). *State-of-the-Art Report on Alkali-Aggregate Reactivity Reported by ACI Committee 221. 98(Reapproved)*, 1–31.
- Fournier, Benoit, & Bérubé, M.-A. (2000). Alkali–Aggregate Reaction in Concrete: a Review of Basic Concepts and Engineering Implications. *Canadian Journal of Civil Engineering*, 27, 167–191. <https://doi.org/10.1139/l99-072>
- Fournier, Benoît, Bérubé, M., Thomas, M. D. A., Smaoui, N., & Folliard, K. J. (2004). Evaluation and Management of Concrete Structures Affected by Alkali-Silica Reaction – A Review. *Seventh CANMET/ACI International Conference on Recent Advances in Concrete Technology*, 5(Mai), 1–60.
- Gao, X. X., Multon, S., Cyr, M., & Sellier, A. (2011a). Optimising an expansion test for the assessment of alkali-silica reaction in concrete structures. *Materials and Structures/Materiaux et Constructions*, 44(9), 1641–1653.  
<https://doi.org/10.1617/s11527-011-9724-y>
- Gao, X. X., Multon, S., Cyr, M., & Sellier, A. (2011b). Optimising an expansion test for the assessment of alkali-silica reaction in concrete structures. *Materials and Structures/Materiaux et Constructions*. <https://doi.org/10.1617/s11527-011-9724-y>
- Godart, Bruno; Wood, Jonathan G. M.; de Rooij, M. (2013). *Guide to Diagnosis and Appraisal of AAR Damage to Concrete in Structures* (M. Godart, Bruno; Wood,

- Jonathan G. M.; de Rooij (ed.)). Springer Netherlands.
- Grattan-Bellew, P.; Danay, A. (1992). Comparison of laboratory and field evaluation of alkali-silica reaction in large dams. *International Conference on Concrete AAR in Hydroelectric Plants and Dams*.
- Kraig Warnemuende, Hwai-Chung Wu. (2004). Actively modulated acoustic nondestructive evaluation of concrete. *Cement and Concrete Research, Volume 34*(Issue 4), Pages 563-570.
- Leśnicki, K. J., Kim, J. Y., Kurtis, K. E., & Jacobs, L. J. (2011). Characterization of ASR damage in concrete using nonlinear impact resonance acoustic spectroscopy technique. *NDT and E International, 44*(8), 721–727. <https://doi.org/10.1016/j.ndteint.2011.07.010>
- M. D. A. Thomas, B. Fournier, & K. J. Folliard. (2013). Alkali-Aggregate Reactivity (AAR) Facts Book. *Book*, 224.
- Meissner, H. S. (1941). Cracking in Concrete Due to Expansive Reaction Between Aggregate and High-Alkali Cement as Evidenced in Parker Dam. *ACI Journal Proceedings, 37*.
- Merz, C., & Leemann, A. (2013). Assessment of the residual expansion potential of concrete from structures damaged by AAR. *Cement and Concrete Research, 52*(November 2017), 182–189. <https://doi.org/10.1016/j.cemconres.2013.07.001>
- Mindess, A., & Francis, J. (2003). *Concrete* (2nd ed.). Prentice Hall, Pearson Education, Inc. Upper Saddle River, NJ 07458, U.S.A.
- Multon, S. (2004). Evaluation expérimentale et théorique des effets mécaniques de l'alcali-réaction sur des structures modèles. In *Etudes et recherches des Laboratoires des ponts et chaussées. Série Ouvrages d'art*.
- Multon, S., Sellier, A., & Cyr, M. (2009). Chemo-mechanical modeling for prediction of alkali silica reaction (ASR) expansion. *Cement and Concrete Research, 39*(6), 490–500. <https://doi.org/10.1016/j.cemconres.2009.03.007>
- Nixon, P. J; Bollinghaus, R. (1985). The effect of alkali aggregate reaction on the tensile and compressive strength of concrete. *Durability of Building Materials. 1985, Vol 2, Num 3, Pp 243-248 ; Ref : 5 Ref, Vol 2*(Num 3), pp 243-248 ; ref : 5 ref.

- Nixon, P. J., & Sims, I. (2015). RILEM recommendations for the prevention of damage by alkali-aggregate reactions in new concrete structures: State-of-the-Art report of the RILEM technical committee 219-ACS. In *RILEM Recommendations for the Prevention of Damage by Alkali-Aggregate Reactions in New Concrete Structures: State-of-the-Art Report of the RILEM Technical Committee 219-ACS*. <https://doi.org/10.1007/978-94-017-7252-5>
- Noël, M., Sanchez, L., & Tawil, D. (2018). Structural implications of internal swelling reactions in concrete: Review and research needs. *Magazine of Concrete Research*, 70(20), 1052–1063. <https://doi.org/10.1680/jmacr.17.00383>
- Paul, S. C., Pirskawetz, S., Van Zijl, G. P. A. G., & Schmidt, W. (2015). Acoustic emission for characterising the crack propagation in strain-hardening cement-based composites (SHCC). *Cement and Concrete Research*, 69, 19–24. <https://doi.org/10.1016/j.cemconres.2014.12.003>
- Sanchez, L. F. M., Fournier, B., Jolin, M., & Bastien, J. (2014). 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*. <https://doi.org/10.1016/j.cemconres.2013.11.003>
- Sanchez, L. F. M., Fournier, B., Jolin, M., & Bastien, J. (2015). Evaluation of the Stiffness Damage Test (SDT) as a tool for assessing damage in concrete due to alkali-silica reaction (ASR): Input parameters and variability of the test responses. *Construction and Building Materials*. <https://doi.org/10.1016/j.conbuildmat.2014.11.071>
- Sanchez, L. F. M., Fournier, B., Jolin, M., Bastien, J., & Mitchell, D. (2016). Practical use of the Stiffness Damage Test (SDT) for assessing damage in concrete infrastructure affected by alkali-silica reaction. *Construction and Building Materials*. <https://doi.org/10.1016/j.conbuildmat.2016.08.101>
- Sanchez, L. F. M., Fournier, B., Jolin, M., Bedoya, M. A. B., Bastien, J., & Duchesne, J. (2016a). Use of Damage Rating Index to quantify alkali-silica reaction damage in concrete: Fine versus coarse aggregate. *ACI Materials Journal*, 113(4), 395–407. <https://doi.org/10.14359/51688983>

- Sanchez, L. F. M., Fournier, B., Jolin, M., Bedoya, M. A. B., Bastien, J., & Duchesne, J. (2016b). Use of Damage Rating Index to quantify alkali-silica reaction damage in concrete: Fine versus coarse aggregate. *ACI Materials Journal*.  
<https://doi.org/10.14359/51688983>
- Sanchez, L. F. M., Fournier, B., Jolin, M., & Duchesne, J. (2015). Reliable quantification of AAR damage through assessment of the Damage Rating Index (DRI). *Cement and Concrete Research*, 67, 74–92. <https://doi.org/10.1016/j.cemconres.2014.08.002>
- Sanchez, L. F. M., Fournier, B., Jolin, M., Mitchell, D., & Bastien, J. (2017a). Overall assessment of Alkali-Aggregate Reaction (AAR) in concretes presenting different strengths and incorporating a wide range of reactive aggregate types and natures. *Cement and Concrete Research*, 93, 17–31.  
<https://doi.org/10.1016/j.cemconres.2016.12.001>
- Sanchez, L. F. M., Fournier, B., Jolin, M., Mitchell, D., & Bastien, J. (2017b). Overall assessment of Alkali-Aggregate Reaction (AAR) in concretes presenting different strengths and incorporating a wide range of reactive aggregate types and natures. *Cement and Concrete Research*, 93, 17–31.  
<https://doi.org/http://dx.doi.org/10.1016/j.cemconres.2016.12.001>
- Stanton, T. E. (2008). Expansion of concrete through reaction between cement and aggregate (this article originally appeared in Proceedings of the ASCE, December 1940, v. 66(10), pp. 1781-1811). In *Selected Landmark Paper Collection on Concrete Materials Research*.
- Stark, D., Diamond, S., & Moranville-regourd, M. (n.d.). *Alkali-Silica Reactivity : An Overview of Research*.
- Swenson, E G. (1957). A Reactive aggregate undetected by ASTM tests. *ASTM Bulletin*.
- Swenson, Edwin George, & Gillott, J. E. (1960). Characteristics of Kingston carbonate rock reaction. *Highway Research Board Bulletin*, 275, 18–31.
- Thomas E. Stanton, O. J. Porter, L. C. Meder, and A. N. (1942). California Experience With the Expansion of Concrete Through Reaction Between Cement and Aggregate. *ACI Journal Proceedings*, 38.

- Thomas, M. D.A., & Innis, F. A. (1999). Use of the accelerated mortar bar test for evaluating the efficacy of mineral admixtures for controlling expansion due to alkali-silica reaction. *Cement, Concrete and Aggregates*, 21(2), 157–164.  
<https://doi.org/10.1520/cca10429j>
- Thomas, M., Fournier, B., Folliard, K., Ideker, J., & Shehata, M. (2006). Test methods for evaluating preventive measures for controlling expansion due to alkali-silica reaction in concrete. *Cement and Concrete Research*.  
<https://doi.org/10.1016/j.cemconres.2006.01.014>
- Thomas, Michael D.A., Folliard, K. J., Fournier, B., Rivard, P., Drimalas, T., & Garber, S. I. (2013). Methods for Evaluating and Treating ASR-Affected Structures: Results of Field Application and Demonstration Projects. Volume II: Details of Field Applications and Analysis Final Report. *Federal Highway Administration, FHWA-HIF-1*, 338.
- Van Den Abeele, K. E. A., Sutin, A., Carmeliet, J., & Johnson, P. A. (2001). Micro-damage diagnostics using nonlinear elastic wave spectroscopy (NEWS). *NDT and E International*. [https://doi.org/10.1016/S0963-8695\(00\)00064-5](https://doi.org/10.1016/S0963-8695(00)00064-5)
- Villeneuve, V., Fournier, B., & Duchesne, J. (2012). Determination of the damage in concrete affected by ASR- the damage rating index (DRI). *Proceedings of the 14th International Conference on Alkali-Aggregate Reaction in Concrete*.
- Walsh, J. B. (1965). The effect of cracks on the uniaxial elastic compression of rocks. *Journal of Geophysical Research*. <https://doi.org/10.1029/jz070i002p00399>
- Wigum, B. J., Lindgård, J., Sims, I., & Nixon, P. (2016). Rilem activities on alkali-silica reactions: From 1988-2019. *Proceedings of Institution of Civil Engineers: Construction Materials*. <https://doi.org/10.1680/jcoma.15.00070>

# Chapter Three: Evaluation of the potential of residual expansion in concrete affected by Alkali Aggregate Reaction

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## 3.1. Abstract

One of the biggest challenges nowadays when dealing with critical AAR-affected infrastructure is to determine the induced expansion and damage attained to date in the different locations of the structure (i.e. diagnosis), to forecast its potential for further distress over time (i.e. prognosis), as well as its structural implications. Most of the techniques that have been developed for these purposes are residual expansion procedures based on accelerated laboratory tests performed on cores extracted from damaged structures. However, most of the results gathered from these tests have been found to be inaccurate when compared to the swelling behavior of the respective structure in the field and thus several potential issues have been raised with respect to the test setup and alkali leaching. This work aims to evaluate the efficiency of the various commonly used laboratory setups and propose a novel setup to assess the residual expansion of AAR-affected concrete. Three different setups (i.e. 100% RH and 38°C; samples soaked in 1M NaOH at 38°C and; wrapped in 0.7M NaOH at 38°C) and two types of reactive aggregates (fine and coarse) were selected for this research. Expansions were monitored over time and four damage degrees (i.e. 0.05%, 0.12%, 0.20% and 0.30%) were selected for further chemical, microscopic (DRI) and non-destructive test (NIRAS). Results demonstrated that the 1 M NaOH protocol is more aggressive than the other two setups. Moreover, it provides the samples with a distinct damage pattern than the one expected from field affected concrete. Finally, the proposed test protocol shows to be efficient in providing tested samples with similar deterioration mechanisms than expected. Yet, more

efficiency in the reaction kinetics and understanding of the alkalis exchange from the system is still required.

**Keywords:** alkali aggregate reaction, reactive aggregate, residual expansion, accelerated laboratory test.

### **3.2. Introduction**

Alkali-aggregate reaction (AAR) is one of the most deleterious mechanisms affecting the durability and long-term performance of concrete infrastructure worldwide. AAR is a chemical reaction between the alkalis from the concrete pore solution and some siliceous phases of the aggregates used in concrete. AAR provides a gel that swells in the presence of water leading to tensile stresses and cracking in concrete (Benoit Fournier & Bérubé, 2000).

Over the past decades, a wide number of chemical, non-destructive, microscopic and mechanical techniques have been developed to appraise AAR-induced expansion and associated damage (i.e. diagnosis) in concrete. Yet, there is still a great gap on the development of protocols to evaluate the potential of further deterioration (i.e. prognosis) of affected structures (Merz & Leemann, 2013). Although several researchers (Bérubé et al., 2005; Benoit Fournier & Bérubé, 2000; Merz & Leemann, 2013; Multon et al., 2009) developed procedures that showed to be quite promising in the laboratory, their efficiency in assessing aging structures in the field is still not confirmed, especially due to the lack of understanding on their use, limitations and results implementation, which prevents the development of comprehensive management and rehabilitation protocols.

Amongst the methods proposed to assess AAR-prognosis, the residual expansion (RE), seems to be the simplest and most used procedure around the globe. RE is a test protocol where cores are extracted from the structure or structural members under consideration and stored in the laboratory under conditions enabling further AAR development.

Currently, there are over 10 distinct RE procedures being used worldwide, yet in North America researchers perform the test according to one of the following methods: a) concrete cores are extracted from affected members and stored under conditions enabling further and accelerated AAR development (i.e. 38°C and 100% RH) and b) concrete cores are extracted and soaked in 1M NaOH solution at 38°C (Bérubé et al., 2002; Maarten A.T.M. Broekmans, 2002). The samples are monitored for one year in both cases. The test performed at 38°C and 100% RH aims to evaluate the “residual potential” of AAR development in the field whereas the method soaked in 1M NaOH solution at 38°C assesses the “maximum” expansion capacity of the material (ASTM International, 2009; Merz & Leemann, 2013).

Although RE test methods are quite easy and straightforward to be conducted, most of the results gathered from these tests have been found to be inaccurate when compared to the swelling behavior of the respective structure in the field (Merz & Leemann, 2013). Moreover, several potential issues have been raised with respect to the test setups adopted (i.e. alkalis leaching in the case of 38°C and 100% RH and extremely aggressive solution when performed at 1M NaOH). Furthermore, concrete structures are often under different stress conditions (due to confinement effects, presence of reinforcement, loadings, etc.) when compared to laboratory tests which makes the physicochemical process to be different (Bérubé et al., 2002; Merz & Leemann, 2013; M. Thomas et al., 2006). Recently, a number of research studies have demonstrated that AAR strongly influences the mechanical properties of the affected concrete, especially its tensile strength and modulus of elasticity, where important losses of about 85% and 50% were measured, respectively, for very high expansion levels (Bérubé et al., 2005). Therefore, to be able to evaluate the potential for further induced expansion and damage of an AAR-affected member, the following questions (that are still open to debate) should be properly answered: a) how to use the RE results obtained from cores extracted from AAR-affected members in the reassessment of their potential of further damage?; and b) how to use the results from cores as input for numerical/analytical models to predict the future behavior of aging structures? This work aims to 1) evaluate the efficiency of the commonly

used North American RE laboratory techniques and 2) propose a novel setup to assess the residual expansion of AAR-affected concrete.

### **3.3. Diagnosis of AAR-affected concrete**

In the literature, there are various documents related to the diagnosis and quantification of AAR-induced damage in concrete, especially in AAR-affected structures. Some documents thoroughly illustrate the different steps required to assess aging structure (Noël et al., 2018; Sanchez et al., 2017a; M. Thomas et al., 2006). Usually, the first step while the condition assessment of concrete infrastructure is the review of available documents related to the appraised structure, such as: a) age, type and location of the structure and its exposure conditions; b) drawings and specifications; c) details of concrete mixtures used, source of cement and aggregates; d) previous inspections and testing reports and; e) information from other structures in the area that may have been constructed with similar materials (Crawford et al., 2006; M. D. A. Thomas et al., 2013). Once the analysis of the available documents is conducted, in-situ assessment and, when necessary, coring for further laboratory procedures might be required. Among these procedures, the petrographic ones, such as Damage Rating Index (DRI), are the most common and considered extremely reliable when diagnosing structures (Sanchez, Fournier, Jolin, & Duchesne, 2015). Also, several researchers have found the Nonlinear Impact Resonance Acoustic Spectroscopy (NIRAS) technique as an effective protocol to appraise damage progression (X. J. Chen et al., 2008).

#### **3.3.1. Nonlinear Impact Resonance Acoustic Spectroscopy (NIRAS) technique**

Nowadays, nonlinear ultrasonic and acoustics-based testing methods are commonly used non-destructive techniques for concrete specimens affected by AAR. These methods are found responsive to identify micro cracks and damage compared to traditional linear acoustic methods (Buck et al., 1978; J. Chen et al., 2010; K. E. A. V. Den Abeele, Johnson, et al., 2000; K. E. A. Van Den Abeele et al., 2001). Numerous nonlinear resonance techniques such as the nonlinear resonance ultrasound spectroscopy (NRUS) was applied on

specimens to understand the thermal damage of concrete; the nonlinear reverberation spectroscopy (NRS) method was applied to assess damage in reinforced concrete; whereas the nonlinear wave modulation spectroscopy (NWMS) procedure identified the initial AAR damage (X. J. Chen et al., 2008; Leśnicki et al., 2011; K. E. A. Van Den Abeele et al., 2001).

Chen et al. (X. J. Chen et al., 2008) proposed a new technique based on impulse excitation of concrete samples measuring their free vibration responses and named it nonlinear impact resonance acoustic spectroscopy (NIRAS) improving both NRUS and NRS methods and applied on mortar bars to evaluate AAR damage. The authors explained that concrete is heterogeneous and nonlinear by nature, hence while affected by AAR; NIRAS can recognize the microcracks through the assessment of resonance frequencies. Several authors comply with this idea mentioning the cracks as “imperfect bond system” and demonstrating that this system decreases the mechanical stiffness of the structure together with the resonance frequencies escalating the nonlinear effects. This resonance frequency shift is accepted by researchers as a function of concrete macroscopic nonlinearity property to quantify damage (J. Chen et al., 2010; X. J. Chen et al., 2008; Leśnicki et al., 2011). Van et al.(K. E. A. Van Den Abeele et al., 2001) demonstrated the correlation between strain and frequency shift of the material and Chen et al (X. J. Chen et al., 2008) proposed an equation of elastic modulus based on this idea:

$$(f_0-f) / f_0 = \acute{\alpha}\Delta\varepsilon \quad \text{Equation 3.1}$$

$$E = E_0 [1 + \beta\varepsilon + \delta\varepsilon^2 + \alpha (\Delta\varepsilon + \varepsilon \text{sgn}(\acute{\varepsilon}))] \quad \text{Equation 3.2}$$

Here, in equation (3.1)  $f_0$  represents the linear resonance frequency where  $f$  is the resonance frequency at increased excitation amplitude,  $\acute{\alpha}$  is proportional to  $\alpha$ . In addition, equation (3.2) parameters are:  $E_0$  refers the linear elastic modulus for small deformation,  $\beta$  represents the parameter for quadratic anharmonicity,  $\delta$  refers the parameter for cubic anharmonicity,  $\varepsilon$  is strain,  $\Delta\varepsilon$  refers the strain amplitude,  $\alpha$  is the hysteresis nonlinearity

property,  $\dot{\epsilon}$  is strain rate and  $\text{sgn}(\dot{\epsilon}) = 1$  if  $\dot{\epsilon} > 0$ ;  $-1$  if  $\dot{\epsilon} < 0$ ;  $0$  if  $\dot{\epsilon} = 0$  (X. J. Chen et al., 2008; Leśnicki et al., 2011).

Krzysztof et al. performed NIRAS test on AAR affected concrete prisms fabricated with three different types of reactive aggregates subjected to ASTM C1293 method. Each prism was vibrated using a low amplitude hammer and the results were compared. The outcome validates the qualitative assessment of the NIRAS test to distinguish reactive and non-reactive aggregates and AAR damage in terms of nonlinearity parameters (Leśnicki et al., 2011).

### **3.3.2. Damage Rating Index (DRI)**

The Damage Rating Index (DRI) is a widely used semi-quantitative petrographic technique recommended by Grattan-Bellow and Danay to evaluate the damage degree of AAR affected polished concrete samples (Grattan-Bellew, P.; Danay, 1992). Later, some researchers from Laval University improved this method so that it might better represent “damage” in its broader sense, while reducing its subjectivity and variability amongst operators (Multon et al., 2009; Sanchez, Fournier, Jolin, & Bastien, 2015; Sanchez, Fournier, Jolin, & Duchesne, 2015).

A stereomicroscope of about 15-16x magnification is used to analyze the microscopic features corresponding to AAR damage. Polished concrete samples are prepared, and each surface is divided into sections of  $1\text{cm}^2$  grids. Maximum  $200\text{cm}^2$  surface area is suggested for petrographic analysis for each sample or higher surface area for concrete with large aggregate particles ( $> 20\text{mm}$ ). The number of each microscope features are counted and multiplied by corresponding weighing factors and the results are represented as DRI numbers normalizing to a  $100\text{cm}^2$  areas (Sanchez et al., 2017a; Sanchez, Fournier, Jolin, & Bastien, 2015; Sanchez, Fournier, Jolin, & Duchesne, 2015; Villeneuve et al., 2012).

Recently, Sanchez et al. performed the DRI on concrete samples presenting different strengths and fabricated with a wide range of coarse and fine aggregates. The authors also modified the commonly used DRI version recommending a new one (Sanchez et al.,

2017a; Sanchez, Fournier, Jolin, & Duchesne, 2015; Sanchez, Fournier, Jolin, Bedoya, et al., 2016b). They suggested the same weighing factors for open cracks in the aggregate with or without reaction particles and cracks in cement paste with or without reaction particles to decrease variation and hence improving the DRI results. Moreover, several research works confirmed the relationship between AAR expansion levels and DRI results. Therefore, DRI is considered to be a very effective and powerful method for assessing AAR affected concrete regardless of aggregate type and concrete strength (Noël et al., 2018; Sanchez et al., 2017a; Sanchez, Fournier, Jolin, & Duchesne, 2015; Sanchez, Fournier, Jolin, Bedoya, et al., 2016b).

### **3.4. Forecasting AAR-induced expansion and damage**

The determination of the potential of residual expansion is a key factor in prognosis of AAR-affected concrete. To monitor the current condition and extend the service life of damaged structures, understanding the potential of further expansion is a powerful tool. Hence, numerous laboratory test procedures have been developed over the past decades to forecast the behavior of in-situ concrete. However, uncertainties are very common in accelerated laboratory test procedures when compared to field structures exposed to complex environmental conditions (Benoit Fournier & Bérubé, 2000; Merz & Leemann, 2013; Multon et al., 2009).

Currently, numerous residual expansion (RE) techniques are used to predict the future behavior of AAR-affected concrete. Yet, the use of RE test outcomes is still quite discussed and unknown. Moreover, mechanically speaking, one does not know whether the process “reproduced in the laboratory” through RE tests is “similar or comparable” to what is happening in the field. In this regard, the use of non-destructive (e.g. nonlinear impact resonance acoustic spectroscopy –NIRAS) and microscopic (damage rating index - DRI) techniques might be beneficial to help understanding similarities and different obtained from distinct RE test setups.

### **3.4.1. Residual Expansion**

Residual expansion (RE) tests aim to assess the potential of further induced expansion that might occur in affected structures. Those tests are carried out on cores extracted from AAR-affected structures and then the cores are monitored in terms of expansion over time. The specimens are stored in a controlled temperature (usually 38 °C for AAR) and moist environment in the laboratory and measured over one year; RE may forecast the “prognosis” of the problem (e.g. expansion rate per year) that can be used as an input data in numerical tools to predict the mechanical behavior of damaged structures (M. D. A. Thomas et al., 2013; M. Thomas et al., 2006).

Usually, laboratory test setups and storage conditions are controlled whereas concrete structures in field are exposed to different environmental conditions. Therefore, the inner chemical reaction and swelling behavior might be different under laboratory conditions, which may not represent the real scenario. Currently, to assess the residual expansion of AAR-affected concrete in Canada, two storage conditions are considered: a) 38°C temperature and 100 RH (considered similar to ASTM C 1293) and b) 38°C temperature and 1M NaOH solution. Although these conditions may quickly trigger further AAR-development in the laboratory, the outcomes reliability of the above tests is still unknown. It has been found that some RE laboratory conditions such as very aggressive and unrealistic environments (e.g. 1M NaOH), alkali leaching and stress relaxation (i.e. specimens are under non-confined or free conditions in the laboratory) may jeopardize the test outcomes. Moreover, there is currently no consensus on the technical community on how to use RE results to re-appraise AAR-affected structures (ASTM International, 2009; Fernandes & Broekmans, 2013; Merz & Leemann, 2013; Multon et al., 2009).

### **3.5. Scope of the Work**

It is known that there is an important discrepancy between the outcomes of the current RE techniques and the real behaviour of affected structures in the field. The latter might

be related to issues in the test setups such as aggressive environments or alkali leaching. Therefore, this work aims to evaluate the efficiency of the current RE laboratory setups and to propose a novel approach showing comparable distress mechanisms of the affected structures (i.e. efficient kinetics, less leaching etc.) to assess the potential for further expansion of AAR-affected concrete specimens in the laboratory. Three different setups (i.e. 100% RH at 38°C; samples soaked in 1M NaOH at 38°C and; and wrapped in 0.7M NaOH at 38°C) and two types of reactive aggregates (fine and coarse) were selected for this research. Once fabricated, expansion has been monitored over time on reactive specimens and four damage levels (i.e. 0.05%, 0.12%, 0.20% and 0.30%) were selected for further non-destructive and microscopic analyses. Finally, results are compared and pros and cons from each technique are highlighted.

### **3.6. Materials and methods**

#### **3.6.1. Materials and mixture proportions**

Two highly reactive aggregates (i.e. Springhill coarse aggregate and Texas sand) were selected for this research to fabricate 35 MPa concrete specimens (100 by 200 mm cylinders). Non-reactive fine and coarse aggregates (Ottawa natural sand and non-reactive limestone) from natural quarries of Ottawa were also selected for concrete manufacturing. The coarse aggregates ranged in size from 5 to 20 mm. A conventional Portland cement (CSA Type GU, ASTM type 1) containing high alkali content (0.88%  $\text{Na}_2\text{O}_e$ ) was used in the mixture. Reagent grade NaOH was used to raise the total alkali content of the mixtures to 1.25%  $\text{Na}_2\text{O}_e$  by cement mass, for accelerating AAR expansion process. The properties of the aggregates and concrete mix design selected for this study are presented in Table 3.1 and Table 3.2, respectively:

Table 3.1.: Aggregate properties selected for this study.

<b>Aggregate</b>						
<b>Type</b>	<b>Reactivity</b>	<b>Location</b>	<b>Name</b>	<b>Rock type</b>	<b>Specific gravity (g/cm<sup>3</sup>)</b>	<b>Absorption (%)</b>
<b>Coarse</b>	Reactive	New Brunswick	Sp	Greywacke	2.72	0.602
	Non-reactive	Ottawa	Ls	Natural derived from quarries	2.68	0.53
<b>Fine</b>	Reactive	Texas (USA)	Tx	Polymictic sand	2.60	0.55
	Non-reactive	Ottawa	Ot	Natural derived from granite	2.65	1.18

Table 3.2.: Concrete mix design.

<b>Constituents (kg/m<sup>3</sup>)</b>	<b>Springhill coarse</b>	<b>Texas sand</b>
<b>Cement</b>	420	420
<b>Fine aggregate</b>	681	732
<b>Coarse aggregate</b>	1044	1072
<b>Water</b>	176	176
<b>NaOH</b>	1.35	1.35

### 3.6.2. Fabrication and conditioning:

A total of 132 concrete specimens (i.e. 66 per aggregate type) were fabricated, demolded after 24 hours, and moist cured for over 24 hours. Small holes, 5 mm in diameter by 15 mm long, were then drilled in both ends of each test specimen and stainless-steel gauge studs were glued in place, with fast-setting cement slurry for longitudinal expansion measurements. After the completion of the first 72 h (i.e. three days from casting), the zero reading was conducted, and the specimens were stored at three distinct conditions:

- Sealed plastic containers (22 litres) lined with a damp cloth (4 cylinders per bucket). All buckets were stored at 100% RH and 38°C (Figure 3.1(a));
- Sealed plastic containers (22 litres) containing a 1M NaOH solution (4 cylinders per bucket). All cylinders were soaked at the solution at 38°C (Figure 3.1(b));

- Plastic jars displaying a slightly bigger diameter than the concrete specimens and lined with a damp sponge containing a 0.7M NaOH solution. The specimens were placed inside the jars and wrapped by the sponge. It is worth noting that there was no free space between the specimen and the jar (i.e. the gap between the jar and concrete specimen was fully covered by the sponge) and it was anticipated that the use of damp sponge would decrease the leaching of alkali content (Figure 3.1(c)).

All the test cylinders were regularly monitored over time. Also, the containers were cooled down to 23°C for  $16 \pm 4$  h prior to periodic expansion measurements. Five levels of expansion were selected for further analysis: 0.05% (low); 0.12% (moderate); 0.20% (high) and; 0.30% (very high) and ultimate expansion. Once the test specimens reached the above expansion levels, they were wrapped in plastic film and stored at 12°C to stop AAR further development until non-destructive and microscopic tests were conducted. Table 3.3 displays the testing matrix of the proposed research program.

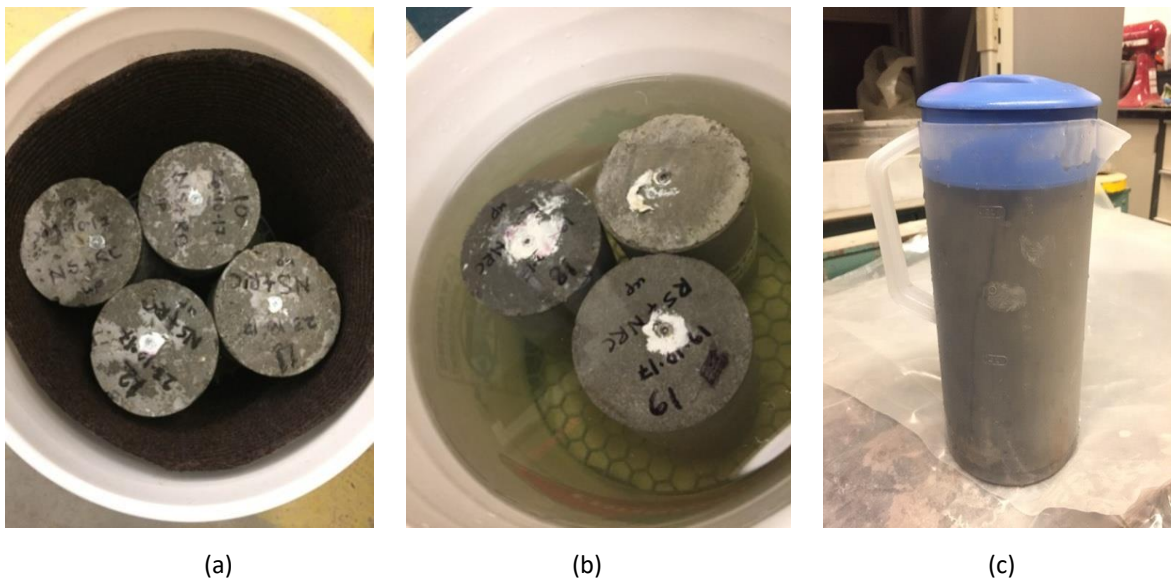


Figure 3.1.: Different storage conditions for AAR RE testing: (a) 38°C and 100% R.H; (b) 1M NaOH solution at 38°C and; (c) damp sponge containing a 0.7M NaOH solution at 38°C.

Table 3.3: Testing matrix proposed for this research.

Specimen type	Number of samples for each expansion level					
	0.00%	0.05%	0.12%	0.20%	0.30%	Ultimate expansion
100 RH and 38°C	2	4	4	4	4	4
1M NaOH solution and 38°C	2	4	4	4	4	4
0.7M NaOH sponge and 38°C	2	4	4	4	4	4
<b>Total = 66 samples per aggregate type</b>						

### 3.6.3. Concrete assessment and analysis

The specimens were unwrapped just before testing and expansion readings were taken to confirm that no outstanding expansion (and or shrinkage) took place during the storage period. Nonlinear impact resonance acoustic spectroscopy (NIRAS) and Damage Rating Index (DRI) were then performed on test specimens containing coarse and fine reactive aggregates and expansion levels.

#### 3.6.3.1. Nonlinear Impact Resonance Acoustic Spectroscopy (NIRAS) technique

Nonlinear impact resonance acoustic spectroscopy (NIRAS) is considered highly responsive to determine micro cracks and defects in concrete through resonance frequencies even at early stage of damaged concrete. According to Chen et al. (J. Chen et al., 2010; X. J. Chen et al., 2008; K. E. A. V. Den Abeele, Carmeliet, et al., 2000; Leśnicki et al., 2011; K. E. A. Van Den Abeele et al., 2001), this technique is based on a correlation between normalized resonance frequency shift and strain amplitude. In this study NIRAS was applied to assess the expansion and damage development as well as AAR potential in concrete samples. The NIRAS test setup is illustrated in Figure 3.2:

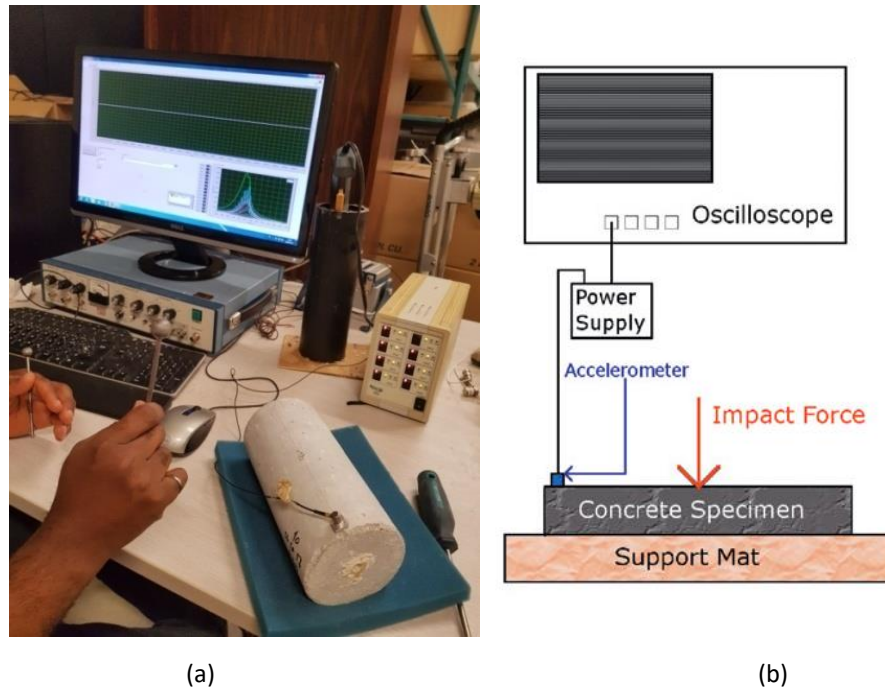


Figure 3.2.: NIRAS test; (a) Experimental setup and (b) schematic setup (Leśnicki et al., 2011)

First of all, the studs from all evaluated specimens were completely removed from their ends. Then, the specimens were placed on a supporting mat and connected to a high-frequency accelerometer using a quick setting adhesive which is combined with an oscilloscope. Then, specimens were vibrated at the center with a low amplitude hammer stimulating the transverse flexural vibration mode. This vibration spreads to the entire specimen and evaluates its inner condition, being recorded by the oscilloscope connected to the accelerometer. The Fast Fourier Transform (FFT) is then used to acquire the vibration signals and frequency spectrum. At least 10 individual impacts of different strengths were applied to each specimen to interpret the difference in resonance frequency. The analysis is then performed according to the resonance frequency and impact amplitude as follows: the greater the damage, the lower the resonance frequency and the higher the impact amplitude (J. Chen et al., 2010; Leśnicki et al., 2011).

### 3.6.3.2 Damage rating Index (DRI):

One specimen per expansion level per reactive aggregate was removed from 12°C storage, unwrapped and its steel studs were completely removed. Then, the specimens were cut in

two, axially, and one of the flat surfaces was polished using a standard polishing device which uses diamond-impregnated rubber disks (No 50 [coarse], 100, 400, 800, 1500, 3000 [very fine]); this device was found most suitable for the work, as it does not lose abrasive powders that can fill up cracks or voids in concrete, and high-quality polishing is obtained with minimal water supply so that AAR-gel leaching is avoided. Afterwards, the DRI was performed as per Sanchez et al. (Sanchez, Fournier, Jolin, & Duchesne, 2015; Sanchez, Fournier, Jolin, Bedoya, et al., 2016b).

## **3.7. Results**

### **3.7.1. AAR-induced Expansion**

The results for AAR-induced expansion as a function of time are presented for the three different setups (i.e. 38°C and 100% RH; soaked in 1M NaOH solution at 38°C and; wrapped in a sponge containing 0.7M NaOH) and for concrete incorporating two reactive aggregate types (i.e. Texas sand and Springhill coarse aggregate).

Figure 3.4(a) illustrates the expansion measurements gathered for samples fabricated with the reactive Texas sand (Tx) whereas Figure 3.3 (b) displays the results for specimens proportioned with the reactive Springhill (Sp) coarse aggregate.

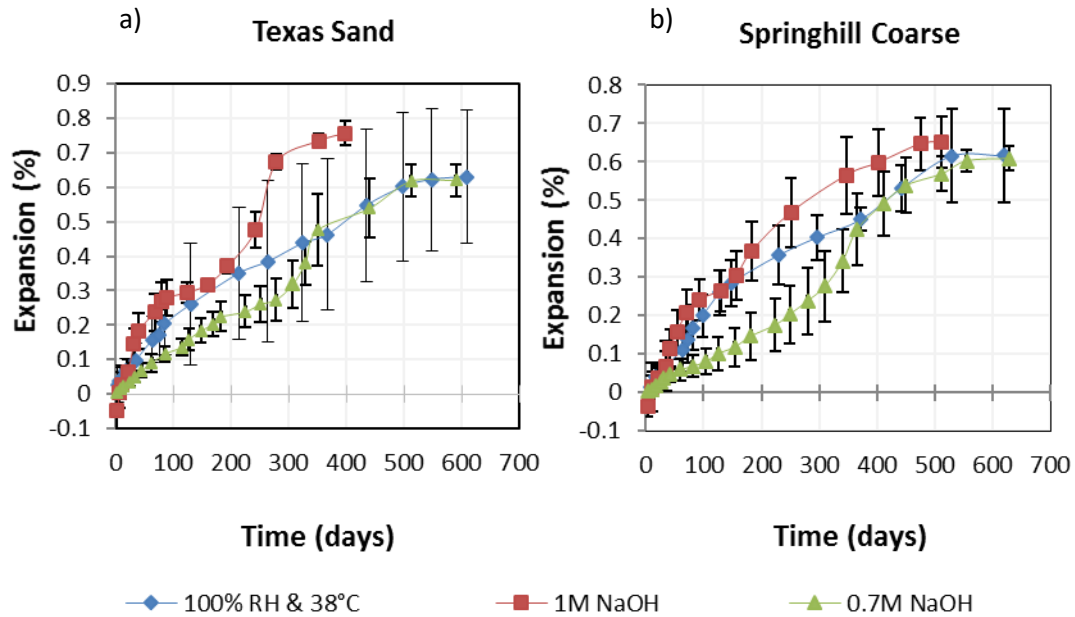


Figure 3.3: Expansion vs. time obtained for concrete tested with distinct setups and incorporating (a) reactive Texas sand, and (b) reactive Springhill coarse aggregate.

It can be observed that faster AAR kinetics was found for the samples fabricated with the Tx sand when compared to Sp coarse aggregate whatever is the test setup, as expected and reported in previous researches (Bérubé et al., 2002; Sanchez, Fournier, Jolin, Bedoya, et al., 2016b; M. Thomas et al., 2006). Furthermore, specimens soaked in 1M NaOH presented the fastest kinetics and highest ultimate expansion when compared to the other two setups. The ultimate expansion was reached at 400 days for concrete samples fabricated with Texas sand, while for Springhill aggregate it took place at 450 days. Moreover, the final expansion achieved with this setup was about 0.8% and 0.7% for the reactive sand and coarse aggregate, respectively.

The 100% RH and 0.7 M NaOH setups yielded slower reaction kinetics and lower ultimate expansions when compared to the 1M NaOH soaking solution. Specimens under the 38°C and 100% RH displayed roughly ultimate expansions at 600 days for both aggregate types. The ultimate expansions measured were 0.62% for Tx and 0.6% for Sp. The specimens wrapped in 0.7M NaOH solutions presented roughly the same results as the 38°C and 100% RH specimens but with slower reaction kinetics at the beginning.

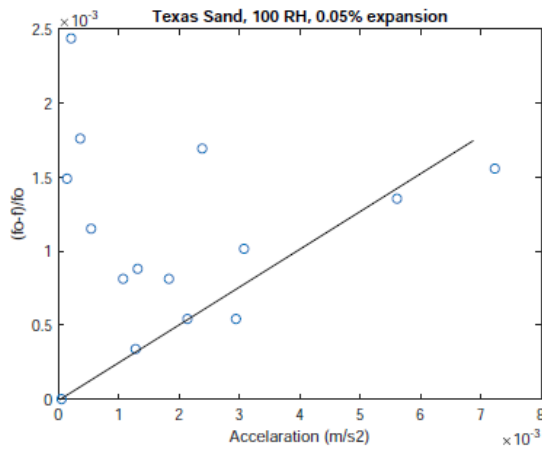
Finally, it is worth noting that the variability among the specimens was lower for the 1M NaOH soaking solution setup, followed by the 0.7 M NaOH and 38°C and 100% RH setups.

### 3.7.2. Nonlinear Impact Resonance Acoustic Spectroscopy (NIRAS) technique

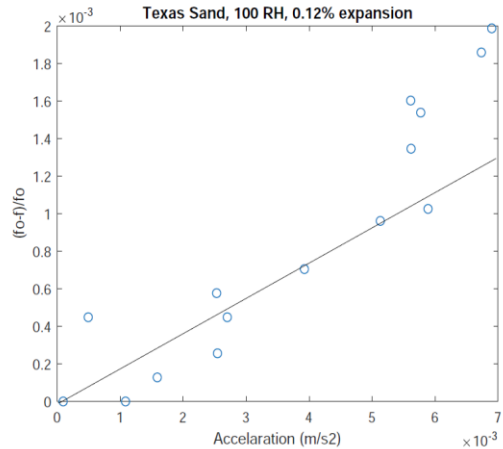
The results from NIRAS test on concrete specimens can be observed in figure 3.3(A-L), for Texas sand, and Figure 3.4(A-L) displays the results with the reactive Springhill coarse aggregate. These results show the average values of the non-linear parameter at different expansion levels in a linear format.

It is anticipated that NIRAS test appraises microcracks and damage in concrete through resonance frequency shift and impact amplitude. Several studies demonstrated that the lower the resonance frequency and the higher the impact amplitude, the higher the concrete damage (J. Chen et al., 2010; X. J. Chen et al., 2008; Leśnicki et al., 2011).

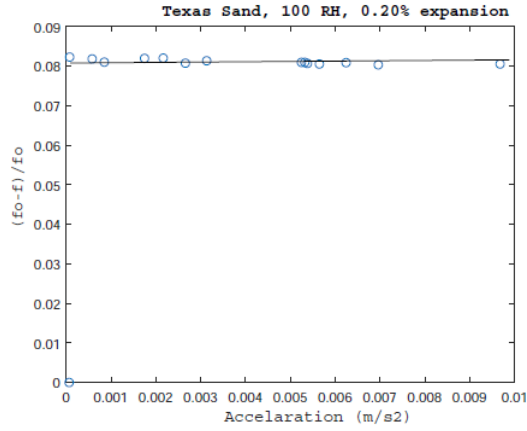
A. Texas sand, 100% RH, 0.05% expansion



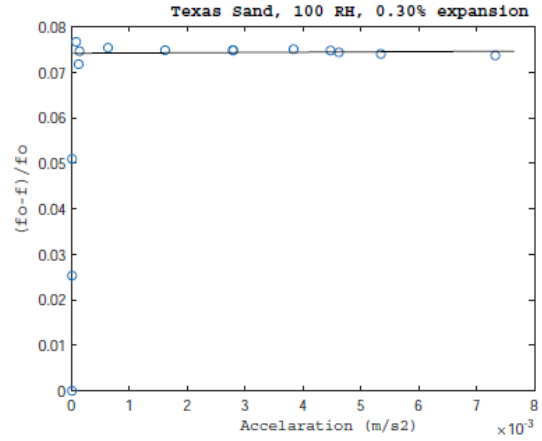
B. Texas sand, 100% RH, 0.12% expansion



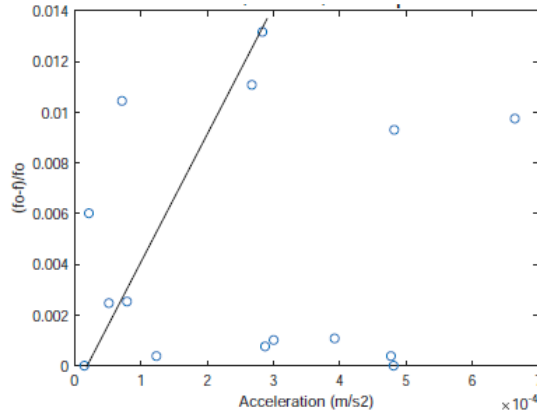
C. Texas sand, 100% RH, 0.2% expansion



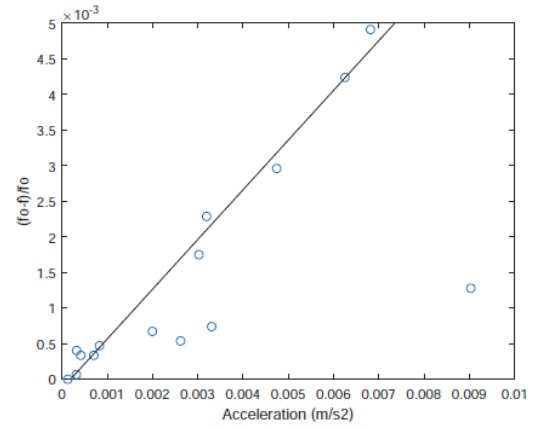
D. Texas sand, 100% RH, 0.3% expansion



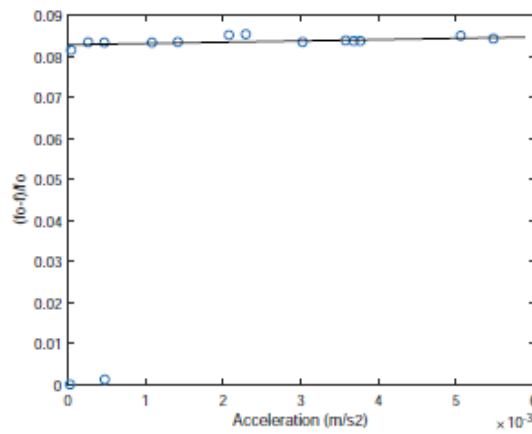
E. Texas sand, 1M NaOH, 0.05% expansion



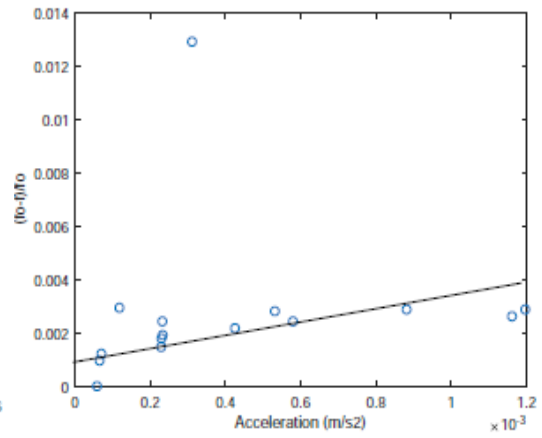
F. Texas sand, 1M NaOH, 0.12% expansion



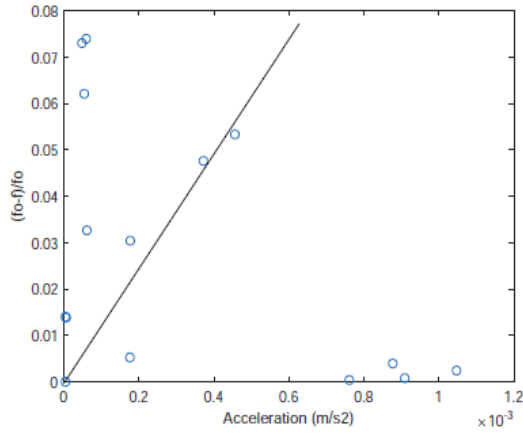
G. Texas sand, 1M NaOH, 0.2% expansion



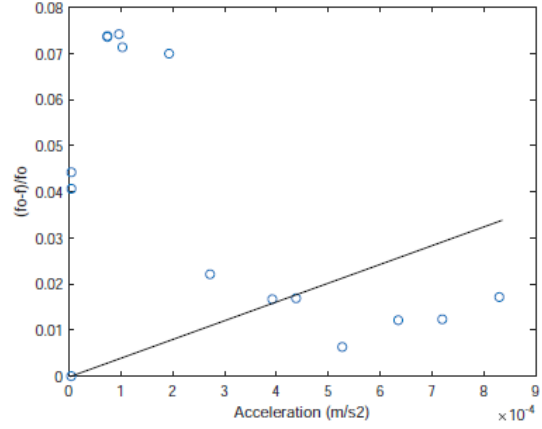
H. Texas sand, 1M NaOH, 0.3% expansion



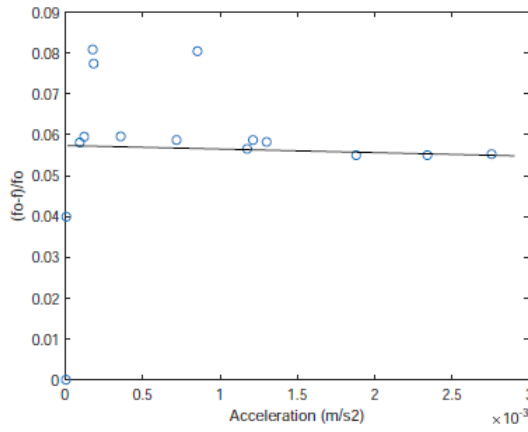
I. Texas sand, 0.7M NaOH, 0.05% expansion



J. Texas sand, 0.7M NaOH, 0.12% expansion



K. Texas sand, 0.7M NaOH, 0.2% expansion



L. Texas sand, 0.7M NaOH, 0.3% expansion

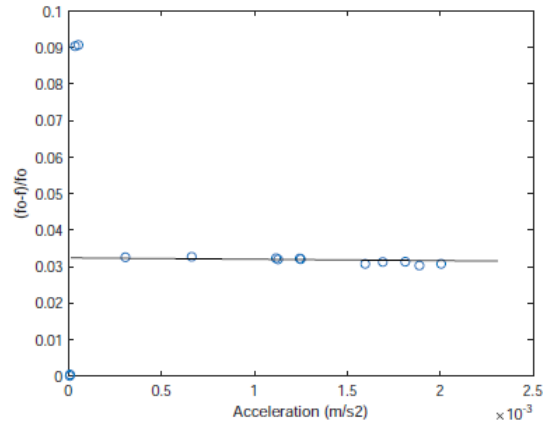
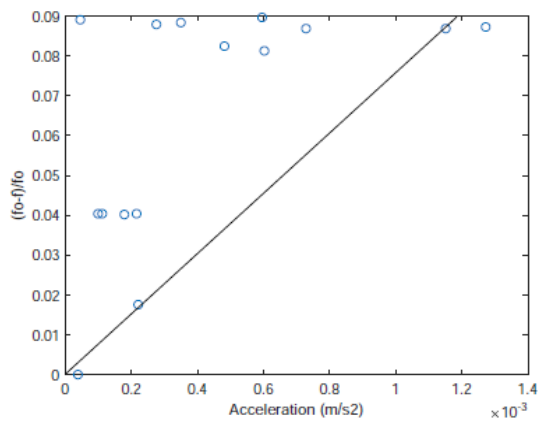
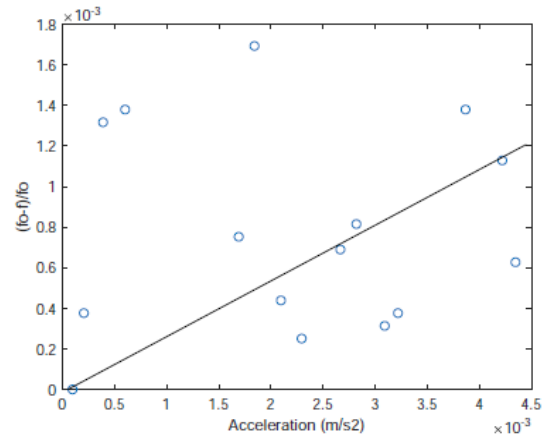


Figure 3.4.: Nonlinearity comparison of different setups at selected expansion levels (Texas sand).

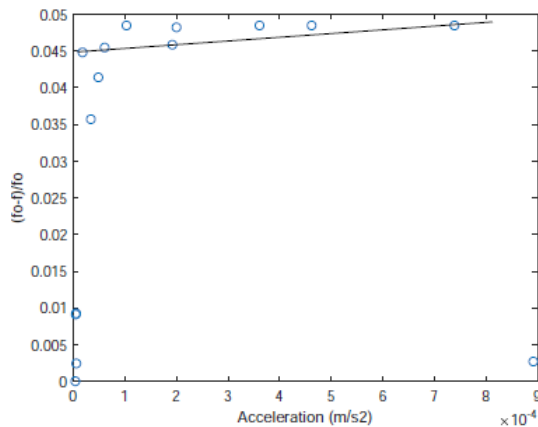
A. Sp coarse, 100% RH, 0.05% expansion



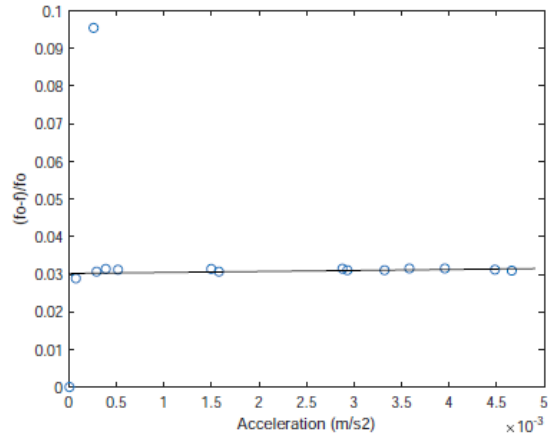
B. Sp coarse, 100% RH, 0.12% expansion



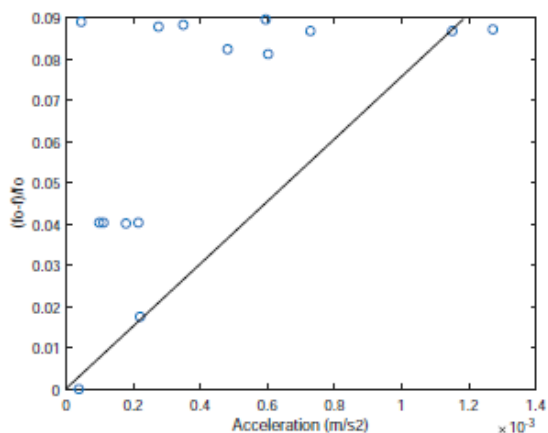
C. Sp coarse, 100% RH, 0.2% expansion



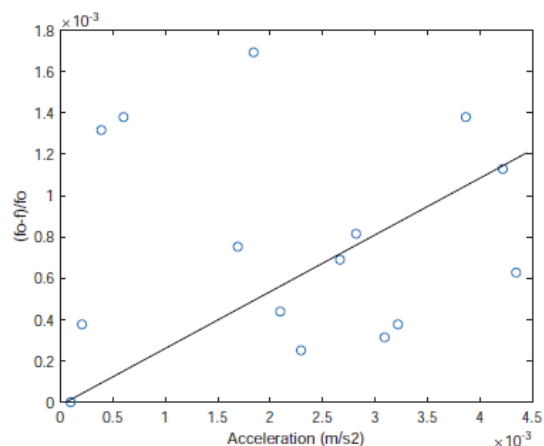
D. Sp coarse, 100% RH, 0.3% expansion



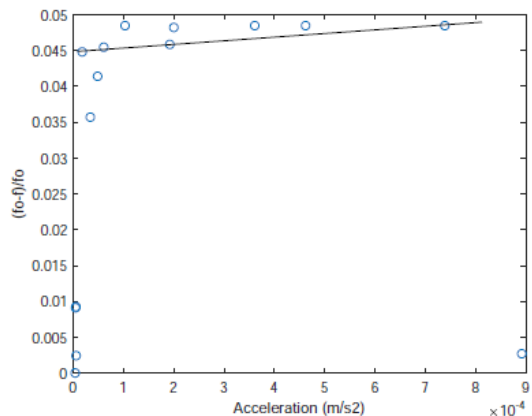
E. Sp coarse, 1M NaOH, 0.05% expansion



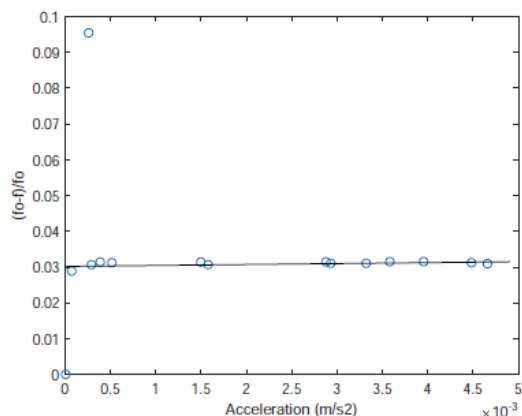
F. Sp coarse, 1M NaOH, 0.12% expansion



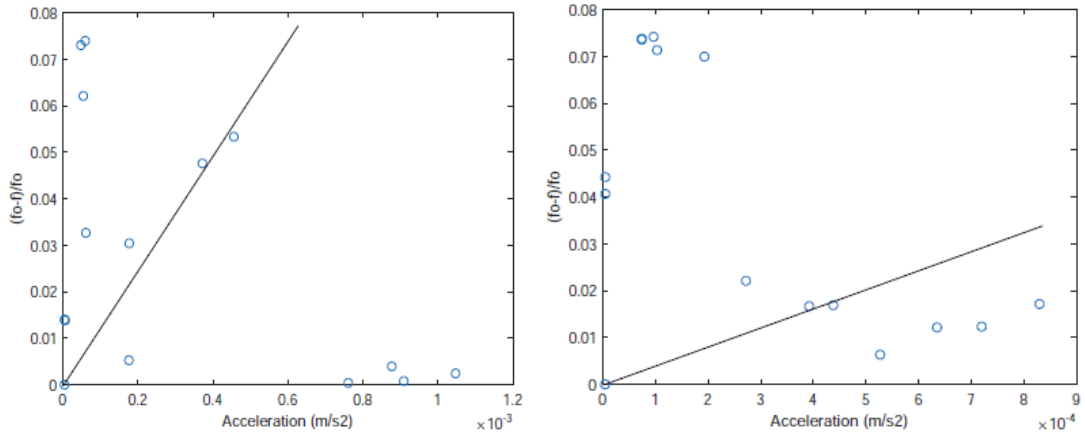
G. Sp coarse, 1M NaOH, 0.2% expansion



H. Sp coarse, 1M NaOH, 0.3% expansion



I. Sp coarse, 0.7M NaOH, 0.05% expansion    J. Sp coarse, 0.7M NaOH, 0.12% expansion



K. Sp coarse, 0.7M NaOH, 0.2% expansion    L. Sp coarse, 0.7M NaOH, 0.3% expansion

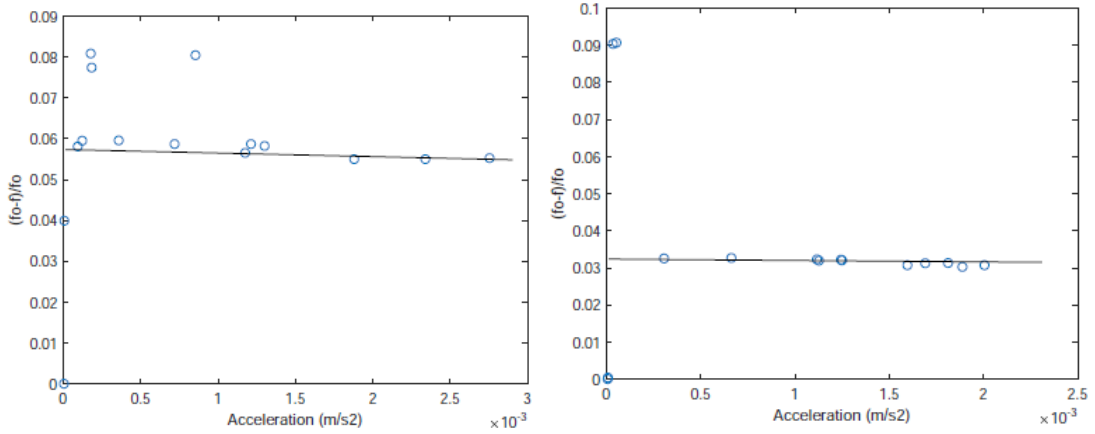


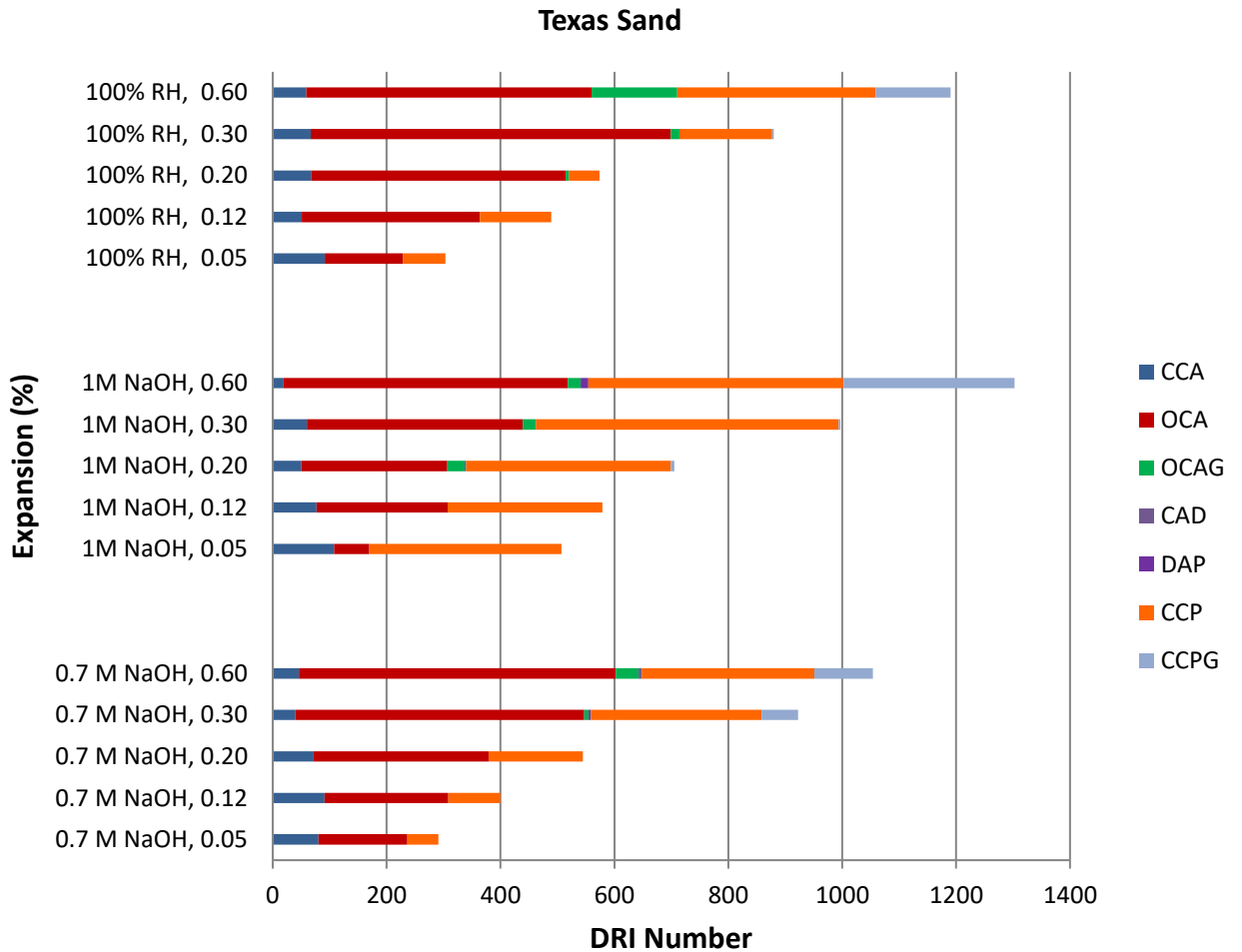
Figure 3.5.: Nonlinearity comparison of different setups at selected expansion levels (Springhill coarse).

Regardless of the aggregate and setup type, one may notice from the data above that at lower expansion level (i.e. 0.05%), the nonlinearity curve is very steep which means that AAR-damage is well captured by the NIRAS technique. As the expansion level increases, the nonlinearity curve (i.e. curve slope) becomes less steep. It should be noted that, the nonlinear parameter considered in this study is extracted by assuming a linear relationship between frequency shift and strain amplitude and the relationship remained linear for all levels of excitation for the sample with low nonlinearity. From 0.20% expansion and onwards, the nonlinearity curve becomes flat, which indicates that NIRAS was not suitable to capture damage at and from this reaction stage.

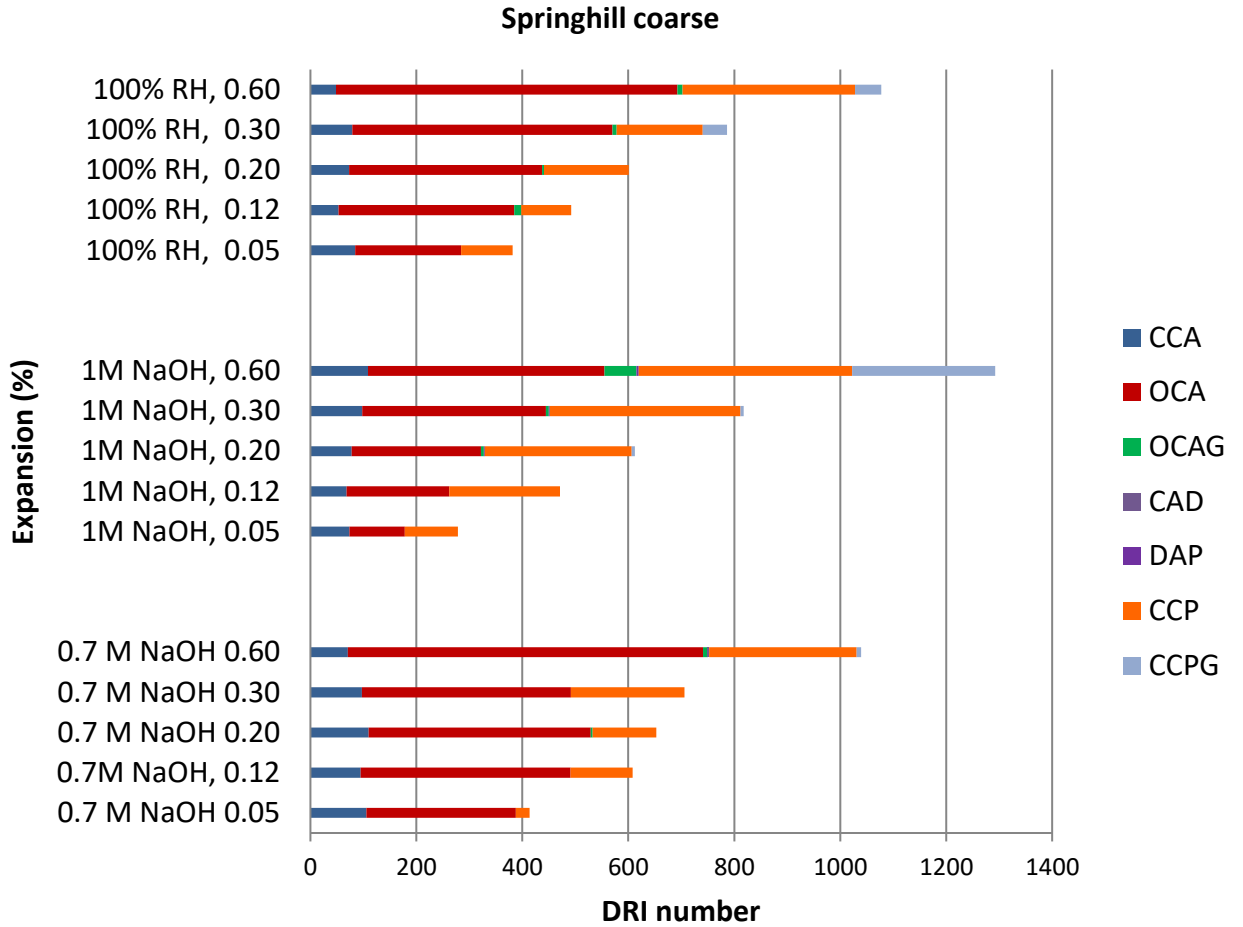
Comparing the test setups, it is clear that the 1M NaOH solution nonlinearity curves obtained were slightly steeper at all expansion levels, for both fine and coarse reactive aggregates. Yet, for the other two setups the results obtained were quite comparable.

### 3.7.3 Damage Rating Index (DRI)

The results of the petrographic analysis in terms of DRI numbers as a function of AAR-induced expansions are presented in Figure 3.6.



(a)



(b)

Figure 3.6.: DRI numbers of concrete specimens in three different setups using reactive sand and coarse aggregates.

It can be observed that the DRI number increases as the expansion level rise, for both aggregate types; the latter indicates that the higher the expansion level, the greater the damage degree, as expected. The number of closed cracks in the aggregate particles (CCA) does not increase with the rise in expansion since it is not a distressing feature linked to AAR-induced development. However, the open cracks in the aggregate particles (with or without reaction products - OCAG and OCA) and the cracks in cement paste (with or without gel - CCPG and CCP) indeed increase as a function of induced expansion.

The DRI numbers are quite similar for fine and coarse reactive aggregates and similar expansion levels; yet they change as a function of the test setup. The 1M NaOH setup shows higher DRI numbers for all expansion levels evaluated in this work. Moreover, the

number of cracks in the cement paste (with or without gel – CCPG and CCP) found for this setup is also higher when compared to the other two different setups. Overall, the DRI numbers ranged from about 300 for low expansion levels (i.e. 0.05%) to about 1200 for very high expansion levels (i.e. 0.6%).

## **3.8. Discussion**

### **3.8.1. Efficiency of NIRAS test for assessing AAR damage**

NIRAS results demonstrate that this test is very responsive in forms of nonlinear features to detect induced cracks and damage formation at early stages of the deterioration process (i.e. lower - 0.05% and moderate - 0.12% expansion levels). However, the procedure showed to be inaccurate to detect the damage progression at high (i.e. 0.20%) and very high (0.30%) expansion levels for all aggregate types and setups studied in this work.

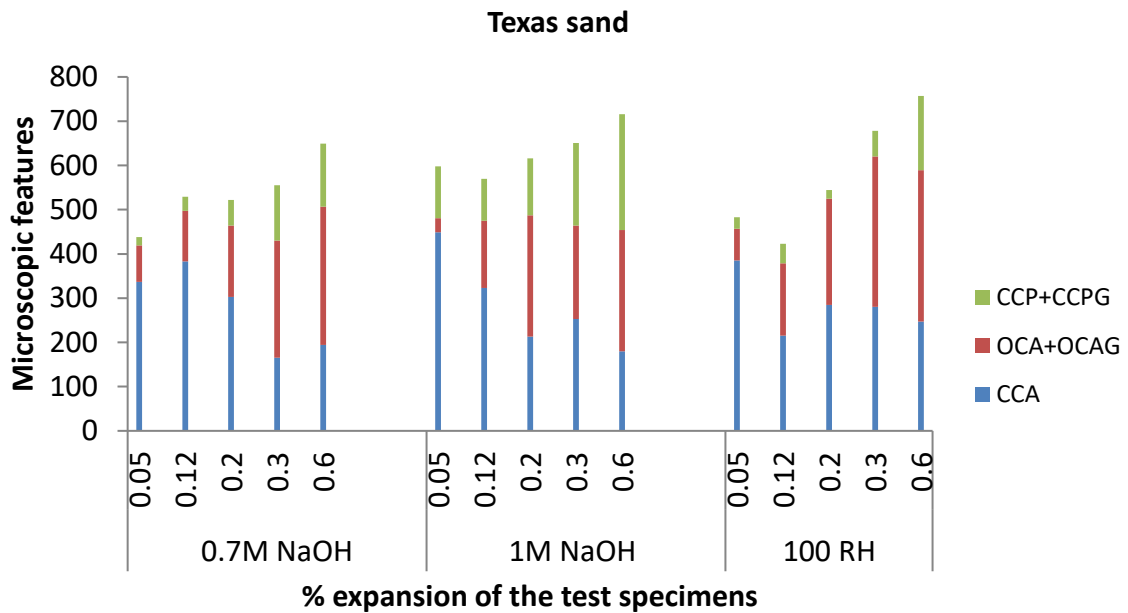
At high and very high levels of induced expansion and deterioration, AAR distress process presents a large number of open cracks within the aggregate particles and cement paste. Moreover, from this point and onwards the amount of reaction products (i.e. AAR gel) increases significantly within the reactive aggregates and in the cement paste. Therefore, the presence of reaction products may somehow harm NIRAS precision to accurately detect AAR net cracking formation and expansion level.

### **3.8.2. Petrographic damage features of AAR-affected concrete**

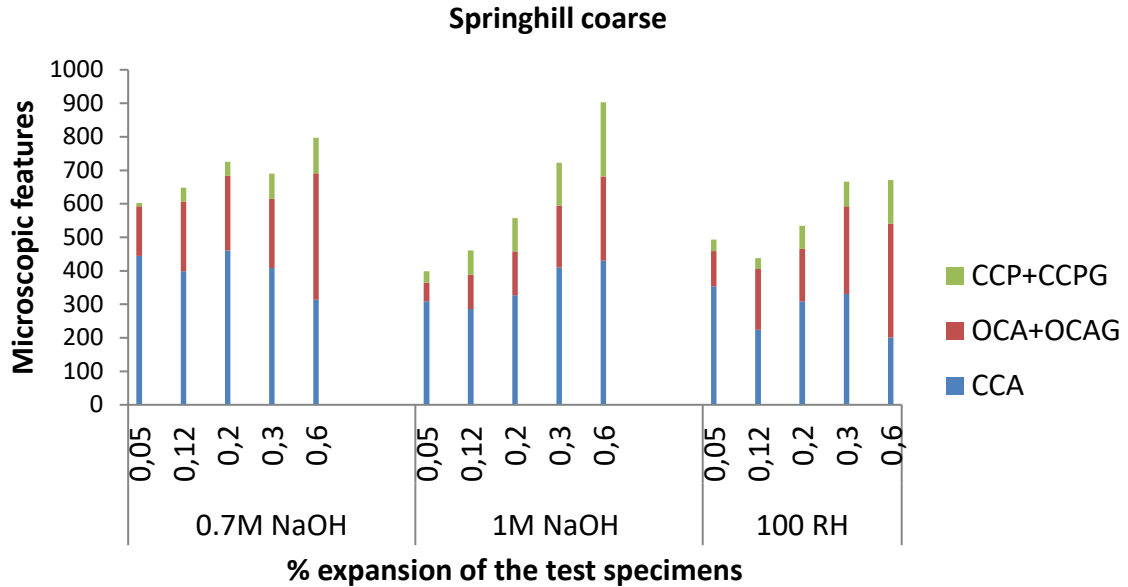
Figure 3.7 compares AAR-induced development through the evaluation of the distress features in counts (i.e. numbers) without accounting for the weighing factors proposed to perform the DRI technique. Evaluating the data, one observes that the most recurrent damage feature found in the closed cracks within the aggregates (CCA), regardless of the setup used or aggregate type. Yet, as mentioned before, CCA is not an AAR features and thus may be linked to the mineralogy of the aggregates, along with crushing and

weathering processes. If one disregards CCA features, then one verifies that the higher the expansion level, the higher the cracks within the aggregate particles (OCA + OCAG) and cement paste (CCA + CCAG) for the two aggregate tested and setups evaluated. The latter was expected and shows indeed AAR-induced development.

If one compares the features displayed according to the distinct setups, it is observed that the 1M NaOH setup distress process shows a much higher number of cracks in the cement paste than the other two setups (100% RH and 0.7M NaOH) for all the expansion levels. The latter seems to indicate that perhaps the damage process developed in the setup is different from the others. Moreover, there is no clear difference between the features observed for AAR-affected concrete when the damage comes from reactive sand versus a reactive coarse aggregate.



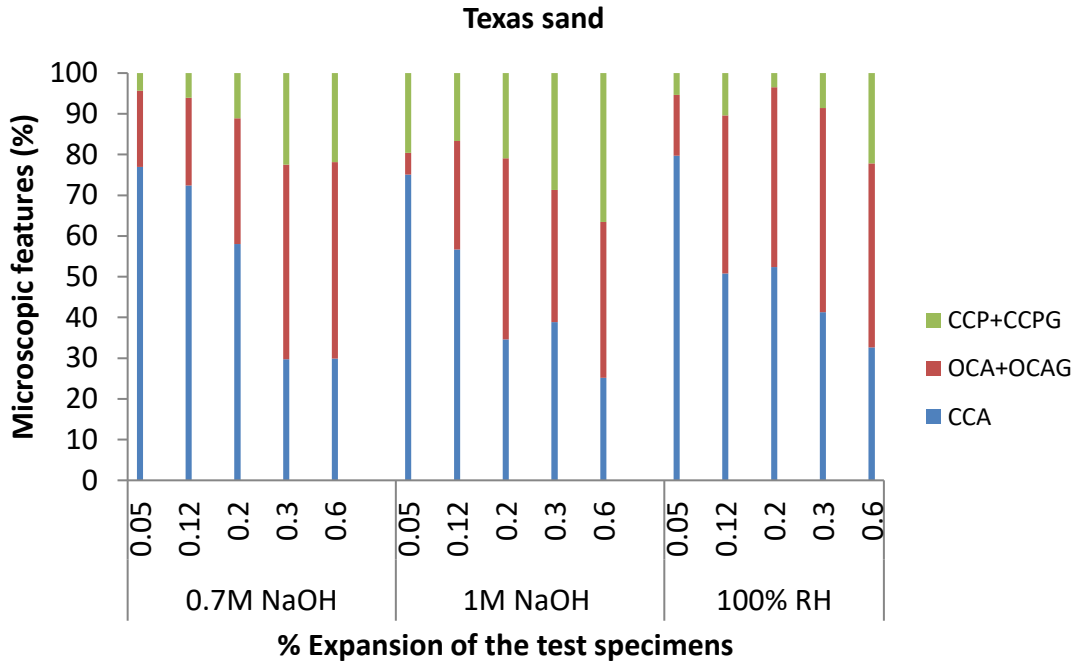
(a)



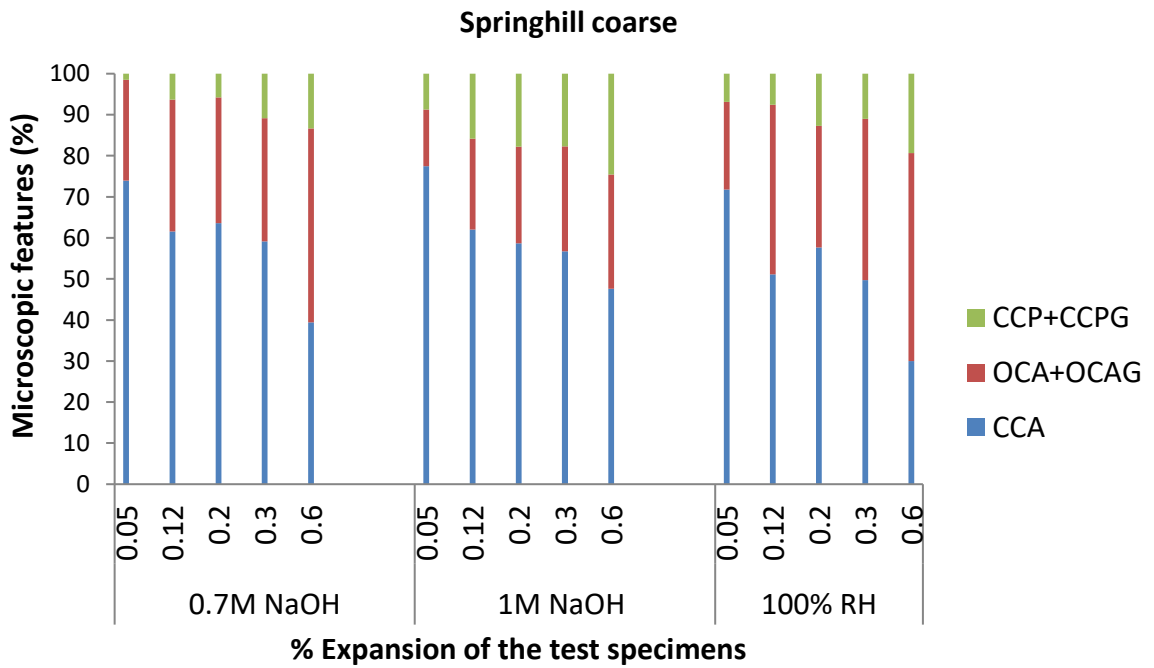
(b)

Figure 3.7: Microscopic features of AAR damage in counts without weighing factors normalized for 100 cm<sup>2</sup> surface area for three different setups.

Maybe an easier way to compare the evolution of damage as a function of the expansion, aggregate types and setups are to evaluate the microscopic distress features in (%). Figure 3.8 illustrates these features. At lower expansion levels and as prior mentioned, the closed cracks in the aggregates (CCA) represent the highest damage features found, being roughly 70% of the features found. AS the expansion levels increase, CCA lessens in importance and OCA + OCAG and CCP and CCPG increase. For high and very high values of expansion, these cracks represent already 70% of the overall AAR-distress. The percentages do not seem to be significantly different from one setup to the other, yet, the CCP and CCPG cracks for the 1 M NaOH setup seems higher for all expansion levels and aggregate types.



(a)

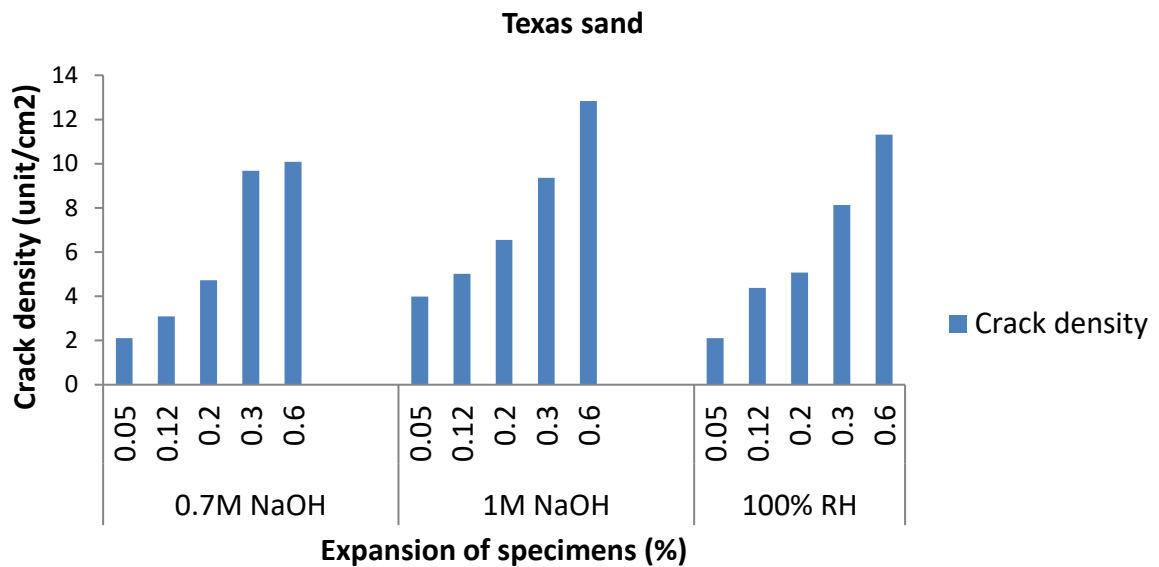


(b)

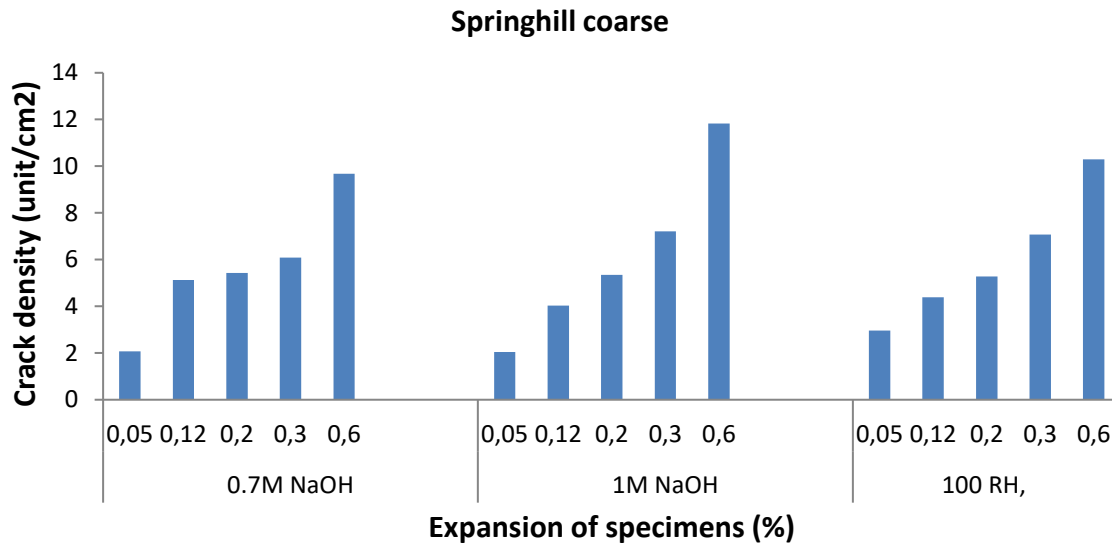
Figure 3.8.: Microscopic features of AAR damage (in % without weighing factor) normalized for 100 cm<sup>2</sup> surface area for three different setups

The crack density (i.e. the number of cracks in counts/ area in  $\text{cm}^2$ ) as a function of expansion level for all the setups and aggregates is displayed in Figure 3.9. It is worth noting that to calculate the cracking index, only the open cracks were accounted for (i.e. OCA and OCAG and CCP and CCPG) for all expansion levels. From the data below, one verifies that the higher the expansion level, the higher the overall cracking index, as expected. The cracking index results varied from 2 for low expansion levels to 12 for very high expansion levels. Moreover, similar results were obtained from AAR coming from the reactive Texas (Tx) sand when compared to the reactive Springhill (Sp) aggregate.

Comparing the distinct test setups, the 1M NaOH setup specimens experienced higher crack density when compared to the other setups for most of the expansion levels and two aggregate types. The crack density values obtained from the other two setups were quite similar.



(a)



(b)

Figure 3.9.: Crack density normalized to counts/cm<sup>2</sup> as a function of expansion.

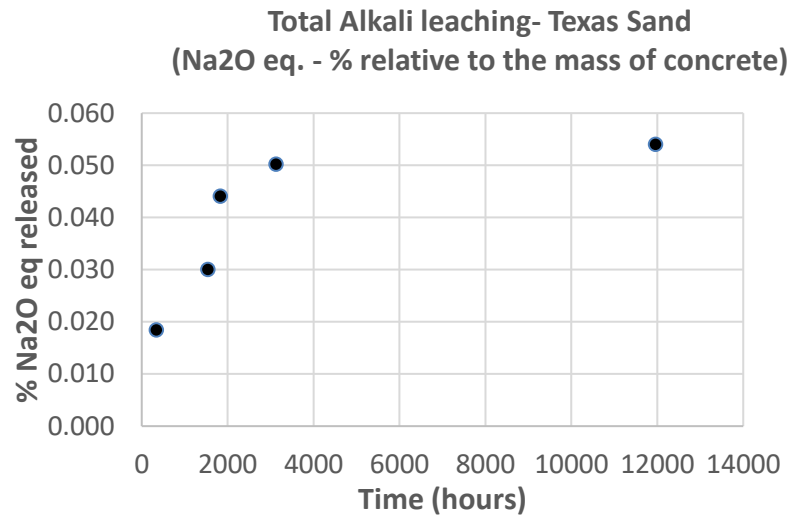
### 3.8.3. AAR-induced expansion vs setups

The expansion vs. time plot presented in section 3.7.1 compares and evaluates the variations in expansion for the different setups. Although the average expansion increases as a function of time for all setups, the expansion curve (or in other words, expansion kinetics) for specimens soaked in 1M NaOH solution at 38°C was faster when compared to specimens stored at the other two conditions (which showed similar reaction kinetics).

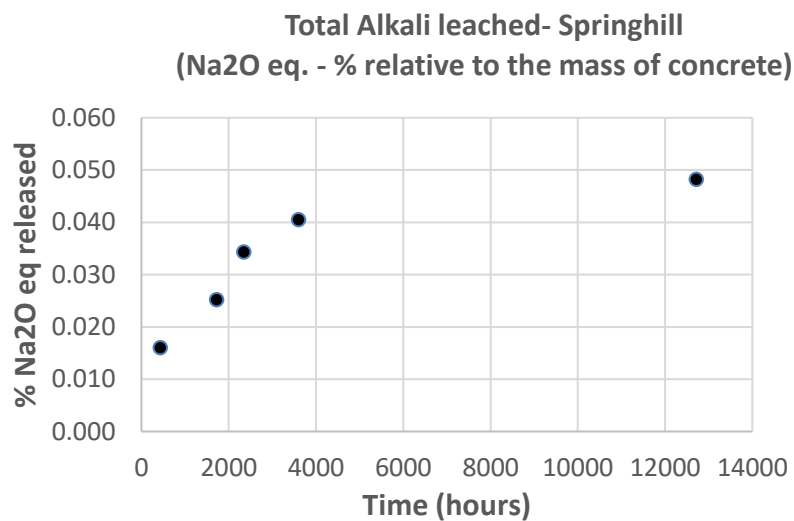
The above information seems to indicate that AAR-induced development in the 1M NaOH setup is somehow different from the others. Previous petrographic analysis already verified the presence of an important and greater amount of cracks in the cement paste for this setup when compared to others. Yet, there might have been beneficial to have chemical explanations or at least evidences for the differences found in the induced expansion and distress processes from the setups.

Trying to answer the above question (at least partially), samples were taken from the water film from the 100% RH setup at distinct time periods. Then, atomic absorption tests

were conducted to obtain the amount of Na and K (in percentage) presented in the samples reclaimed at different ages. Finally, the values were converted to the so-called alkali equivalent, expressed by  $\text{Na}_2\text{O}_e$  (i.e.  $\% \text{Na}_2\text{O} + 0.6583 \% \text{K}_2\text{O}$ ) and are illustrated in Figure 3.10.



(a)



(b)

Figure 3.10.: Total alkali leaching expressed in terms of  $\% \text{Na}_2\text{O}_e$  from 100% RH setup over time for reactive sand and coarse aggregate

The data above clearly indicates that the samples retrieved from the water film from the 100% RH setup presented an increase in alkali equivalent (i.e.  $\text{Na}_2\text{O}_e$ ) over time, which indicates that some alkalis are being leached out from the concrete samples. The latter explains the slower reaction kinetics and lower ultimate expansion values obtained on samples tested at 100% RH when compared to the 1M NaOH setup. Conversely, it is worth mentioning that preliminary evaluations on the solutions used in both 1M NaOH and 0.7M NaOH setups did not yield conclusive results. Therefore, further research is still required to understand why the kinetics of the 0.7M samples was slower and the ultimate expansion lower when compared to the 1 M NaOH solution samples.

Finally, pictures taken from samples displaying 0.30% expansion from the three setups used illustrate once more their difference in color of the distinct setup, which suggest that the reaction products might have been formed differently at those conditions. The below pictures also suggest the presence of whitish products (probably AAR gel) being leached from the samples, especially in samples A and C, whereas a brownish color is found for samples b (i.e. 1 M NaOH), which could indicate differences in composition and viscosity.

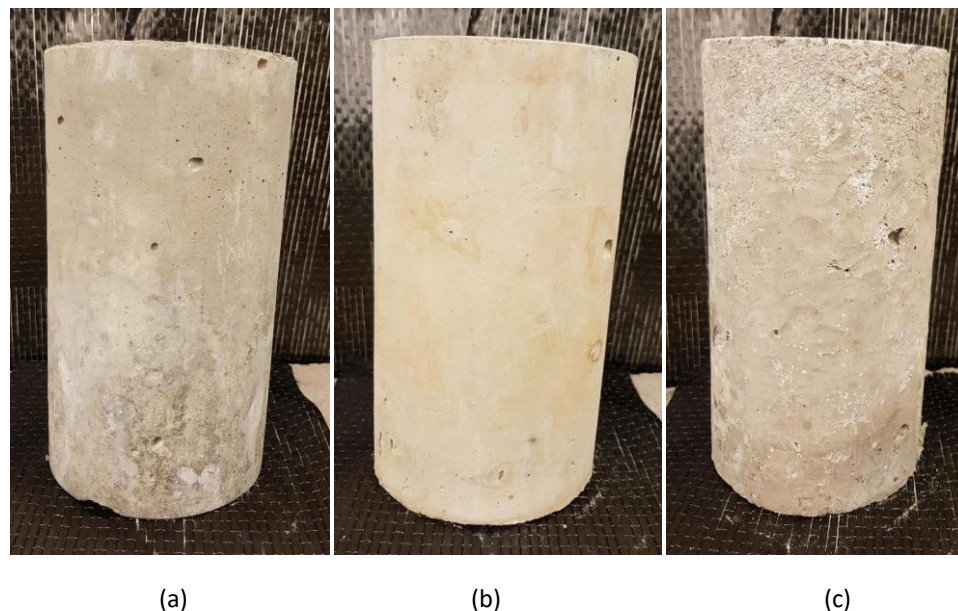


Figure 3.11.: Concrete specimens from different setups at 0.3% expansion level: (a) 38°C and 100% R.H. setup; (b) 1M NaOH solution at 38°C setup; (c) samples wrapped with sponge soaked in 0.7M NaOH at 38°C setup

### 3.8.4. AAR proposed damage model

Sanchez et al. (Sanchez, Fournier, Jolin, & Duchesne, 2015) proposed a qualitative and descriptive model to explain AAR damage in concrete based on a wide range of affected specimens evaluated in the laboratory. According to this model (Figure 3.12, AAR-induced damage development comprises two types of cracks: sharp cracks (A), which are cracks that tend to cut the aggregate particles in parts and, onion skin cracks (B), which are cracks that outline the aggregate particles.

According to Sanchez et al. (Sanchez, Fournier, Jolin, & Duchesne, 2015), AAR-induced damage progress starts with cracks A and B and developed within the aggregate particles for low expansion levels (i.e. 0.05%). As the expansion levels raises, new A and B cracks are developed in the system, but more importantly, pre-existing A and B cracks formed at 0.05% keep increasing in length and width. At moderate expansion levels (0.12%), type A cracks reach the cement paste, at least at one side of the aggregate particle. At high levels of damage (i.e. 0.20%), type A cracks are already at the cement paste at the two sides of the aggregate particle while type B cracks have almost finished outlining that given particle. Finally, at very high levels of expansion and onwards, the cracks formed in distinct particles reach them out in the cement paste and form a high crack networking, which directly impacts on the mechanical properties of the affected material.

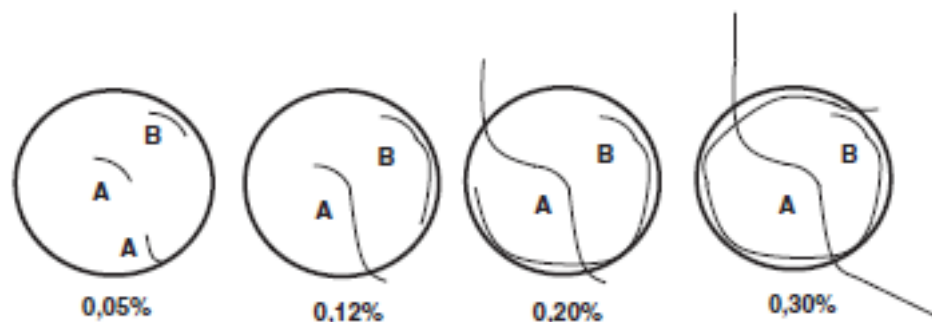
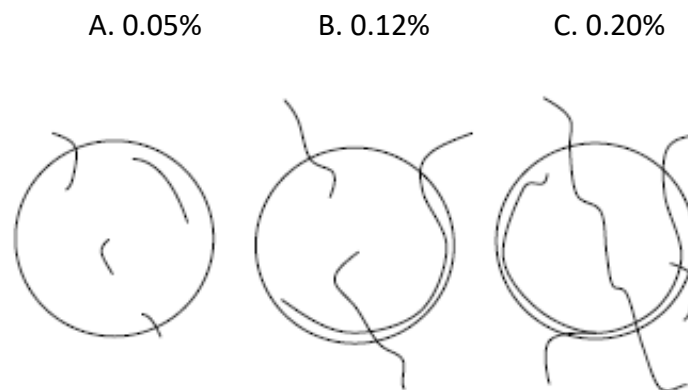


Figure 3.12: Qualitative AAR damage model at different expansion levels (Sanchez, Fournier, Jolin, & Duchesne, 2015)

The model proposed by Sanchez et al. (Sanchez, Fournier, Jolin, & Duchesne, 2015) represents the common cracking pattern of AAR-induced damage and development at various expansion stages. In this study, similar patterns were observed for specimens at 100% RH and 0.7M NaOH setups at similar expansion levels. Yet, specimens soaked in 1M NaOH setup showed a different pattern progress as per Figure 3.13 At early damage stages (0.05% expansion), sharp and onion skin cracks (A and B) were observed within the aggregate particles as per Sanchez's model; however several of them extended to the cement paste, which was even more evident for moderate expansion levels (i.e. 0.12%). These cracks start building a cracking network and some aggregates start de-bonding at high and very high (0.2% and 0.3%) expansion levels.



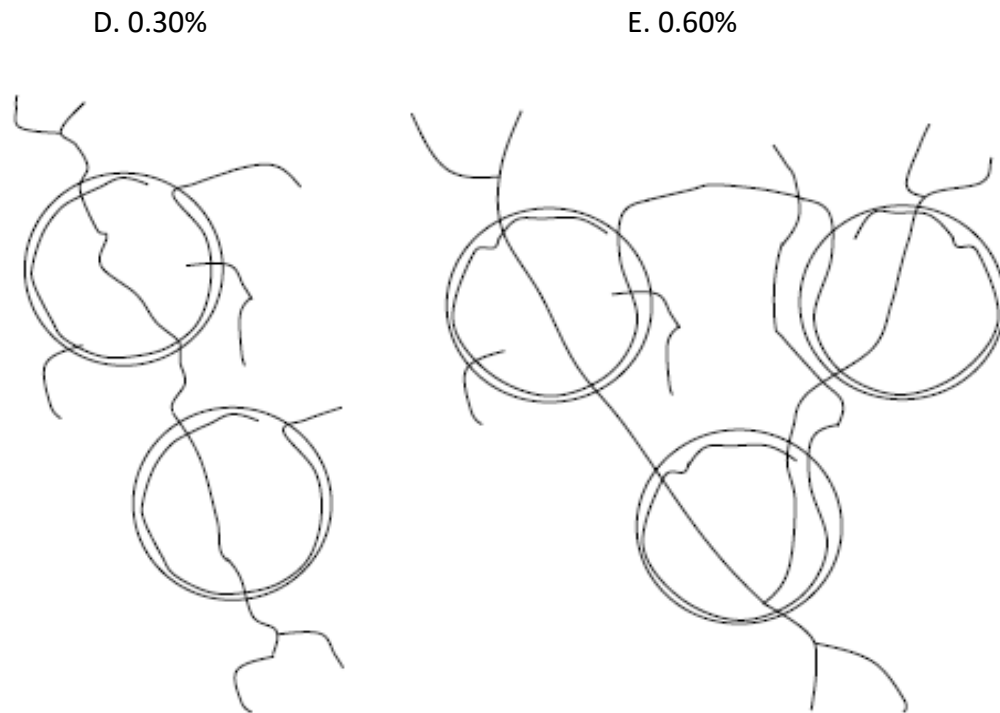


Figure 3.13- AAR damage model at various expansion levels in 1M NaOH setup.

At the maximum expansion level reached (0.6%), multiple cracks in the aggregates and cement paste are observed and the presence of important de-bonding is verified. Comparison of this model with the one proposed by Sanchez et al. (Sanchez, Fournier, Jolin, & Duchesne, 2015), adding to all the prior visual, chemical and petrographic evaluations, seems to evidence that the 1M NaOH setup provides the specimens with a faster and different damage mechanism than the other setups that display a more expected and closer to the field damage behavior.

### 3.9. Conclusion

The main goal of the current research was to better understand the outcomes yielded by two of the most used residual expansion setups, used to study the potential of further AAR-induced expansion in concrete. Moreover, a novel test setup was proposed and compared to the two existing procedures. The main findings of the current research are presented hereafter:

- The NIRAS test has been found effective to understand and detect the damage degree up to moderate level (0.12%); yet, the method showed to be inaccurate to appraise AAR-affected concrete at high and very high induced expansion and distress levels. The latter might be at least partially due to the AAR-gel formation that significantly raises at these damage levels. Further analysis is still required to better understand how the technique could be applied to appraise high levels of AAR damage;
- The DRI was found very effective, not only to describe AAR-induced expansion and damage from one reactive aggregate to another, but rather to compare setups to each other. The results clearly indicated that the proposed setup and the 100% RH protocol provide evaluated samples with the same distress mechanism. Conversely, its analysis evidenced that the 1M NaOH setup triggers a distinct damage process in the affected samples;
- The 1 M NaOH setup seems to be much more aggressive than the proposed setup (i.e. 0.7 M NaOH) and the 100% RH procedure. The reaction kinetics and ultimate expansion gathered for this particular test was faster and higher respectively. Moreover, the crack pattern found in samples deteriorated using this setup was very different from the model proposed by Sanchez et al. [19] and the other two setups studied;
- The proposed setup (i.e. wrapped samples in 0.7M NaOH solution at 38°C) seemed to be effective to provide samples with a similar damage mechanism than expected in the field and as per Sanchez et al. [19]. Yet, its kinetics and ultimate expansion were slower and the same respectively, when compared with the 100% RH setup. The latter lessens its impact, since it is known that the 100% RH setup does not react as fast as it should nor swell as high as it has potential for due to alkali leaching. Thus, further studies are still needed to better understand and improve the reaction kinetics found with this setup.
- Chemical analysis of the solutions from each setup at distinct expansion levels clearly shows that all the setups demonstrate some leaching; thus, the alkalinity of the water and solution increases over time for all procedures. This suggests that either the potential of further expansion is not being accurately measured due to this “lost” of alkalis from the

system or some reaction products are being deposited in the water or solutions (or both). Further studies are still required on this topic.

### 3.10. References

- A23.2-28A, C. (2014). *Standard practice for laboratory testing to demonstrate the effectiveness of supplementary cementing materials and lithium-based admixtures to prevent alkali-silica reaction in concrete.*
- ASSHTO. (2011). AASHTO Guide Manual for Bridge Element Inspection - 1st Edition - 2011.pdf. In *Bridge Element Inspection Manual.*
- ASTM, C. (2008). *1293 Standard test method for determination of length change of concrete due to alkali-silica reaction.* ASTM International.
- ASTM Committee C09.65. (2012). ASTM C295-12 Standard Guide for Petrographic Examination of Aggregates for Concrete. In *Annual Book of ASTM Standards Volume 04.02.* [https://doi.org/10.1520/C0295\\_C0295M-12](https://doi.org/10.1520/C0295_C0295M-12)
- ASTM International. (2009). ASTM C1293-01: Standard Test Method for Length Change of Concrete Due to Alkali-Carbonate Rock. *Annual Book of ASTM Standards.* <https://doi.org/10.1520/C1105-08A.2>
- Benoit Fournier, Marc-André Bérubé, Kevin J. Folliard, M. T. (2010). Report on ASR Mitigation. *Federal Highway Administration Publications FHWA-HRT-04-113 (2004) and Techbrief FHWA-HRT-06-071.*
- Bérubé, M. A., Duchesne, J., Dorion, J. F., & Rivest, M. (2002). Laboratory assessment of alkali contribution by aggregates to concrete and application to concrete structures affected by alkali-silica reactivity. *Cement and Concrete Research.* [https://doi.org/10.1016/S0008-8846\(02\)00766-4](https://doi.org/10.1016/S0008-8846(02)00766-4)
- Bérubé, M. A., Smaoui, N., Fournier, B., Bissonnette, B., & Durand, B. (2005). 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(3), 463–479. <https://doi.org/10.1139/L04-104>

- Blight, G. E., & Alexander, M. G. (2011). Alkali-Aggregate Reaction and Structural Damage to Concrete. In *Alkali-Aggregate Reaction and Structural Damage to Concrete*.  
<https://doi.org/10.1201/b10773>
- Bruno Godart, Mario de Rooij, J. G. M. W. (2013). *Guide to Diagnosis and Appraisal of AAR Damage to Concrete in Structures: Part 1 Diagnosis* (J. G. M. W. Bruno, Mario de Rooij (ed.)). Springer Netherlands.
- Buck, O., Morris, W. L., & Richardson, J. M. (1978). Acoustic harmonic generation at unbonded interfaces and fatigue cracks. *Applied Physics Letters*.  
<https://doi.org/10.1063/1.90399>
- Carles-Gibergues, A., & Cyr, M. (2002). Interpretation of expansion curves of concrete subjected to accelerated alkali-aggregate reaction (AAR) tests. *Cement and Concrete Research*. [https://doi.org/10.1016/S0008-8846\(01\)00747-5](https://doi.org/10.1016/S0008-8846(01)00747-5)
- Chen, J., Jayapalan, A. R., Kim, J. Y., Kurtis, K. E., & Jacobs, L. J. (2010). Rapid evaluation of alkali-silica reactivity of aggregates using a nonlinear resonance spectroscopy technique. *Cement and Concrete Research*.  
<https://doi.org/10.1016/j.cemconres.2010.01.003>
- Chen, W., Hao, H., Jong, M., Cui, J., Shi, Y., & Chen, L. (2017). Quasi-static and dynamic tensile properties of basalt fibre reinforced polymer Quasi-static and dynamic tensile properties of basalt fibre reinforced polymer. *Composites Part B*, 125(May), 123–133. <https://doi.org/10.1016/j.compositesb.2017.05.069>
- Chen, X. J., Kim, J. Y., Kurtis, K. E., Qu, J., Shen, C. W., & Jacobs, L. J. (2008). Characterization of progressive microcracking in Portland cement mortar using nonlinear ultrasonics. *NDT and E International*.  
<https://doi.org/10.1016/j.ndteint.2007.08.009>
- Crawford, B., Kasmidi, M., Korompis, F., & Pollnac, R. B. (2006). Factors influencing progress in establishing community-based marine protected areas in Indonesia. *Coastal Management*. <https://doi.org/10.1080/08920750500379300>
- CSA A23.1. (2014). Concrete Materials and Methods of Concrete Construction. In *Canadian Standards Association: Vol. APPENDIX B*.

- CSA A23.2-14A. (2014). *Potential expansivity of aggregates (Procedure for Length Change due to Alkali-Aggregate Reaction in Concrete Prisms at 38°C)*. Canadian Standards Association.
- Den Abeele, K. E. A. V., Carmeliet, J., Ten Cate, J. A., & Johnson, P. A. (2000). Nonlinear elastic wave spectroscopy (NEWS) techniques to discern material damage, Part II: Single-mode nonlinear resonance acoustic spectroscopy. *Research in Nondestructive Evaluation*, 12(1), 31–42. <https://doi.org/10.1080/09349840009409647>
- Den Abeele, K. E. A. V., Johnson, P. A., & Sutin, A. (2000). Nonlinear elastic wave spectroscopy (NEWS) techniques to discern material damage, Part I: Nonlinear wave modulation spectroscopy (NWMS). *Research in Nondestructive Evaluation*. <https://doi.org/10.1080/09349840009409646>
- ElMohandes, F., & Vecchio, F. J. (2013). *VecTor3: A. User's Manual; B. Sample Coupled Thermal and Structural Analysis*. November, 43–119. <https://doi.org/10.1016/B978-0-12-398460-9.00002-0>
- Farny, J. A., & Kerkhoff, B. (2007). Diagnosis and Control of Alkali-Aggregate Reactions in Concrete. *Portland Cement Association*, 1–24. [http://www.cement.org/docs/default-source/fc\\_concrete\\_technology/is413-02---diagnosis-and-control-of-alkali-aggregate-reactions-in-concrete.pdf?sfvrsn=2](http://www.cement.org/docs/default-source/fc_concrete_technology/is413-02---diagnosis-and-control-of-alkali-aggregate-reactions-in-concrete.pdf?sfvrsn=2)
- Fernandes, I., & Broekmans, M. A. T. M. (2013). Alkali-Silica Reactions: An Overview. Part I. *Metallography, Microstructure, and Analysis*, 2(4), 257–267. <https://doi.org/10.1007/s13632-013-0085-5>
- Forster, S. W., Boone, R. L., Hammer, M. S., Lamond, J. F., Lane, D. S., Miller, R. E., Parker, S. E., Pergalsky, A., Pierce, J. S., Robert, M. Q., Schmitt, J. W., & Tobin, R. E. (1998). *State-of-the-Art Report on Alkali-Aggregate Reactivity Reported by ACI Committee 221. 98(Reapproved)*, 1–31.
- Fournier, Benoit, & Bérubé, M.-A. (2000). Alkali-Aggregate Reaction in Concrete: a Review of Basic Concepts and Engineering Implications. *Canadian Journal of Civil Engineering*, 27, 167–191. <https://doi.org/10.1139/l99-072>
- Fournier, Benoît, Bérubé, M., Thomas, M. D. A., Smaoui, N., & Folliard, K. J. (2004).

- Evaluation and Management of Concrete Structures Affected by Alkali-Silica Reaction – A Review. *Seventh CANMET/ACI International Conference on Recent Advances in Concrete Technology*, 5(Mai), 1–60.
- Gao, X. X., Multon, S., Cyr, M., & Sellier, A. (2011a). Optimising an expansion test for the assessment of alkali-silica reaction in concrete structures. *Materials and Structures/Materiaux et Constructions*, 44(9), 1641–1653.  
<https://doi.org/10.1617/s11527-011-9724-y>
- Gao, X. X., Multon, S., Cyr, M., & Sellier, A. (2011b). Optimising an expansion test for the assessment of alkali-silica reaction in concrete structures. *Materials and Structures/Materiaux et Constructions*. <https://doi.org/10.1617/s11527-011-9724-y>
- Godart, Bruno; Wood, Jonathan G. M.; de Rooij, M. (2013). *Guide to Diagnosis and Appraisal of AAR Damage to Concrete in Structures* (M. Godart, Bruno; Wood, Jonathan G. M.; de Rooij (ed.)). Springer Netherlands.
- Grattan-Bellew, P.; Danay, A. (1992). Comparison of laboratory and field evaluation of alkali-silica reaction in large dams. *International Conference on Concrete AAR in Hydroelectric Plants and Dams*.
- Kraig Warnemuende, Hwai-Chung Wu. (2004). Actively modulated acoustic nondestructive evaluation of concrete. *Cement and Concrete Research, Volume 34*(Issue 4), Pages 563-570.
- Leśnicki, K. J., Kim, J. Y., Kurtis, K. E., & Jacobs, L. J. (2011). Characterization of ASR damage in concrete using nonlinear impact resonance acoustic spectroscopy technique. *NDT and E International*, 44(8), 721–727. <https://doi.org/10.1016/j.ndteint.2011.07.010>
- M. D. A. Thomas, B. Fournier, & K. J. Folliard. (2013). Alkali-Aggregate Reactivity (AAR) Facts Book. *Book*, 224.
- Maarten A.T.M. Broekmans. (2002). *the Alkali-Silica Reaction : Aspects of Some Dutch Concretes*. 217.
- Meissner, H. S. (1941). Cracking in Concrete Due to Expansive Reaction Between Aggregate and High-Alkali Cement as Evidenced in Parker Dam. *ACI Journal Proceedings*, 37.

- Merz, C., & Leemann, A. (2013). Assessment of the residual expansion potential of concrete from structures damaged by AAR. *Cement and Concrete Research*, 52(November 2017), 182–189. <https://doi.org/10.1016/j.cemconres.2013.07.001>
- Mindess, A., & Francis, J. (2003). *Concrete* (2nd ed.). Prentice Hall, Pearson Education, Inc. Upper Saddle River, NJ 07458, U.S.A.
- Multon, S. (2004). Evaluation expérimentale et théorique des effets mécaniques de l'alcali-réaction sur des structures modèles. In *Etudes et recherches des Laboratoires des ponts et chaussées. Série Ouvrages d'art*.
- Multon, S., Sellier, A., & Cyr, M. (2009). Chemo-mechanical modeling for prediction of alkali silica reaction (ASR) expansion. *Cement and Concrete Research*, 39(6), 490–500. <https://doi.org/10.1016/j.cemconres.2009.03.007>
- Nixon, P. J; Bollinghaus, R. (1985). The effect of alkali aggregate reaction on the tensile and compressive strength of concrete. *Durability of Building Materials. 1985, Vol 2, Num 3, Pp 243-248 ; Ref : 5 Ref, Vol 2(Num 3), pp 243-248 ; ref : 5 ref.*
- Nixon, P. J., & Sims, I. (2015). RILEM recommendations for the prevention of damage by alkali-aggregate reactions in new concrete structures: State-of-the-Art report of the RILEM technical committee 219-ACS. In *RILEM Recommendations for the Prevention of Damage by Alkali-Aggregate Reactions in New Concrete Structures: State-of-the-Art Report of the RILEM Technical Committee 219-ACS*. <https://doi.org/10.1007/978-94-017-7252-5>
- Noël, M., Sanchez, L., & Tawil, D. (2018). Structural implications of internal swelling reactions in concrete: Review and research needs. *Magazine of Concrete Research*, 70(20), 1052–1063. <https://doi.org/10.1680/jmacr.17.00383>
- Paul, S. C., Pirskawetz, S., Van Zijl, G. P. A. G., & Schmidt, W. (2015). Acoustic emission for characterising the crack propagation in strain-hardening cement-based composites (SHCC). *Cement and Concrete Research*, 69, 19–24. <https://doi.org/10.1016/j.cemconres.2014.12.003>
- R.B. Figueira, R. Sousa, L. Coelho, M. Azenha, J.M. de Almeida, P.A.S. Jorge, C. J. R. S. (2019). Alkali-silica reaction in concrete: Mechanisms, mitigation and test methods.

- Construction and Building Materials*, Volume 222, Pages 903-931.  
<https://doi.org/https://doi.org/10.1016/j.conbuildmat.2019.07.230>.
- Sanchez, L. F. M., Fournier, B., Jolin, M., & Bastien, J. (2014). 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*. <https://doi.org/10.1016/j.cemconres.2013.11.003>
- Sanchez, L. F. M., Fournier, B., Jolin, M., & Bastien, J. (2015). Evaluation of the Stiffness Damage Test (SDT) as a tool for assessing damage in concrete due to alkali-silica reaction (ASR): Input parameters and variability of the test responses. *Construction and Building Materials*. <https://doi.org/10.1016/j.conbuildmat.2014.11.071>
- Sanchez, L. F. M., Fournier, B., Jolin, M., Bastien, J., & Mitchell, D. (2016). Practical use of the Stiffness Damage Test (SDT) for assessing damage in concrete infrastructure affected by alkali-silica reaction. *Construction and Building Materials*.  
<https://doi.org/10.1016/j.conbuildmat.2016.08.101>
- Sanchez, L. F. M., Fournier, B., Jolin, M., Bedoya, M. A. B., Bastien, J., & Duchesne, J. (2016a). Use of Damage Rating Index to quantify alkali-silica reaction damage in concrete: Fine versus coarse aggregate. *ACI Materials Journal*, 113(4), 395–407.  
<https://doi.org/10.14359/51688983>
- Sanchez, L. F. M., Fournier, B., Jolin, M., Bedoya, M. A. B., Bastien, J., & Duchesne, J. (2016b). Use of Damage Rating Index to quantify alkali-silica reaction damage in concrete: Fine versus coarse aggregate. *ACI Materials Journal*.  
<https://doi.org/10.14359/51688983>
- Sanchez, L. F. M., Fournier, B., Jolin, M., & Duchesne, J. (2015). Reliable quantification of AAR damage through assessment of the Damage Rating Index (DRI). *Cement and Concrete Research*, 67, 74–92. <https://doi.org/10.1016/j.cemconres.2014.08.002>
- Sanchez, L. F. M., Fournier, B., Jolin, M., Mitchell, D., & Bastien, J. (2017a). Overall assessment of Alkali-Aggregate Reaction (AAR) in concretes presenting different strengths and incorporating a wide range of reactive aggregate types and natures. *Cement and Concrete Research*, 93, 17–31.

<https://doi.org/10.1016/j.cemconres.2016.12.001>

Sanchez, L. F. M., Fournier, B., Jolin, M., Mitchell, D., & Bastien, J. (2017b). Overall assessment of Alkali-Aggregate Reaction (AAR) in concretes presenting different strengths and incorporating a wide range of reactive aggregate types and natures. *Cement and Concrete Research*, 93, 17–31.

<https://doi.org/http://dx.doi.org/10.1016/j.cemconres.2016.12.001>

Stanton, T. E. (2008). Expansion of concrete through reaction between cement and aggregate (this article originally appeared in Proceedings of the ASCE, December 1940, v. 66(10), pp. 1781-1811). In *Selected Landmark Paper Collection on Concrete Materials Research*.

Stark, D., Diamond, S., & Moranville-regourd, M. (n.d.). *Alkali-Silica Reactivity : An Overview of Research*.

Swenson, E G. (1957). A Reactive aggregate undetected by ASTM tests. *ASTM Bulletin*.

Swenson, Edwin George, & Gillott, J. E. (1960). Characteristics of Kingston carbonate rock reaction. *Highway Research Board Bulletin*, 275, 18–31.

Thomas E. Stanton, O. J. Porter, L. C. Meder, and A. N. (1942). California Experience With the Expansion of Concrete Through Reaction Between Cement and Aggregate. *ACI Journal Proceedings*, 38.

Thomas, M. D.A., & Innis, F. A. (1999). Use of the accelerated mortar bar test for evaluating the efficacy of mineral admixtures for controlling expansion due to alkali-silica reaction. *Cement, Concrete and Aggregates*, 21(2), 157–164.

<https://doi.org/10.1520/cca10429j>

Thomas, M., Fournier, B., Folliard, K., Ideker, J., & Shehata, M. (2006). Test methods for evaluating preventive measures for controlling expansion due to alkali-silica reaction in concrete. *Cement and Concrete Research*.

<https://doi.org/10.1016/j.cemconres.2006.01.014>

Thomas, Michael D.A., Folliard, K. J., Fournier, B., Rivard, P., Drimalas, T., & Garber, S. I. (2013). Methods for Evaluating and Treating ASR-Affected Structures: Results of Field Application and Demonstration Projects. Volume II: Details of Field Applications and

- Analysis Final Report. *Federal Highway Administration, FHWA-HIF-1*, 338.
- Van Den Abeele, K. E. A., Sutin, A., Carmeliet, J., & Johnson, P. A. (2001). Micro-damage diagnostics using nonlinear elastic wave spectroscopy (NEWS). *NDT and E International*. [https://doi.org/10.1016/S0963-8695\(00\)00064-5](https://doi.org/10.1016/S0963-8695(00)00064-5)
- Villeneuve, V., Fournier, B., & Duchesne, J. (2012). Determination of the damage in concrete affected by ASR- the damage rating index (DRI). *Proceedings of the 14th International Conference on Alkali-Aggregate Reaction in Concrete*.
- Walsh, J. B. (1965). The effect of cracks on the uniaxial elastic compression of rocks. *Journal of Geophysical Research*. <https://doi.org/10.1029/jz070i002p00399>
- Wigum, B. J., Lindgård, J., Sims, I., & Nixon, P. (2016). Rilem activities on alkali-silica reactions: From 1988-2019. *Proceedings of Institution of Civil Engineers: Construction Materials*. <https://doi.org/10.1680/jcoma.15.00070>

## Chapter Four: Summary and Conclusion

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Alkali aggregate reaction (AAR) one of the deleterious reactions is nowadays an important issue worldwide, especially in Northern America. While dealing with AAR affected structures, experts rely on various standards and techniques available to diagnose the current damage (i.e. damage type and extent) and forecast the potential of further distress over time. Although most of these techniques are based on accelerated laboratory procedures, it is critical to understand whether the results obtained in the laboratory might be applied to the field.

In this study, the efficiency of various techniques available in Canada to assess the potential residual expansion of AAR-affected was evaluated. Chapter 3 illustrates the evaluation of RE techniques through non-destructive NIRAS test and the DRI method; moreover, a new technique (i.e. 0.7M NaOH) is proposed, aiming to overcome some of the issues reported in the literature with the current methods. The main conclusions of the current Thesis are presented hereafter:

- The NIRAS test has been found effective to understand and detect damage up to moderate levels (0.12%); yet, this non-destructive procedure was not able to appraise damage at high and very high induced expansion and distress levels, which might have been related with the present of AAR-reaction products. Conversely, the DRI was found to be very effective to describe both AAR-induced expansion and damage and to compare distinct setups;
- The 1 M NaOH setup seems to be much more aggressive than the other setups. The reaction kinetics and ultimate expansion obtained with the use of this setup was faster and higher respectively. Moreover, the crack patten found in samples deteriorated using this setup was very different from AAR-damage found in the field;
- The proposed setup seems to be compatible with damage found in field structures. Yet, the reaction rate and ultimate expansion found were not different from the 100% RH setup, which indicates that further studies are still needed to improve this procedure;

- Finally, chemical analysis indicated that for all setups tested, there is some exchange between the alkalis inside the specimens and the water or solution from the test setups. On the one hand, this demonstrates why the 100% RH setup yields lower results than expected (i.e. alkali leaching). On the other hand, it is not quite clear why the alkalis from solution with similar to higher amount of alkalis keep increasing over time. Further studies are still needed in this regard.

## Chapter Five: Recommendations for future research

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Further investigations can be suggested after this research work:

- Mechanical tests such as the Stiffness Damage Test (SDT) should be performed to understand the mechanical deterioration of specimens tested at different conditions;
- Further studies are still required to improve AAR kinetics in the proposed setup;
- Further understanding is still needed on the alkali exchange (inside/outside) with respective water or solution from distinct expansion setups;
- The study on the confinement effect on AAR-induced expansion and damage is still opened. Moreover, it is not clear how to reuse data gathered from mechanical test procedures to evaluate real affected structures.
- Image analysis and high-resolution x-ray micro-computed tomography tests can give a clearer insight of the cracking pattern and propagation of damaged concrete for distinct conditions and might be used for comparison purposes with 2D cracking analysis methods such as the DRI.