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

**Nusrat Zubaida [(1)], Andisheh Zahedi [(2)], Leandro Sanchez [(3)], Patrice Rivard [(4)]**
*(1) MASc Candidate, Civil Engineering, University of Ottawa, Ottawa, Canada, nzuba086@uottawa.ca*
*(2) PhD Candidate, Civil Engineering, University of Ottawa, Ottawa, Canada, azahe049@uottawa.ca*
*(3) Assistant Professor, Civil Engineering, University of Ottawa, Ottawa, Canada, leandro.sanchez@uottawa.ca*
*(4) Full Professor, Civil Engineering, University of Sherbrooke, Sherbrooke, Canada, patrice.rivard@usherbrooke.ca*

## 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 behaviour 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 to assess the residual expansion of AAR-affected concrete. Three different setups (i.e. 100% RH and 38°C; 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. Expansion was 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 1M 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 a similar deterioration mechanism 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; accelerated laboratory test; reactive aggregate; residual expansion*

## 1. INTRODUCTION

Alkali-aggregate reaction (AAR) is one of the most deleterious mechanisms affecting the durability and long-term performance of concrete infrastructure worldwide. 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 [1, 2]. Although several researchers [1-4] 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. Although these methods are quite easy and straightforward to be conducted, the vast majority of the results gathered from these tests have been found to be inaccurate when compared to the swelling behaviour of the respective structure in the field and thus 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). Moreover, concrete structures are often under different stress state conditions (due to confinement effects, presence of reinforcement, loadings, etc.) when compared to laboratory tests which makes the physicochemical process to be different. 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 [5, 6]. 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 behaviour 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.

## 2. DIAGNOSIS AND FORCASTING OF AAR-AFFECTED CONCRETE

A number of experiments related to the diagnosis and quantification of AAR-induced damage in concrete structures thoroughly illustrate different steps required to assess aging infrastructure [7–9]. Usually, the first step while the condition assessment of concrete infrastructure is the review of available documents related to the appraised structure [10]. Once the analysis of the available document is conducted, in-situ assessment and, when necessary, coring for further laboratory procedures might be required. Among these procedures, petrographic methods such as Damage Rating Index (DRI), are the most common and considered extremely reliable when diagnosing affected structures. Furthermore, several researchers have found that non-destructive techniques such as the Nonlinear Impact Resonance Acoustic Spectroscopy (NIRAS) might be an effective protocol to appraise damage initiation and progression.

Nowadays, nonlinear ultrasonic and acoustics-based methods are commonly used non-destructive techniques for concrete specimens affected by AAR. These methods are found responsive to identify microcracks and damage compared to traditional linear acoustic methods [11–13]. Chen et al. [11] proposed a new technique based on the impulse excitation of concrete samples measuring their free vibration responses and named it as nonlinear impact resonance acoustic spectroscopy (NIRAS). The authors explained that concrete is a heterogeneous and nonlinear material by nature, hence while affected by AAR; NIRAS can recognize microcracks through the assessment of its resonance frequencies. Several authors comply with this idea, claiming that cracks are “imperfect bond systems” and thus affected material might display lessened stiffness while the resonance frequencies should escalate the nonlinear effects. This resonance frequency shift is accepted by researchers as a function of concrete macroscopic nonlinearity property to quantify damage [12-16]. As a consequence, equations (1) and (2) were proposed based on this idea [11]:

$$(f_0 - f)/f_0 = \acute{\alpha}\Delta\varepsilon \quad (1)$$

$$E = E_0\left[1 + \beta\varepsilon + \delta\varepsilon^2 + \alpha\left(\Delta\varepsilon + \varepsilon\,\mathrm{sgn}(\acute{\varepsilon})\right)\right] \quad (2)$$

Here, in equation (1) $f_0$ represents the linear resonance frequency where f is the resonance frequency at increased excitation amplitude, $\acute{\alpha}$ is proportional to α. In addition, equation (2) parameters are: $E_0$ that refers the linear elastic modulus for small deformation, β represents the parameter for quadratic anharmonicity, δ refers the parameter for cubic anharmonicity, ε is strain, Δε refers the strain amplitude, α is the hysteresis nonlinearity property, $\acute{\varepsilon}$ is strain rate and sgn ($\acute{\varepsilon}$) = 1 if $\acute{\varepsilon}>0$; –1 if $\acute{\varepsilon}<0$; 0 if $\acute{\varepsilon}=0$ [11].

The Damage Rating Index (DRI) is a widely used semi-quantitative petrographic technique proposed by Grattan-Bellew and Danay to evaluate the damage degree of AAR affected concrete [17-19]. It consists of an evaluation of affected polished concrete sections under a stereomicroscope with 15-16x magnification, where distinct damage features associated with AAR are quantified through 1 $cm^2$ grids drawn on the polished samples. The damage features are then multiplied by weighing factors whose purpose is to balance their relative importance. At the end of the analysis, a DRI number is calculated; the higher the number, the higher AAR-induced damage. Over time, researchers from Laval University improved the procedure so that it might better represent “damage” in its broader sense, while reducing its subjectivity and variability amongst operators [19]. They suggested the same weighing factors to be used for open cracks within the aggregates with or without reaction products (i.e. gel) along with cracks in cement paste with or without reaction products. Recently, Sanchez et al. performed the DRI on concrete samples presenting a wide range of strengths and fabricated with numerous coarse and fine aggregates [19]. This work confirmed the relationship between AAR-induced expansion levels and DRI numbers. Therefore, the DRI was considered to be a very effective method for assessing AAR affected concrete [17-22].

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 RE is absolutely required. Hence, numerous laboratory test procedures have been developed over the past decades to forecast the behavior of in-situ concrete. However, physiochemically 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 and microscopic techniques might be beneficial to help understanding similarities and differences obtained from distinct RE test setups [1-3].

## 3. SCOPE OF THE WORK

It is known that there is an important discrepancy between the outcomes of the current RE techniques and the real behavior 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 used in Canada, and to propose a novel approach 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; 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 is highlighted.

## 4. EXPERIMENTAL PROGRAM

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% $Na_2O_e$) was used in the mixture. Reagent grade NaOH was used to raise the total alkali content of the mixtures to 1.25% $Na_2O_e$ by cement mass, for accelerating AAR expansion process.

A total of 132 concrete specimens (i.e. 66 per aggregate type) were fabricated, de-molded 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 a 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 liters) lined with a damp cloth (4 cylinders per bucket). All buckets were stored at 100% RH and 38°C (Figure 4.1(a));
- Sealed plastic containers (22 liters) containing a 1M NaOH solution (4 cylinders per bucket). All cylinders were soaked at the solution at 38°C (Figure 4.1(b));
- Plastic jars displaying a slightly larger diameter than the concrete specimens, and lined with a damp sponge containing a 0.7 M NaOH solution. The specimens were placed inside the jars and wrapped with 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) (Figure 4.1(c)).

All the test cylinders were regularly monitored over time. Furthermore, the containers were cooled down to 23°C for 16 ± 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.

(a) (b) (c)

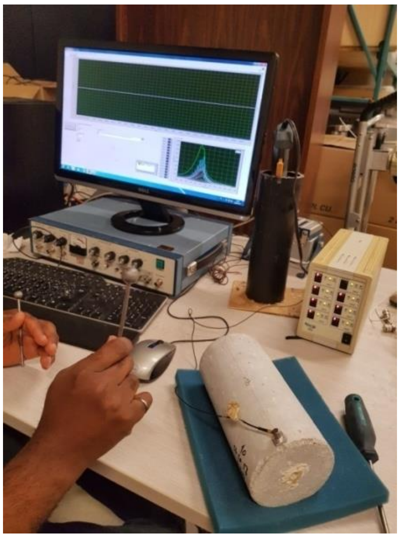
Figure 4.1: Different storage conditions for AAR RE testing: (a) 38°C and 100% R.H; (b) 1M NaOH solution at 38°C and; (c) damp sponge containing a 0.7M NaOH solution and 38°C.

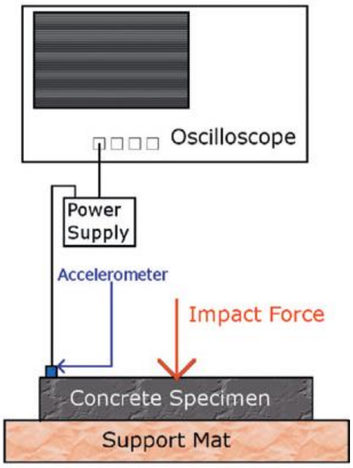
## 4.1 Concrete assessment and analysis

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.

### 4.1.1 Nonlinear Impact Resonance Acoustic Spectroscopy (NIRAS) technique

To perform the test, 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 (Figure 4.2). After, 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 used to acquire the vibration signals and frequency spectrum. At least 10 individual impacts of different strength were applied on each specimen to interpret the differences in resonance frequency. The analysis is finally performed according to the resonance frequency and impact amplitude obtained, as follows: the greater the damage, the lower the resonance frequency and the higher the impact amplitude [11].






(a) (b)

Figure 4.2: NIRAS test; (a) Experimental setup and (b) schematic setup [11]

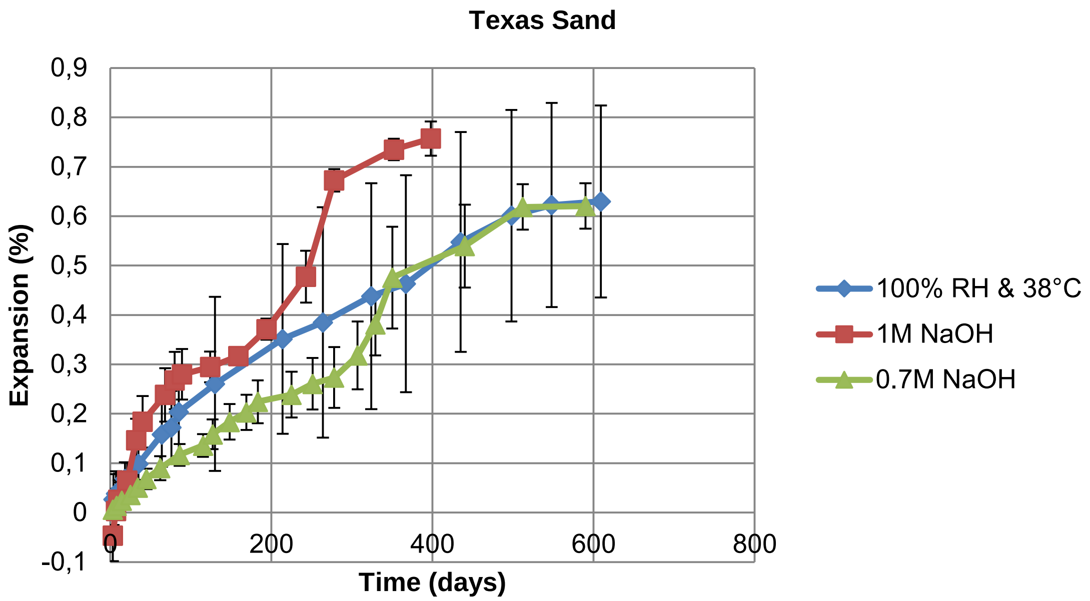
#### 4.1.2 Damage rating Index (DRI)

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 loose 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. [19].

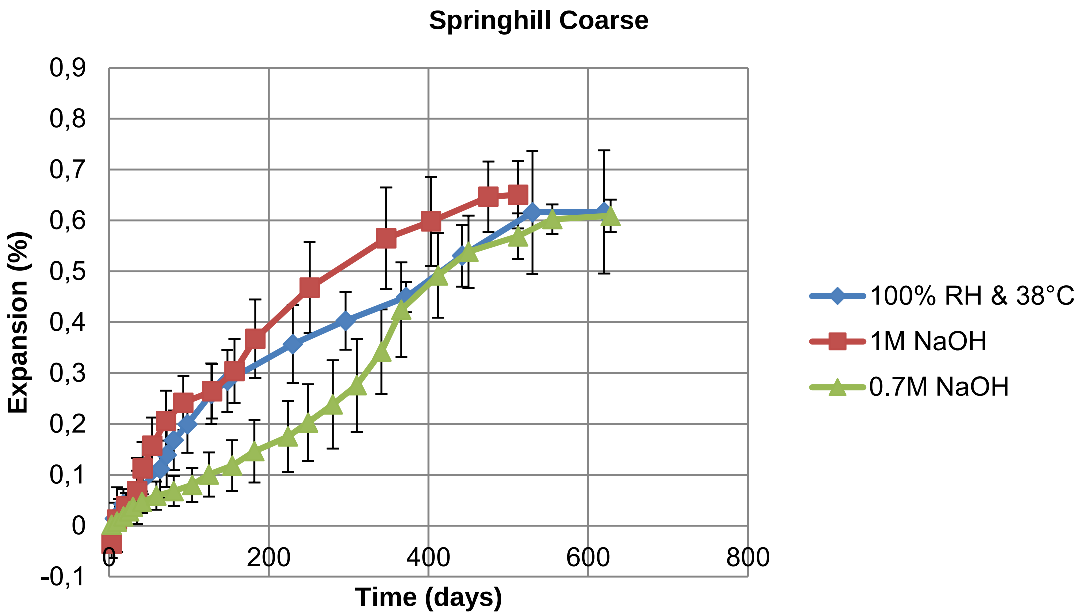
## 5. RESULTS

### 5.1 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 5.1 (a) illustrates the expansion measurements gathered for samples fabricated with the reactive Texas sand (Tx) whereas Figure 5.1 (b) displays the results for specimens proportioned with the reactive Springhill (Sp) coarse aggregate.




(a)




(b)

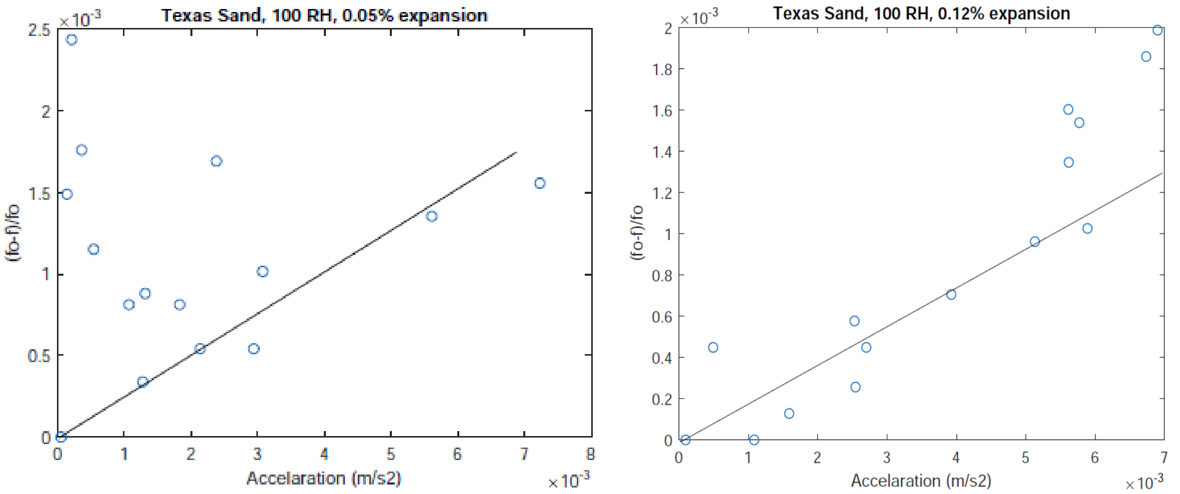
Figure 5.1: Expansion vs. time obtained for concrete tested with distinct setups and incorporating (a) reactive Texas sand and (b) reactive Springhill coarse aggregate.

It can be observed that a faster AAR kinetics was found for the samples fabricated with the Tx sand when compared to Sp coarse aggregate whatever the test setup used, as expected and reported in previous researches [7, 8, 19]. Furthermore, specimens soaked in 1M NaOH presented the fastest kinetics and highest ultimate expansion when compared to the other two setups. 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.

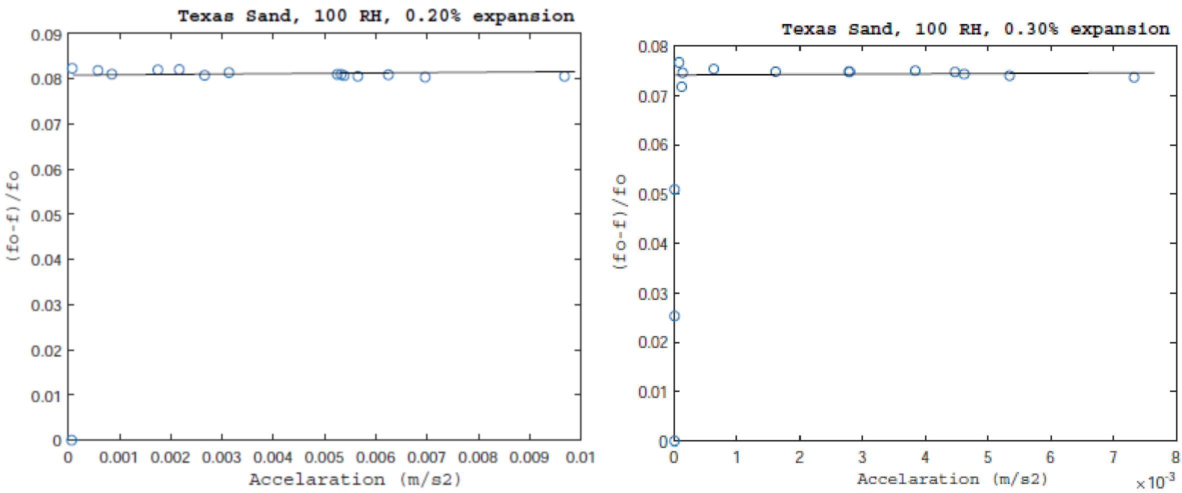
The 100% RH and 0.7 M NaOH setups yielded slower reaction kinetics and lower ultimate expansions when compared to the 1M NaOH soaking solution. Specimens under the 38°C and 100% RH displayed roughly ultimate expansions at 600 days for both aggregate types. The ultimate expansions measured were 0.62% 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 a slower reaction kinetics at the beginning of the expansion process. 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.

## 5.2 Nonlinear Impact Resonance Acoustic Spectroscopy (NIRAS) technique

The results from NIRAS test on concrete specimens can be observed in Figure 5.2 (a-d) for Texas sand and the 38°C and 100% RH setup. It is anticipated that NIRAS test appraises microcracks and damage in concrete through resonance frequency shift and impact amplitude; the lower the resonance frequency and the higher the impact amplitude, the higher the concrete damage as per [11-16].




(a) 100% RH, 0.05% expansion (b) 100% RH, 0.12% expansion




(c) 100% RH, 0.2% expansion (d) 100% RH, 0.3% expansion

Figure 5.2: Nonlinearity comparison of 38°C and 100% RH setup at selected expansion levels (Texas sand).

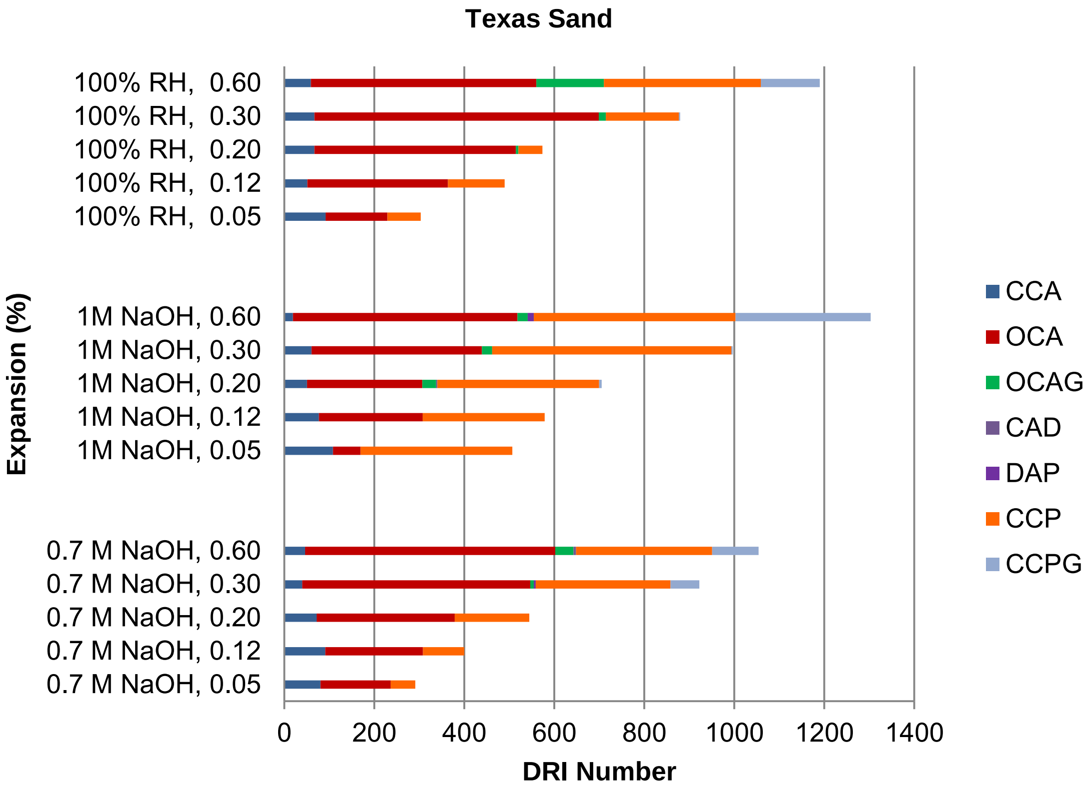
It is noticed from the data above that at lower expansion levels (i.e. 0.05%), the nonlinearity curve is very steep which means that AAR-damage is well captured. As the expansion level increases, the nonlinearity curve (i.e. curve slope) becomes less steep. From 0.20% expansion and onwards, the nonlinearity curve becomes flat, which indicates that NIRAS is not suitable to capture damage from this reaction stage.

The results from other setups and mixtures made of SP aggregates were quite similar and are not being presented herein to avoid redundancy and due to the lack of space.

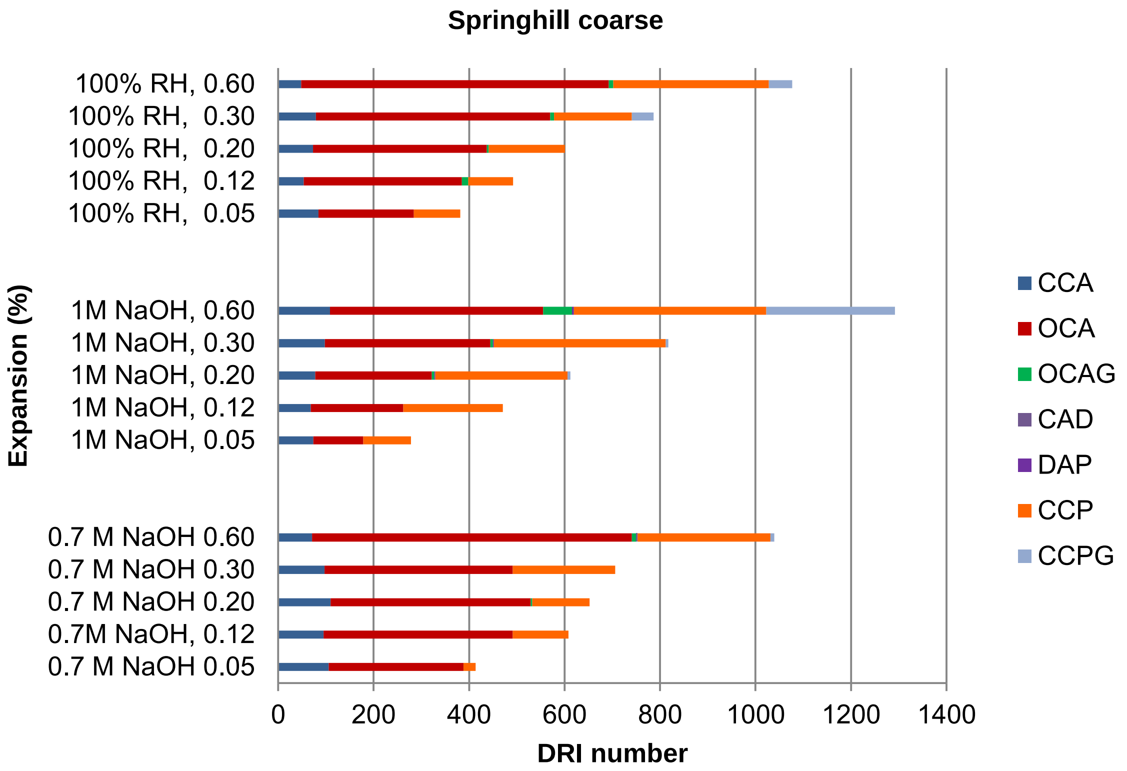
## 5.3 Damage Rating Index (DRI)

The results of petrographic analysis in terms of DRI numbers as a function of AAR-induced expansions are presented in Figure 5.3. It can be observed that the DRI number increases as the expansion level rises, for all setups used and both aggregate types; the latter indicates that the higher the expansion level, the greater AAR-induced damage degree, as expected. The number of closed cracks in the aggregate particles (CCA) does not increase with the raise in expansion, since it is not a distress feature linked to AAR development. However, the open cracks in the aggregate particles (without or with reaction products - OCA and OCAG) and the cracks in cement paste (without or with gel - CCP and CCPG) indeed increase as a function of induced expansion for both aggregate types and setups tested.

Comparing the results presented below, it is clear that the 1M NaOH setup samples display a greater damage degree for all expansion levels studied and for both aggregate types assessed. Moreover, the damage features found on specimens evaluated through this setup is slightly different from the samples of the other two procedures, since a much higher amount of cracks in the cement paste with and without gel (i.e. CCP – orange and CCPG – light blue charts) was obtained in the 1M NaOH environment; the latter seems to indicate a discrepancy in the damage procedure amongst setups.




(a)




(b)

Figure 5.3: DRI numbers of concrete specimens in three different setups using reactive sand and coarse aggregates.

## 6. DISCUSSION

The expansion vs. time plot presented in the Figure 5.1 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 actually showed similar reaction kinetics, expect for early ages). The above information seems to indicate that AAR-induced development in the 1M NaOH setup is somehow different from the others.

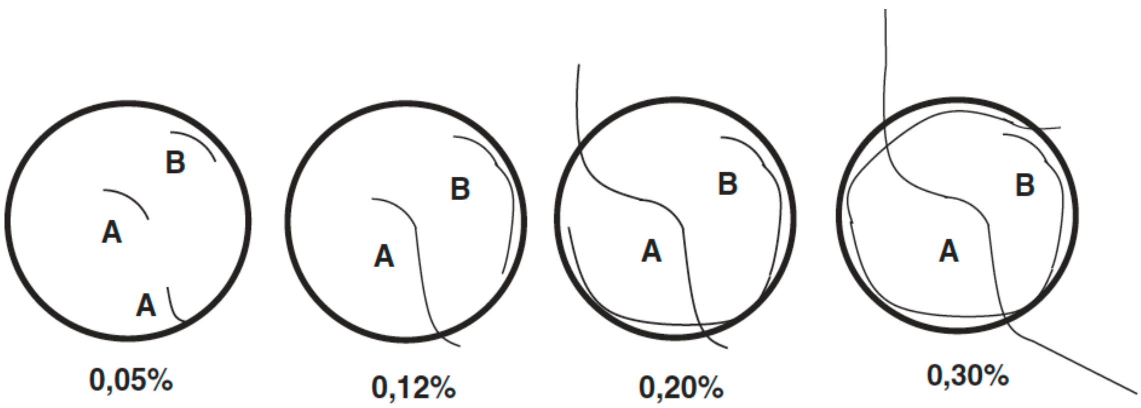



Figure 6.1: Qualitative AAR damage model at different expansion levels [19].

Microscopic analysis (i.e. DRI) verified that the 1M NaOH setup specimens show higher DRI numbers and slightly different distress features (especially cracks in the cement paste) for all expansion levels evaluated and for both aggregates. The latter emphasizes that perhaps the damage process developed at 1M NaOH is different from the other test procedures (which by the way displayed similar deterioration features). Trying to understand ASR-induced cracks development as a function of expansion at 38°C and 100% RH, Sanchez et al. [19] created a descriptive qualitative model (Figure 6.1). In this work, after a thorough analysis of the samples evaluated using the three distinct setups, a new descriptive model is proposed for the 1M NaOH protocol and is presented in Figure 6.2.

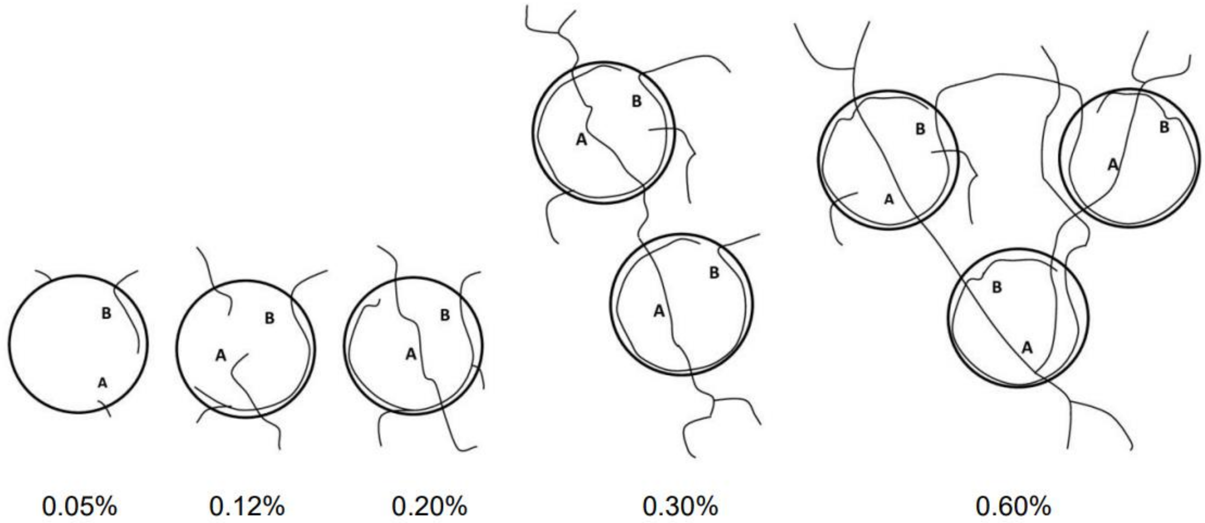



Figure 6.2: AAR damage model at various expansion levels in 1M NaOH setup.

As verified above, AAR-induced damage starts with two types of cracks (i.e. type A: sharp cracks and type B: onion skin cracks) and mainly develops itself within the aggregate particles for low expansion levels (i.e. 0.05%). As the expansion level raise, new A and B cracks are developed in the system but more importantly, the prior existing A and B cracks keep growing in length and width; at moderate expansion levels (0.12%), type A cracks may reach the cement paste, at least at one side of the aggregate particles. At high levels of damage (i.e. 0.20%), type A cracks reach the cement paste at both sides of the aggregate particles while type B cracks have almost finished outlining them. Finally, at very high levels of expansion and onwards, the cracks formed in distinct reactive particles reach each other in the cement paste and form a huge crack networking in the affected material. This model as per [19] was found to be present in this work in samples tested through both 38°C and 100% RH and 0.7M NaOH setups. Conversely, concrete samples tested at 1M NaOH demonstrated a distinct damage process from the beginning of induced expansion as per Figure 6.2; at early damage stages (0.05% expansion), sharp and onion skin cracks (A and B) are also observed within the aggregate particles, yet the vast majority of them already extend to the cement paste. Moreover, at moderate expansion levels (i.e. 0.12%), the pre-existing cracks increase in length and width, and completely reach the cement paste at the two sides of the reactive aggregate particles. These cracks start building an important crack network and some aggregates start de-bonding at high and very high (i.e. 0.2% and 0.3%) expansion levels. At the maximum expansion level reached (i.e. 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. [19], gives an impression that not only the mechanism generated under 1M NaOH is more aggressive than the other two protocols, but also different, since this mechanism is a process that deteriorates primarily the cement paste and not the aggregate as per [19] and structures observed in the field. Therefore, careful consideration should be taken while the use of this protocol to assess the potential of further AAR-induced expansion and damage for affected infrastructure.

## 7. CONCLUSION

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

- The 1 M NaOH setup seems to be much more aggressive than the proposed setup (i.e. 0.7 M NaOH) and the 38°C and 100% RH procedure. The reaction kinetics and ultimate expansion gathered from this particular test was faster and higher, respectively. Moreover, the crack patter found in samples deteriorated using the 1 M NaOH protocol was different from the model proposed by Sanchez et al. [19] and the other two setups studied;
- 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 38°C and 100% RH protocol provide evaluated samples with the same distress mechanism. Conversely, its analysis evidenced that the 1M NaOH setup triggers a distinct and more aggressive damage process in the affected samples;
- 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 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 38°C and 100% RH setup, which was unexpected. The latter lessens its impact, since it is known that the 38°Cand 100% RH protocol 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 the proposed procedure.
- Chemical analysis of the solutions from each setup at distinct expansion levels is currently being performed. These are expected to help understanding some of the differences observed amongst distinct setups.

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