Effect of confinement on AAR-induced expansion and damage

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Abstract

Over the last decades, researchers have proposed a number of distinct tools for the condition assessment of concrete infrastructure affected by alkali-aggregate reaction (AAR). Amongst those, increasing attention has been given to the Stiffness Damage Test (SDT), Damage Rating Index (DRI) and Residual Expansion (RE), laboratory test procedures that aim to determine the diagnosis (i.e., cause and extent) and prognosis (i.e., potential for further damage) of affected concrete. Yet, most of the data gathered so far while the use of the aforementioned tools have been obtained on laboratory test specimens presenting distinct conditions from field concrete, especially confinement effects. This work aims to understand the effect of confinement on AAR-induced expansion and damage. Thirty-two blocks incorporating highly reactive coarse and fine aggregates and distinct reinforcement conditions will be cast and stored at 38°C and 100 R.H. Two expansion levels will be selected for analyses and whenever they are reached, mechanical (i.e., SDT, compressive and shear strength), microscopic (i.e., DRI, scanning electron microscope, etc.) and RE tests will be conducted so that one may understand the influence of confinement on AAR physicochemical development. Models describing the findings will be developed and recommendations on the use of laboratory test procedures to diagnose and prognose reinforced concrete structures will be performed.

Keywords: *alkali-Aggregate reaction (AAR); confinement effects; damage rating index; residual expansion; stiffness damage test*

1. NTRODUCTION

Alkali-Aggregate (AAR) is known as one of the most important damage mechanisms affecting the durability and serviceability of civil infrastructure worldwide. A number of test protocols have been developed in the past to appraise induced expansion and damage (i.e., diagnosis) of AAR-affected concrete. Amongst those, great understanding was obtained through the use of mechanical and microscopic techniques, particularly the *Stiffness Damage Test (SDT)* and *Damage Rating Index (DRI)*, respectively. Yet, much less was discussed and proposed on techniques aiming to evaluate the potential of AAR further development (i.e., prognosis) in the field. Moreover, most of the developed diagnosis and prognosis techniques showed to be suitable to appraise current and/or future damage under "free expansion" conditions which does not reflect the real scenario of concrete members in the field. The latter presents a serious and dangerous gap: current methods outcomes do not necessarily represent the reality in the field and thus many structures may remain without proper appraisal which may lead to serious issues. This project aims to identify the suitability of the current tools (and change them whether needed) to assess AAR-induced expansion and damage and the potential for further deterioration of reinforced concrete members presenting distinct confinement degrees and incorporating different reactive aggregates types (i.e., fine vs coarse).

2. LITERATURE REVIEW

Alkali-aggregate reaction (AAR), a chemical reaction between silica poorly crystalized from the aggregates and the alkali hydroxides from the concrete pore solution, is one of the most harmful distress mechanisms affecting the durability and serviceability of concrete infrastructure worldwide [1]. AAR generates a product that swells in the presence of water, causing volumetric expansion and leading to severe damage of the affected material such as micro/macro cracking, loss of mechanical properties and stiffness [2]. One of the most important challenges while assessing critical infrastructure affected by AAR is to: a) determine the induced expansion and damage attained to date in the different locations of the structure (i.e., diagnosis), b) predict its potential for further distress over time (i.e., prognosis) and c) appraise the potential of important structural implications [2]. Over the past years, several test protocols have been developed/optimized to perform the condition assessment of critical infrastructure affected by AAR. Amongst those, the *Stiffness Damage Test (SDT)* and *Damage Rating Index (DRI)*, respectively mechanical and microscopic procedures, were found to be suitable to diagnose (i.e., cause and extent) damage in concrete whereas techniques such as *Residual Expansion (RE)* and *Soluble Alkalis (SA)* were found promising to provide information on the likelihood of further deterioration (i.e., prognosis) of affected members [3]–[5].

Studies have demonstrated that AAR-induced free expansion generates, especially in alkali-silica reaction (ASR) cases, a damage pattern as per Figure 2.1 [6]:

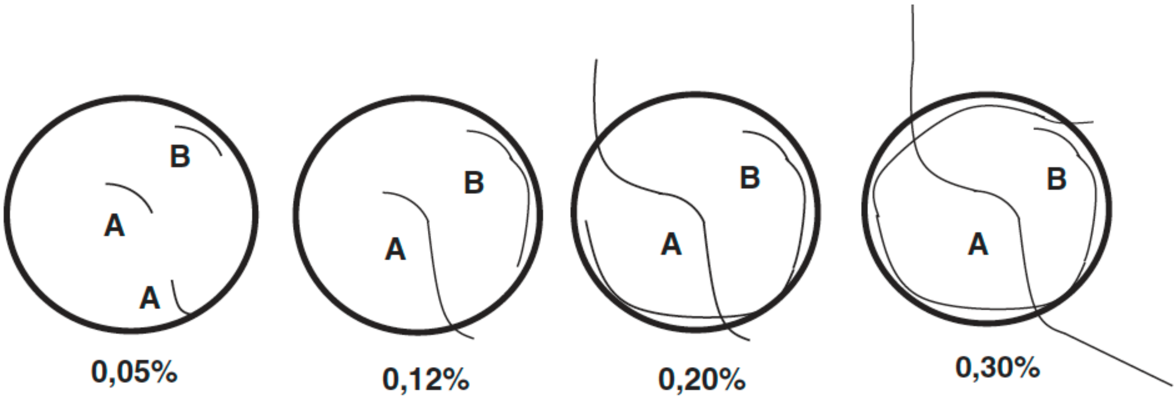


Figure 2.1: Crack patterns of AAR affected concrete [6].

The above Figure clearly shows that at low expansion levels (e.g., 0.05%), cracks are generated within the reactive aggregate particles, with very low (if any) presence of cracks in the cement paste. Moreover, two types of cracks may be recognized, type A cracks (i.e., sharp cracks, which are the ones that split the aggregate particles), and type B cracks (onion skin cracks, which are the cracks that outline the particles). At moderate expansion levels (e.g., 0.12%), new cracks are formed in the system, yet even more importantly, the previously developed cracks increase in length and width, reaching the cement paste (at least at one end of the particle). At high expansion levels (e.g., 0.20%) the cracks previously formed within the aggregate particles reach the cement paste at both aggregate ends, which drastically impacts on the mechanical properties of the affected material. Finally, at very high expansion levels (e.g. 0.30%), cracks developed at distinct particles start linking to each other, which creates an important crack networking in the affected concrete [6].

It has been found that the above AAR crack development may influence on the mechanical properties of affected concrete. Significant reductions of about 85% and 65% are often verified, respectively, for tensile strength and modulus of elasticity at high levels of expansion. The latter raises concerns on the technical community on the structural implications of AAR in affected infrastructure [1]. However, the vast majority of the current results found in the literature were obtained under a “free-expansion/unrestrained” state which does not represent the conditions of real structures in the field.

Very often, concrete structures are under a 2 or 3-D confinement state in the field which likely makes their physicochemical deterioration process largely different from the one obtained under unconfined conditions in the laboratory. Thus, the following questions should still be answered so that one may properly and reliably appraise AAR-affected concrete infrastructure:

- What’s the difference between AAR-induced expansion and damage generation and propagation in “free” vs “confined” scenarios?
- How the above distinction would likely differently impact on the reduction of the mechanical properties of unconfined and confined members?
- How to reliably collect and use data from confined and unconfined members to predict future behaviour of affected infrastructure (e.g., as input for numerical/analytical models)?

3. OBJECTIVES

This work aims to enhance the current knowledge and understanding of the influence of confinement effects on AAR-induced physicochemical development (i.e., induced expansion and damage generation and propagation). At the end, it is anticipated that this project will allow researchers and practitioners to make better assessment and prediction of AAR-affected infrastructure and to select more effective mitigation and/or rehabilitation techniques.

4. EXPERIMENTAL WORK

Thirty-two blocks (Figure 4.1) of 450 by 450 by 675 mm were fabricated using a 35 MPa mix as per ASTM C 1293 [7] and incorporating two different highly reactive aggregate types (i.e., Texas sand – fine aggregate and Springhill - coarse aggregate). Non-reactive fine and coarse aggregates (Ottawa natural sand and non-reactive limestone) from natural quarries in 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% Na2Oe) 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.

To investigate the effect of confinement on AAR-induced expansion and damage generation and propagation, distinct confinement conditions were selected for this research: 1) unconfined concrete blocks, 2) 1D confined blocks and, 3) 2D confined blocks (Figure 2.1 and 4.3). Confinement was introduced to the blocks using internal steel reinforcing bars at a reinforcement ratio of 2% in a) the longitudinal direction (i.e., 1D confined blocks), or b) both the longitudinal and transverse directions (i.e., 2D confined blocks). This reinforcement ratio is considered moderately high, and not uncommon for certain reinforced concrete member types such as columns or wall boundary elements. Hence, for most structural member types this may be viewed as a reasonable upper limit to the degree of restraint provided by internal reinforcement where the reinforcing bars are primarily oriented along one or two orthogonal directions. Embedded 35M steel reinforcing bars, having a nominal diameter of *35 mm*, were selected in order to achieve a sufficiently large bar spacing to accommodate core extraction (Figure 4.1B). Moreover, In the case of confined concrete, the concrete cover and spacing between the top and bottom steel rebars is 50 mm and 280 mm, respectively. In the case of 2D confined blocks, the longitudinal and transverse steel reinforcing bars were professionally welded to facilitate construction (Figure 4.3B). Once fabricated, all blocks were stored in an environmental chamber enabling AAR development (38^{o}C and 100% RH). Their expansions were monitored over time until they have reached low (i.e., 0.07%) and moderate (i.e., 0.15%) expansion levels. At those levels, the blocks were removed from the environmental chamber and cored to produce twelve (100 by 200 mm in size) cylinders for further analysis (Figure). Simultaneously to the blocks and for comparison purposes, 64 concrete cylinders of 100 by 200mm were also manufactured incorporating the same highly reactive aggregates. The specimens were demoulded 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 taken, and the specimens were placed in 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 4.2). 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. The same levels of expansion from the blocks were selected for further analysis (i.e., 0.07% and 0.15%). 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 a number of mechanical and microscopic techniques, particularly the Stiffness Damage Test (SDT) and the Damage Rating Index (DRI) are conducted. In addition, residual expansion (RE) and soluble alkalis (SA) techniques are also selected to be performed to evaluate the potential of AAR further expansion and damage on the cores extracted from the blocks.

Figure 4.1: Concrete blocks fabricated presenting A) 2D confinement (Top View) B) 2D confinement (Side View) C) 2D confinement (Front View) D) Environmental chamber with 38oC and 100% RH.

A)  B) 

Figure 4.2: A) Sealed bucket arrangement for the 38°C and 100% RH test and, B) affected test cylinder.

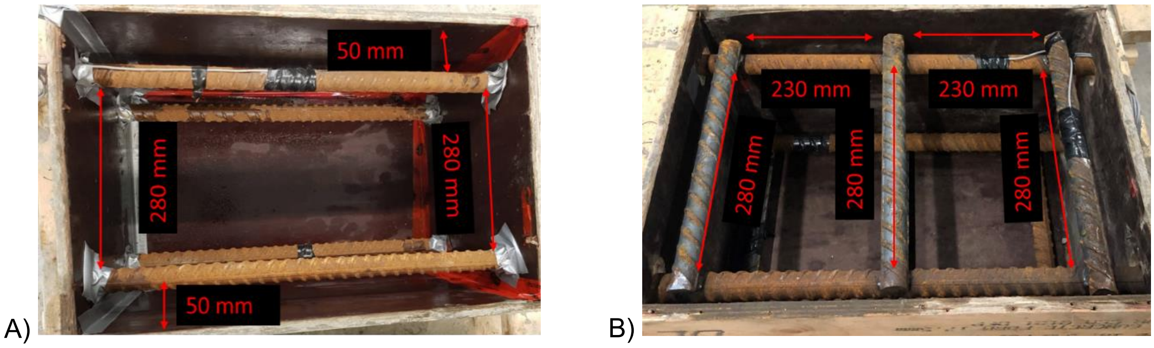


Figure 2.3: Confinement orientations A) 1D confinement B) 2D confinement.

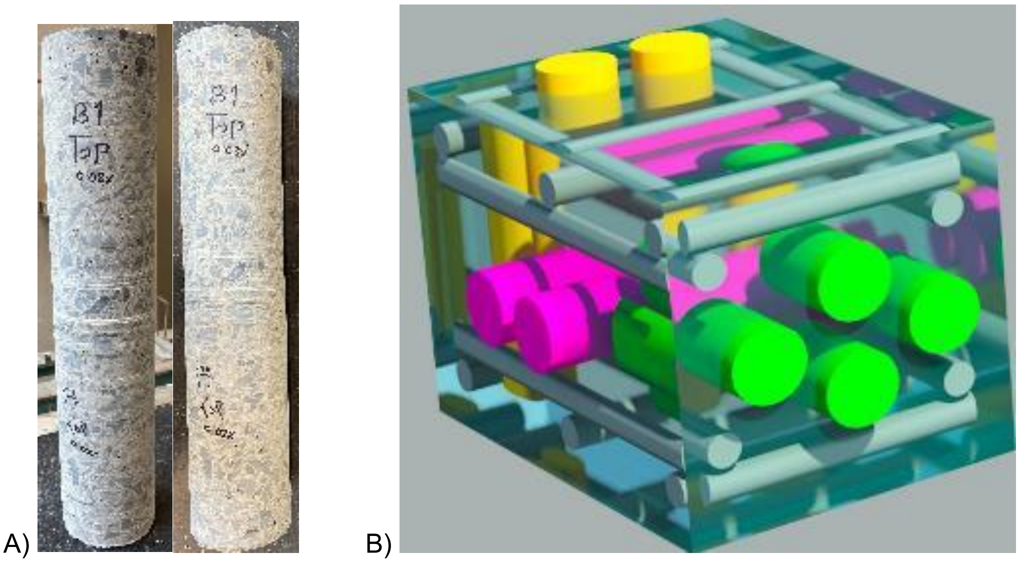


Figure 4.4: A) 100 by 450 mm core from unconfined concrete block, B) sketch from 450 x 450 x 675 mm block’s cores with 2D confinements.

4.1 Test Procedures

In order to monitor the expansion levels, 4 holes of 18mm in diameter by 50 mm length were drilled at the top along with on two sides of the concrete blocks and stainless-steel gauge studs (Figure 4.5A) were glued in place, with a fast setting cement slurry. After the completion of the first 72 h (i.e., three days from casting), the zero reading was taken on the top, longitudinal (i.e., long side) and transversal (i.e., short side) sides of each block with the aid of a micrometer (Figure 4.5B). Later, the specimens were stored in conditions enabling AAR development (i.e., 38C and 100% R.H.) and monitored over time.

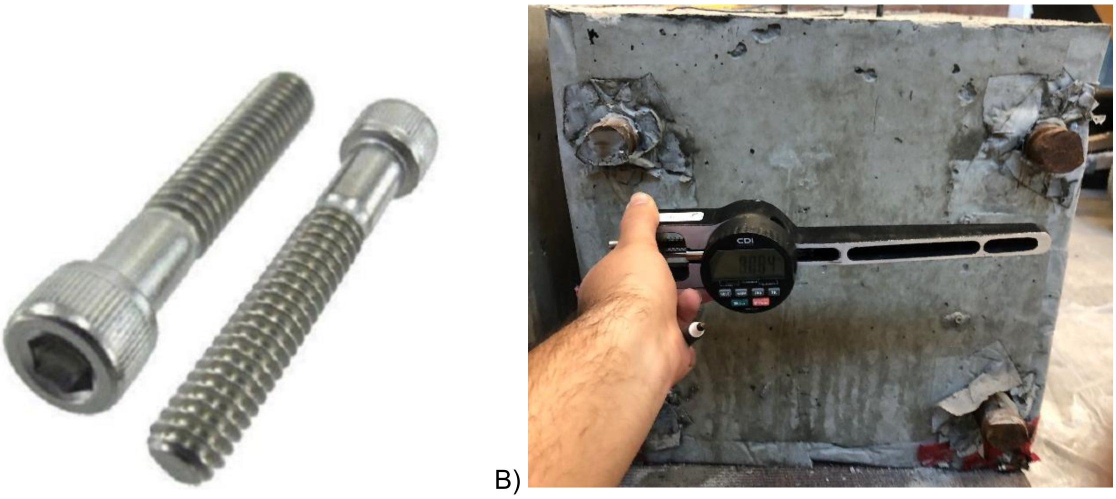
A)  B)

Figure 4.5: A) Stainless- steel studs B) micrometer used in this study.

In this work, damage is appraised as per the multi-level assessment (i.e., mechanical and microscopic), as proposed by [1]. Due to time constraint and laboratory capacity, only the microscopic assessment through the Damage Rating Index (DRI) is provided in this paper.

The Damage Rating Index (DRI) is a microscopic analysis proposed by [6] and used to quantify damage in concrete. It is performed with the use of a stereomicroscope (15–16× magnification), where damage features associated to AAR-induced development are counted through 1 cm2 grids drawn on the surface of polished concrete sections under analysis [8]. These distinct distress features are then multiplied by weighing factors, whose purpose is to balance their relative importance [6-8]. The weighing factor used in this test method were recently modified by Villeneuve and Fournier in 2012 [9] to reduce the variability amongst petrographers. Ideally, the DRI should be performed on at least 200 cm2 and for mass concrete (normally incorporating larger aggregate sizes) it may be even greater. However, the results of this test is normalized to a 100 cm2 area for comparative purposes [6].

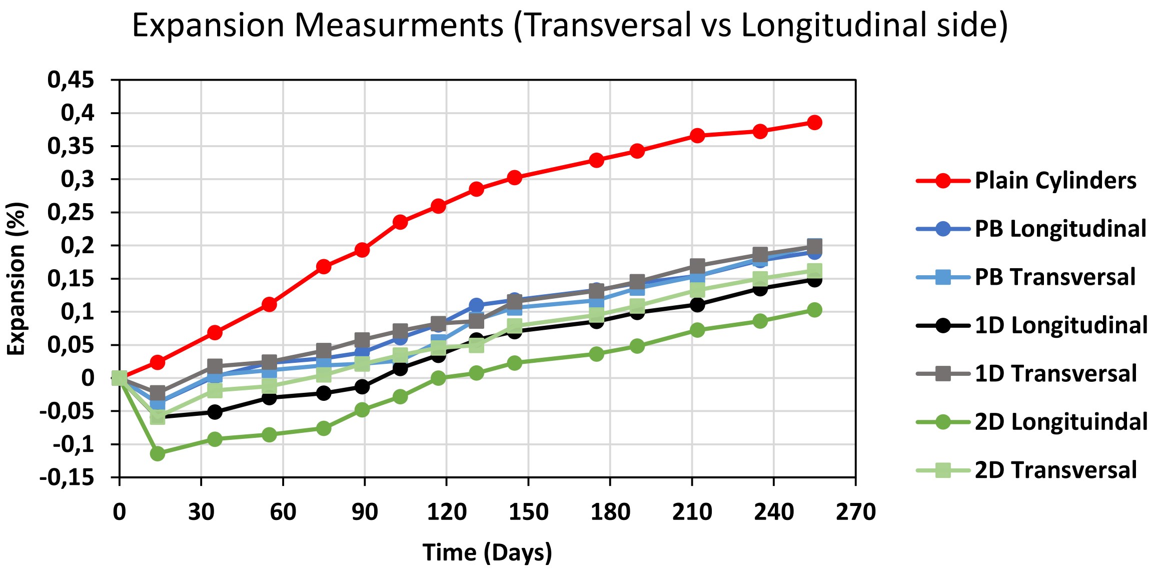
5. RESULTS

5.1 AAR Kinetics

In this section, AAR-induced kinetics and development is presented for all four types of specimens (i.e., concrete cylinders and blocks – non-reinforced, 1D and 2D reinforced) fabricated in the laboratory incorporating a highly reactive coarse aggregate (i.e., Springhill). Figure 5.1A displays the average expansions (i.e., average of 2 consecutive readings as per [10]) of longitudinal (i.e., long side) and transversal (short side) sides from each specimen type, whereas Figure 5.1B illustrates the average expansions of longitudinal top and longitudinal side from each specimen type. It is worth noting that very low standard deviations of about 0.03% were found for all samples over the expansion measurements.

In general, the 100 by 200 mm concrete cylinders presented faster reactivity and ultimate expansion than all concrete blocks, reaching 0.30% within 140-150 days which might be due to the partial restrainment of the blocks. Otherwise, about 0.10% expansion was reached after 117, 130 and 145 days at 38°C and 100% R.H by non-confined blocks on transversal, longitudinal top and longitudinal side measurements, respectively. The latter shows clearly that distinct expansions are gathered in distinct directions, as previously reported by [10] (i.e., transversal > longitudinal top > longitudinal side). Moreover, an interesting behaviour was found for the 1D and 2D concrete blocks which presented an important amount of shrinkage (i.e., all directions) at the beginning of the test. The 1D and 2 D confined blocks displayed slower expansion development than non-confined specimens (i.e., 0.10% expansion was obtained after 140, 175 and 205 days by 1D blocks while 190, 235, and 255 days by 2D blocks on transversal, longitudinal top and longitudinal side measurements, respectively). It is worth mentioning that for the sake of analysis (i.e., microscopic and mechanical), the expansions adopted as "representatives" of a given damage degree was the *longitudinal side* expansions for all blocks, since they are parallel to the main reinforcement and are not (or at least less) influenced by local effects such as the top drying/wetting cycles or differential restriction between bottom and top surfaces.

A)



B)

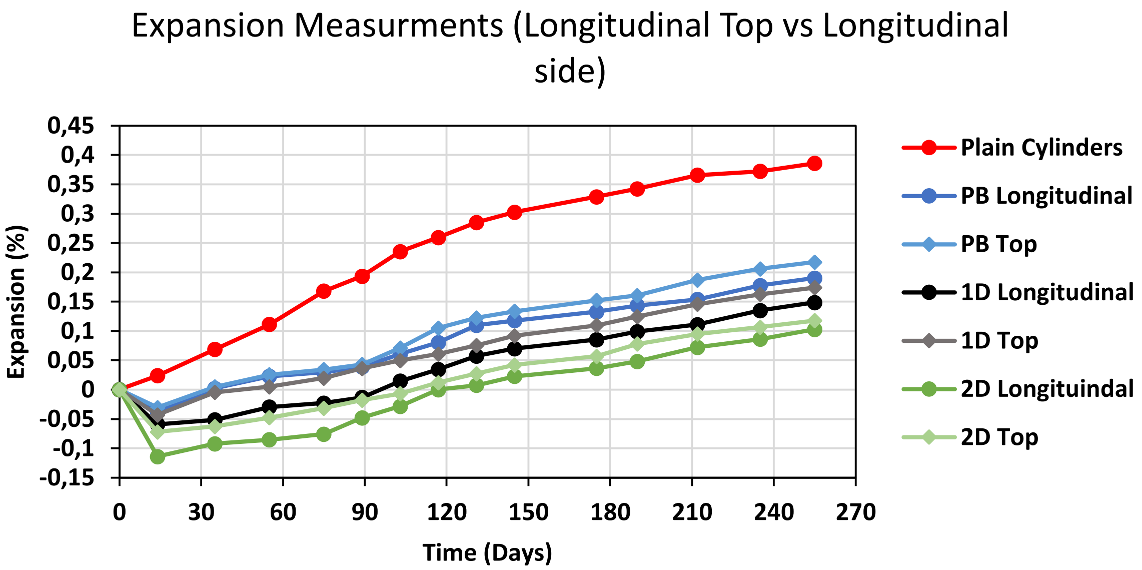


Figure 5.1: AAR kinetics (expansion vs. time) A. the average of expansion measurements of transversal and longitudinal side, B. the average of expansion measurements of longitudinal top and longitudinal side for the 35 MPa concrete mixtures.

5.2 Quantitative assessments of damage obtained through DRI

This section presents the petrographic results obtained for the concrete cylinders and non-confined blocks at the first expansion level selected for further evaluation (i.e., 0.07%±0.01%, longitudinal side for concrete blocks). Due to laboratory capacities and unforeseen laboratory issues, the evaluations on cores extracted from confined blocks was delayed and thus will not be presented throughout this work.

Figure 5.2 demonstrates the DRI results obtained as per [9]. Analyzing the results, one notices that the DRI number obtained for the concrete cylinders and non-confined block cores at the first expansion level selected (i.e., 0.07±0.01%) was quite close (i.e., 381 and 422 respectively). Moreover, the petrographic features found from affected cylinders and cores extracted from deteriorated blocks seem to be very similar. To complement the above analysis, some supplementary petrographic procedures were conducted as per the extended version of the DRI as per [6].

- Assessment of damage features in %, without accounting for weighing factors (Figure 5.3) as well as maximum length and width of the open cracks (Figure 5.4) for each test specimen;
- Assessment of the crack density (i.e., total number of open cracks per area examined) for each test specimen (Figure 5.5).

As can be seen in Figure 5.3, for both concrete cylinder and unconfined concrete block, around 70% of distress generated is due to the presence of closed cracks within the aggregate particles (which is not necessarily an AAR distress feature as per [6]). Furthermore, about 20% of the damage features are comprised of open cracks within the aggregate particles with and without reaction products. Finally, very few cracks (less than 10%) were observed in the cement paste with or without gel.

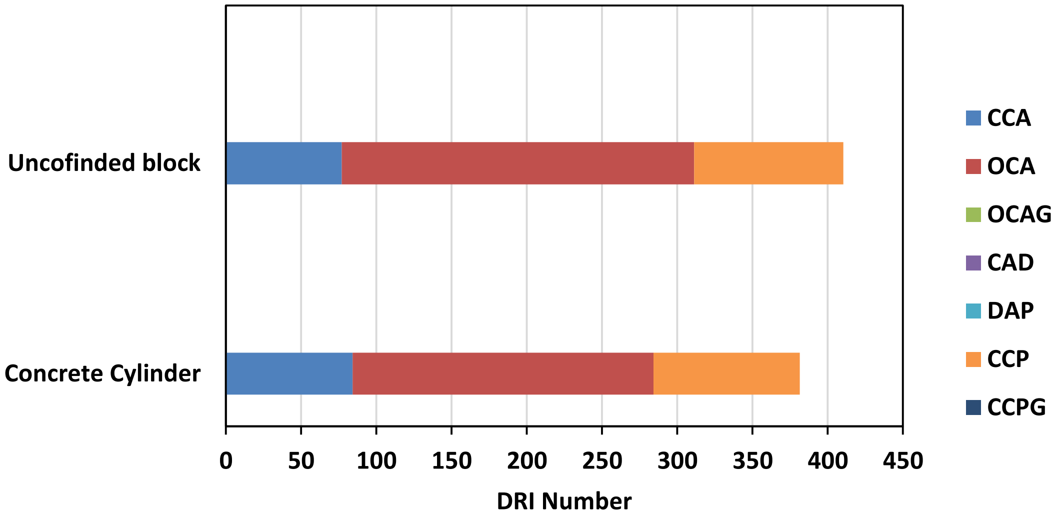


Figure 5.2: DRI charts for concrete samples presenting 0.07±0.01% expansion.

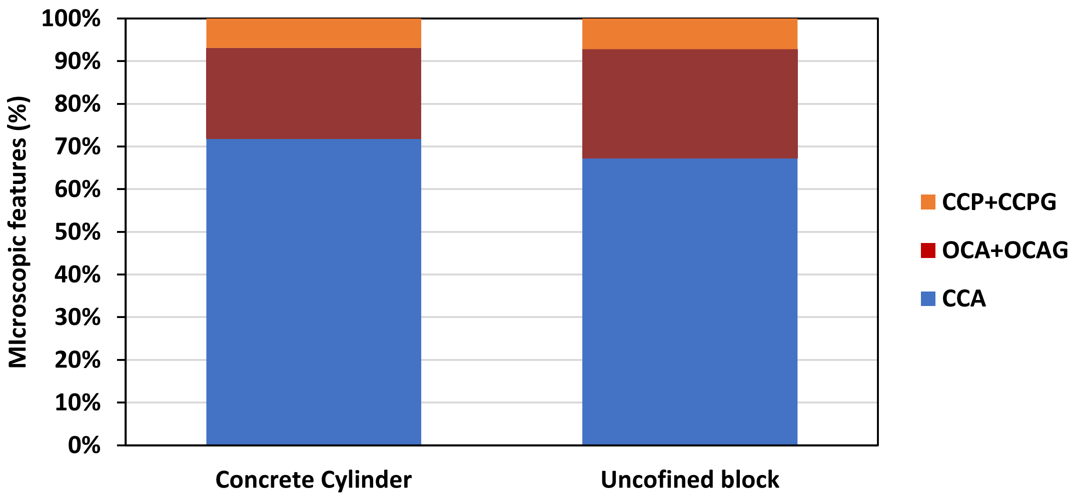


Figure 5.3: Microscopic features of deterioration (in %, without using the DRI weighing factors) normalized for 100 cm2 surface area.

Figure 5.4 indicates that the maximum crack length is slightly longer (i.e., 10 mm) for the core extracted from the unconfined block when compared to the affected concrete cylinder (i.e., 7 mm). Otherwise, the cracks width from the two members is similar (0.1 mm).

Figure 5.5 displays the crack density (i.e., number of open cracks within the aggregates and cement paste, with and without reaction products over the examined area for each specimens) of the unconfined cores and concrete cylinders. Observing the results, one notices that the crack density of the core extracted from the unconfined block and concrete cylinder is roughly the same (i.e., about 3.3 and 2.9 cracks/cm2, respectively).

The above analyses demonstrate that the overall damaged verified at the unconfined block and affected cylinder is very similar for the very first expansion level selected for evaluation. Differences are expected though for confined members. Finally, Figure 5.6 demonstrates typical distress features identified in the concretes cylinder samples as well concrete cored from unconfined blocks incorporating the Springhill aggregate.

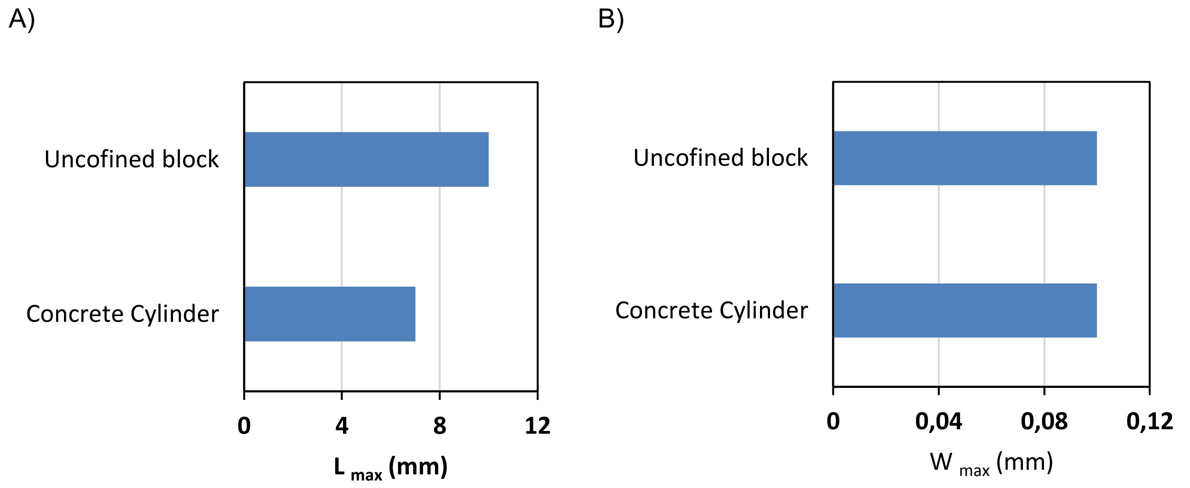


Figure 5.4: Maximum length (A) and width (B) of cracking for both unconfined block and concrete cylinder.

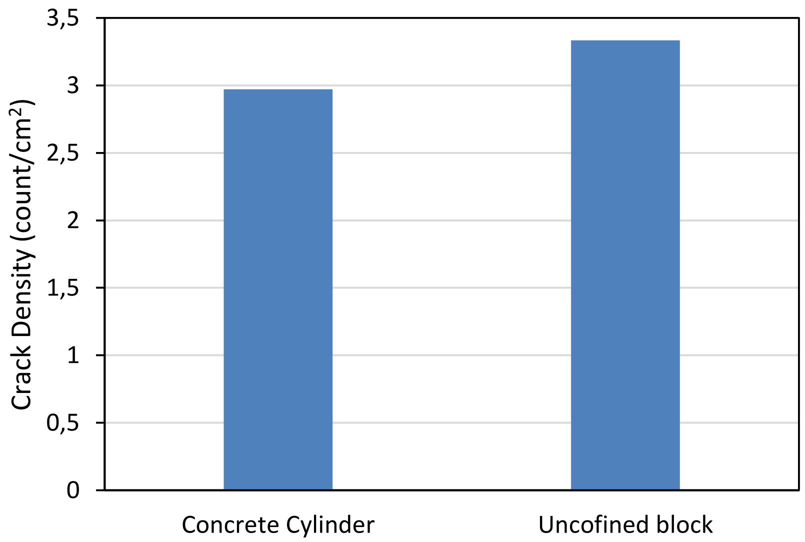


Figure 5.5: Crack density (counts/cm^2) of concrete specimens of this study.

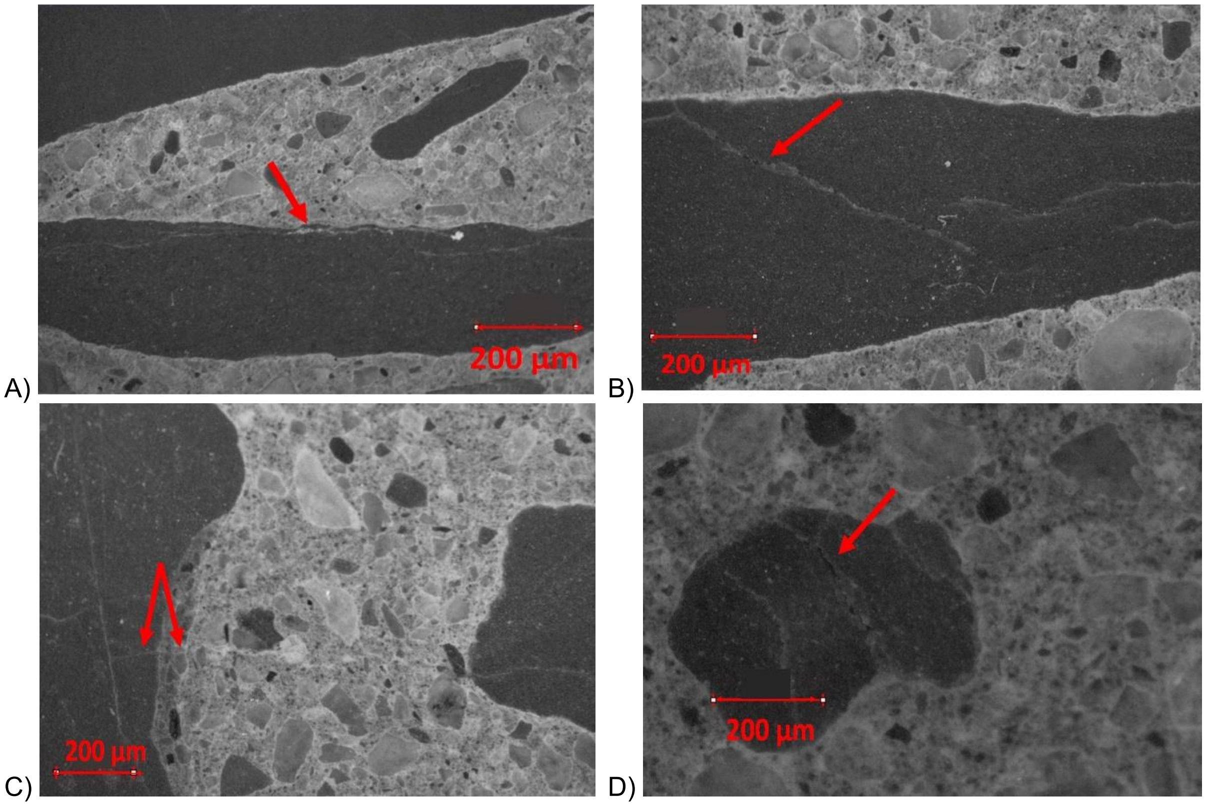


Figure 5.6: Typical cracking features identified in the concretes A and B close crack and open crack in concrete cylinder samples respectively and C and D close and open crack in aggregate in sample cored in unconfined concrete blocks respectively.

6. ANTICIPATED RESULTS AND DISCUSSION

As previously mentioned, further results on confined blocks could not be acquired at this stage. Yet, some anticipated results from the current research are presented hereafter and will be studied in detail in the near future:

- Distinction in expansion kinetics and reaction product features and formation (i.e., amount, chemistry composition, and viscosity) between restrained and unrestrained samples. It is expected that distinct confinement scenarios might change ASR-induced physicochemical development. In this regard, non-destructive (ultrasonic pulse velocity, electrical resistivity, etc.), mechanical (i.e., SDT, compressive strength, etc.) and microscopic techniques (i.e., DRI, SEM, etc.) will be conducted and the results compared and discussed.
- The efficiency of the multi-level assessment techniques as per [6] to appraise current damage (i.e., diagnosis) in concrete presenting distinct confinement scenarios, and to propose modifications whether required to improve reliability of the established multi-level approach;
- Evaluate the current techniques (i.e., residual expansion and soluble alkalis) for appraising AAR potential of further induced development and distress (i.e., prognosis) in affected concrete presenting distinct confinement scenarios. Concrete cores will be extracted from blocks presenting different confinements and prognosis tests will be conducted and compared with monitored blocks (that will not be cored) over time. Adjustments in the proposed prognosis test procedures will be performed whether required;
- It is expected that the overall damage (i.e., cracks initiation, propagation, and orientation) along with the losses in mechanical properties might differ from affected blocks presenting the same expansion levels but distinct confinement scenarios. Non-destructive, microscopic and mechanical techniques will be selected to answer these doubts.

7. CONCLUSIONS

Although a significant number of techniques have been developed for the diagnosis of AAR in unconfined concrete, the suitability of those techniques to appraise damage in affected members presenting distinct confinement scenarios is still not clear. Moreover, there is an important debate on the current techniques used to assess the potential of further deterioration (i.e., prognosis) of AAR-affected concrete. Therefore, the goal of this study is to evaluate the impact of confinement on AAR-induced physicochemical development of members presenting a wide range of confinement scenarios. Moreover, discussion on the suitability and reliability of the current techniques to appraise damage and the potential for further deterioration will be discussed. The preliminary results of this research have yielded the following findings:

- Concrete cylinders (100 by 200 mm) displayed faster AAR-induced development when compared to concrete blocks, both non-confined and confined which is likely due to the blocks' partial restriction. Moreover, the higher the confinement, the later the induced expansion and kinetics and the higher the initial shrinkage obtained;
- Confined blocks displayed distinct induced expansion as per different directions (i.e., transversal > longitudinal top > longitudinal side). The latter also emphasizes that localized effects (i.e., restriction, geometry, moisture, etc.) play and important role on AAR-induced volumetric expansion.
- The preliminary petrographic investigations performed so far through the DRI have verified that non-confined blocks and affected cylinders yield similar damage patterns for the first (and same) expansion level selected for analysis (0.07±0.01%).
- It seems that cracks formed in blocks, even in a non-confined scenario, are more important (i.e., slightly higher amount, longer, etc.) when compared to affected concrete cylinders. The latter might be linked to "scale effect". Yet, only preliminary results are reported here and thus further study is still required on this topic.

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