Assessment of AAR-induced expansion and damage through the direct shear test

Rouzbeh Ziapour (1), Cassandra Trottier (2), Leandro Sanchez (3)

(1) PhD Candidate, University of Ottawa, Ottawa, Canada, rziap098@uottawa.ca

(2) Master of Applied Science Candidate, University of Ottawa, Ottawa, Canada, ctrot059@uottawa.ca

(3) Assistant Professor, University of Ottawa, Ottawa, Canada, Leandro.Sanchez@uottawa.ca

Abstract

Alkali-silica reaction (ASR) is one of the most harmful distress mechanisms affecting concrete infrastructure worldwide. A wide number of studies have been conducted over the past decades on tools able to evaluate the cause and extent of damage (i.e. diagnosis) in concrete. Amongst those, some mechanical and microscopic test procedures have shown to be promising such as the Stiffness Damage Test and the Damage Raring Index. Recently, authors have proposed the use of an even simpler technique, a direct shear setup to appraise ASR-induced expansion and damage. The results were quite promising, yet further research was still required on a larger amount of affected samples. This work presents the use of the proposed shear setup to evaluate ASR-induced expansion and damage coming from reactive coarse and fine aggregates. Concrete samples incorporating coarse and fine highly reactive aggregates were manufactured and stored at conditions enabling ASR development. At selected expansion levels (i.e. 0.05%, 0.12% and 0.20%) the samples were tested through the proposed direct shear setup and evaluations of the outcomes were conducted. Results show that there is a strong correlation between the expansion degree and reduction in shear strength. Moreover, it has been found that the majority of shear strength loss already happens in the early stages of the expansion process and the type of reactive aggregate (coarse vs fine) plays a major role on the shear strength behaviour of affected concrete.

***Keywords**: alkali-silica reaction (ASR); shear strength; shear test setup; damage rating index (DRI)*

1. INTRODUCTION

Alkali-Silica Reaction (ASR) is one of the most harmful distress mechanisms affecting critical concrete infrastructure around the globe [1], [2]. It is a chemical reaction between some unstable siliceous mineral phases from the aggregates used in the concrete and the alkali hydroxides (Na^+, K^+, and OH^-) present in the concrete pore solution. ASR provides a gel that swells upon moisture uptake, leading to important pressure and distress.

One of the main challenges of assessing ASR-affected structures nowadays is to understand the current damage degree of the structure/structural components under appraisal (i.e. diagnosis), the potential for further expansion of those members as well as the current and future structural implications of the mechanism [1], [2]. In this context, a wide number of mechanical and microscopic techniques have been proposed in the past decades to assess the current distress along with the potential for further deterioration of ASR-affected concrete [3], [4]. Amongst the proposed protocols, recent studies have demonstrated the promising character of a simple direct shear test to detect ASR-induced expansion and damage to date.

2. BACKGROUND

2.1 Direct shear setup test

Shear strength of concrete is a property governed by tension and compression forces. Concrete tends to transfer shear forces across inner cracks through two distinct mechanisms: a) Dowel effect and; b) shear friction [5]. While the dowel effect is a mechanism related to reinforcement used in concrete, shear friction is a property governed by the concrete material itself. Shear friction is the frictional resistance of cracks to sliding [5]. It is often called as “aggregate interlock” and is an important component while designing reinforced concrete [6].

To study the aggregate interlock of concrete mixtures presenting distinct characteristics (e.g. mechanical properties) and incorporating different aggregates (e.g. aggregate lithotypes), Barr and Hasso [7] proposed a setup using a modified cylindrical sample, where a semi-circular notch was applied on each side of the samples as shown in Figure 2.1(a). Later on, Gao et al. [8] introduced a new setup to evaluate brittle fracture of reinforced concrete composites, showing promising results (Figure 2.1(b)). Recently, the setup proposed by Gao et al. [8] was adapted by Barr and Hasso [7] for further analysis in 100 by 200 mm samples, yet a circumferential notch of 20-25 mm has been selected for use (Figure 2.1(c)). The notch was expected to ensure a shear failure of the sample without leaving a too small shear plane which may jeopardize the test results.

De Souza et al. [9], utilized the last version of the setup proposed by Barr and Hasso [7] to evaluate AAR-induced development (i.e. induced expansion and damage) on affected concrete specimens. Promising results were achieved in this preliminary trial, yet further testing is still required on a larger amount of affected samples.

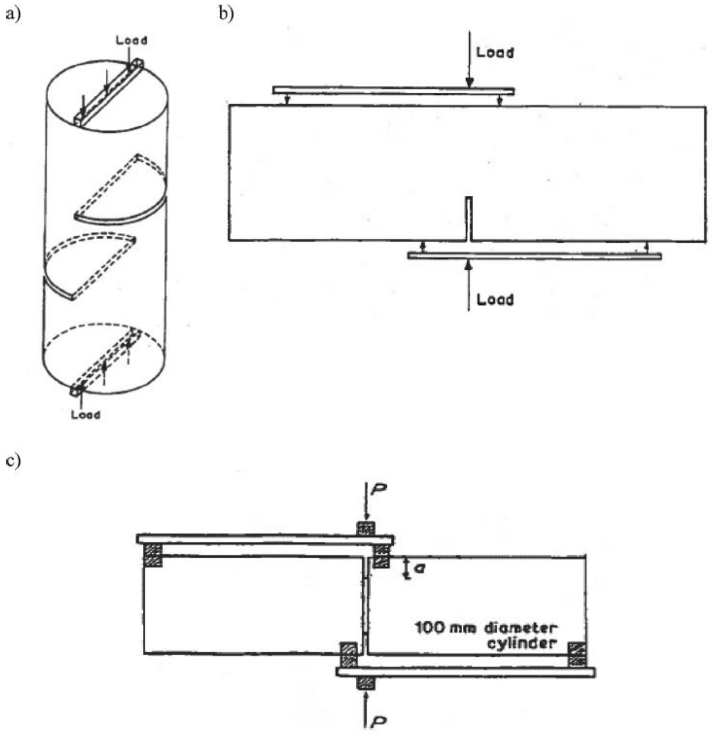

Figure 2.1: Shear setup of test concrete specimens [7,8]

2.2 Damage rating index (DRI)

The Damage Rating Index (DRI) is a microscopic analysis developed by Grattan-Bellew and Danay [10] whose main purpose is to appraise internal damage in affected concrete. The DRI is performed on polished concrete sections with the use of a stereomicroscope (15 to 16x magnification) where damage features are counted through a 1 cm² grid drawn on the surface of a polished concrete section. Ideally, a surface of at least 200 cm² should be used, however for comparative purposes, the final DRI value is normalized to a 100 cm² area. Recently, Sanchez et al. [11] performed the DRI on concrete samples presenting different strengths and fabricated with a wide range of coarse and fine aggregates. The authors proposed a slight modification on the method, to increase its performance and reliability [11]–[13]. They suggested the use of the same weighing factors for open cracks in the aggregate particles and cement paste with or without the presence of reaction products (i.e. ASR gel). Ever since, several research works confirmed the relationship between ASR-induced expansion and DRI results. Thus, the DRI is considered to be a very effective technique for assessing ASR affected concrete regardless of the aggregate type and concrete strength [14], [11].

3. SCOPE OF THE WORK

As previously mentioned, there is a need of simple, fast and yet reliable techniques to assess ASR-induced expansion and damage. The latter is imperative while the condition assessment of critical infrastructure affected by ASR. Amongst possible techniques, a direct shear test seems promising to quantify ASR expansion attained to date, yet a greater amount of results is still required to confirm the suitability of the proposed test procedure. This work focuses on the use of the direct shear setup as per De Souza et al. [9], to appraise ASR-induced expansion. A total of 32 concrete samples were fabricated incorporating two highly reactive aggregate types (i.e. reactive sand and coarse aggregate). At selected levels of expansion (i.e. 0%, 0.05%, 0.12% and 0.20%), the specimens were tested through the direct shear test as per [9] and the DRI as per [11]. The results were compared to previous works conducted by Sanchez et al. [4], [11], [12], [14] on similar aggregates in order to describe the results found through a multi-level assessment.

4. MATERIALS AND METHODS

4.1 Materials, mixture proportions and manufacture concrete specimens

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). These reactive aggregates were combined with non-reactive aggregates obtained from natural quarries in Ottawa (Ottawa natural sand and non-reactive limestone). The coarse aggregates ranged in size from 5mm to 20mm. All concrete specimens were mix-proportioned using the Concrete Prism Test (CPT) mix-design as per ASTM C1293, i.e. 420 kg/m^3 of Portland cement (PC) and a water-to-cement ratio of 0.45. A conventional Portland cement (CSA type GU, ASTM type 1) containing high alkali content (0.90% Na_2O_{eq}) was used in all mixtures. To accelerate ASR development, reagent grade NaOH was used to raise the total alkali content to 1.25% $Na_2O_{eq.}$ by cement mass.

A total of 32 concrete specimens (i.e. 16 per reactive aggregate type) were fabricated, de-molded after 24 hours and moist cured for over 24 hours. In order to measure the longitudinal expansion of the specimens, small holes (5 mm in diameter by 15 mm deep), 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. The samples were left at room temperature for 24 hours before the initial reading took place. The test specimens were then stored at 38^{o}C and 100% relative humidity (RH) using 22-liter plastic containers lined with an absorbent cloth. All the test cylinders were regularly monitored over time. Also, 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%(Control); 0.05% (low); 0.12% (moderate); 0.20% (high); and 0.30% (very high). Once the test specimens reached the above expansion levels, they were wrapped in plastic film and stored at 12°C to stop further ASR development until the direct shear test and DRI were conducted.

4.2 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. The direct shear test and Damage Rating Index (DRI) were then performed on test specimens containing coarse and fine reactive aggregates and expansion levels.

4.2.1 Damage Rating Index (DRI)

One specimen per expansion level per reactive aggregate was taken out from the 12°C storage, 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 ASR-gel leaching is avoided. Afterwards, the DRI was performed as per Sanchez et al. [12].

4.2.2 Direct shear test

As for the shear test, three specimen per expansion level per reactive aggregate was taken out from the 12°C storage, and its steel studs were completely removed. A table saw wielding a diamond blade (203 mm in diameter and 1 mm in thickness) was used to create a circumferential 22 mm deep notch at the center of the specimens to ensure a shear failure without leaving a too small area of the sample to be tested. The specimens were then tested in accordance to the setup and procedure proposed by Barr and Hasso[7] and adapted by De Souza et al. [9] (Figure 4.1).

Figure 4.1: Sample with a 22mm notch in the center and the direct shear setup configuration

The direct shear strength can be determined using the following equation (equation (1)).

$$\tau = \frac{P.4}{(\phi_{cylinder} - 2a)^2.\pi} \qquad (1)$$

Where P is the failure load (N), ϕ is the sample diameter (mm) and a is the depth of the notch (mm)

5. RESULTS

5.1 ASR kinetics and amplitude

The results for ASR-induced expansion as a function of time are presented in Figure 5.1 for the two aggregate types (i.e. Texas sand and Springhill coarse aggregate) used in this study. All specimens monitored displayed standard deviations of about 0.03% for all testing ages. Analyzing the plots, it can be observed that faster ASR kinetics was found for samples incorporating Texas sand when compared to Springhill coarse aggregates. Texas sand specimens reached an expansion of 0.30% in about 50 days where Springhill coarse aggregates only achieved 0.20% in 120 days, the Springhill specimens did not reach the expansion of 030% at the time of testing. It is worth noting that the coefficient of variation (i.e. standard deviation over the average) obtained at all measurements were very low (i.e. 0.01%).

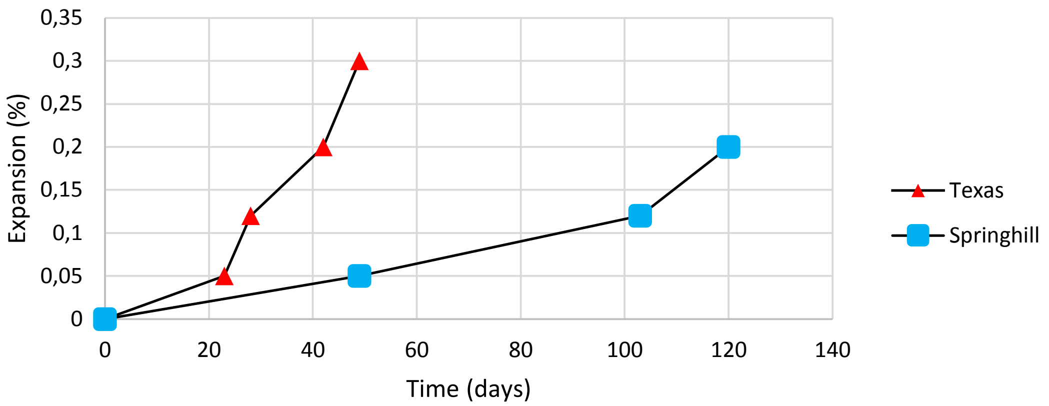

Figure 5.1: Expansion vs. time of ASR-affected specimens

5.2 Damage rating index (DRI)

Figure 5.3 shows the petrographic analysis in terms of DRI numbers as a function of ASR-induced expansion for specimens incorporating Springhill (coarse) and Texas (sand) reactive aggregates. One may notice that the DRI number increases as ASR expansion advances for both aggregate types; indicating 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 raise in expansion, since it is not considered as a distress feature linked to ASR-induced development. However, the open cracks in the aggregate particles (with or without reaction products - OCA and OCAG) and the cracks in cement paste (with or without gel - CCP and CCPG) indeed increase as a function of induced expansion (Figure 5.2). The DRI values observed ranged from 200 for low expansion levels (i.e. 0.05%) to 800 for high expansion levels (i.e. 0.20%). It is worth noting that specimens made of Texas sand reached 0.30% expansion, yielding DRI values of about 900. Furthermore, comparable DRI results were observed for affected concrete made of Texas sand or Springhill coarse aggregate.

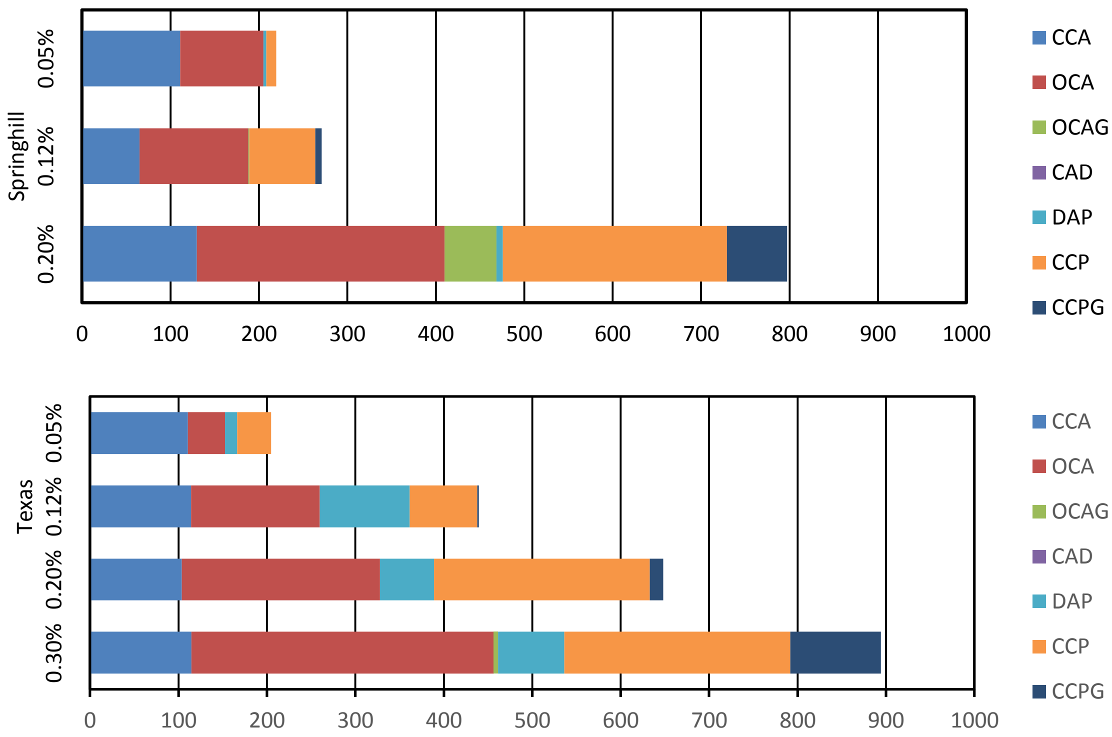

Figure 5.2: DRI values for distinct levels of expansion

5.3 Shear strength of ASR affected concrete

The direct shear test data of ASR-affected concrete at distinct levels are presented in Figure 5.3 and 5.4. Results indicate that the shear strength of ASR-affected concrete lessens as a function of induced expansion and development. The latter is true for both coarse and fine reactive aggregates. However, the shear strength loss seems to decrease at different rates whether the reactive aggregate is coarse or fine.

The direct shear is significantly impacted from the beginning of induced expansion (i.e. 0.05%) for ASR-induced by a reactive sand (18%), while no reduction is observed for ASR-induced by a reactive coarse aggregate. At moderate expansion levels (0.12%), Springhill specimens start being impacted by ASR, losing 20% of their initial shear strength. Conversely, Texas sand specimens presents almost no further shear loss (≈ 20%). At high expansion levels (0.20%), Springhill affected specimens present a significant reduction of shear strength (i.e. 35%), while Texas specimens still remain at about 20%. Finally, at very high expansion levels (0.30%), Texas specimens continue being impacted by ASR, reaching 25% of reduction. However, Springhill specimens did not reach 0.30% expansion level at the time of testing.

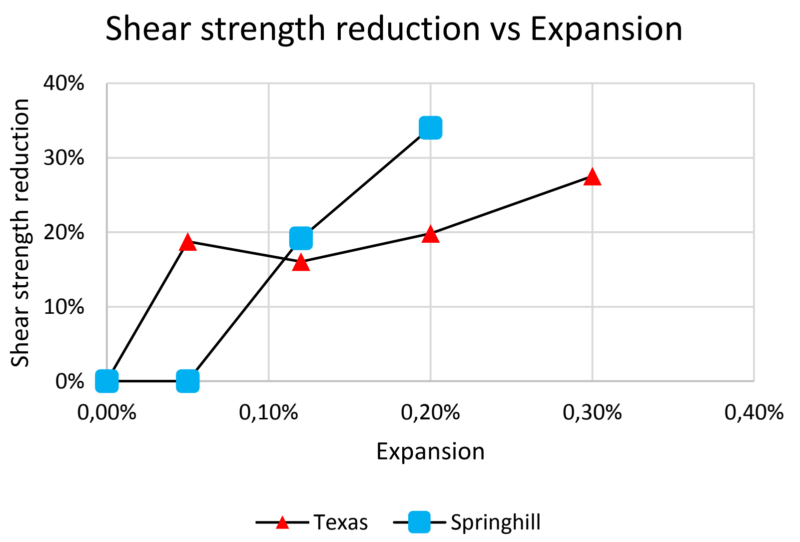

Figure 5.3: Direct shear strength reduction as a function of AAR-induced damage.

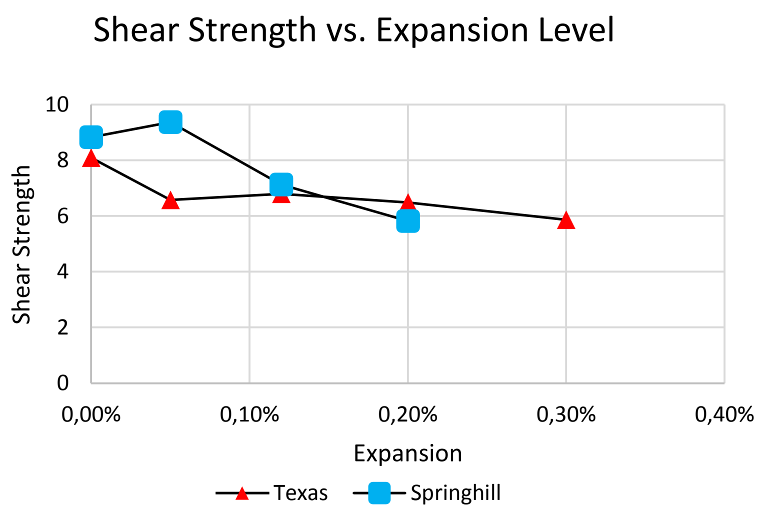

Figure 5.4: Direct shear strength as a *function of AAR-induced damage*

6. DISCUSSION

6.1 Understanding ASR-induced damage

Over the last decades, a wide range of tools were developed in the laboratory to understand ASR-induced expansion and damage generation and propagation under unrestrained conditions. Moreover, multi-level assessment approaches as per [13] have been proposed and showed to be able to describe ASR evolution from low to very high expansion and damage levels (Figure 6.1). Multi-level assessments suggest that ASR-induced deterioration initiates within the reactive aggregate particles at low expansion levels (i.e. 0.05%). As ASR keeps evolving, new cracks are generated within the aggregates, yet the pre-existing cracks keep increasing in length and width, reaching the cement paste at moderate expansion levels (i.e. 0.12%), at least at one side of the aggregates As the reaction further advances (i.e. 0.20%), it seems that based on the minimum energy law, it's easier for the reaction to further develop preexisting cracks instead of creating new ones. At this stage, cracks can be found in the cement paste at both sides of the aggregate particles, which raises significantly the cracking density of the affected material. Finally, at very high expansion levels and onward (i.e. 0.30%), the cracks in the cement paste connect to each other, forming an important crack network which directly impacts on the mechanical properties losses of the affected material, especially compressive strength.

The description above as per Sanchez et al [13] will be used to understand the direct shear results obtained in this work.

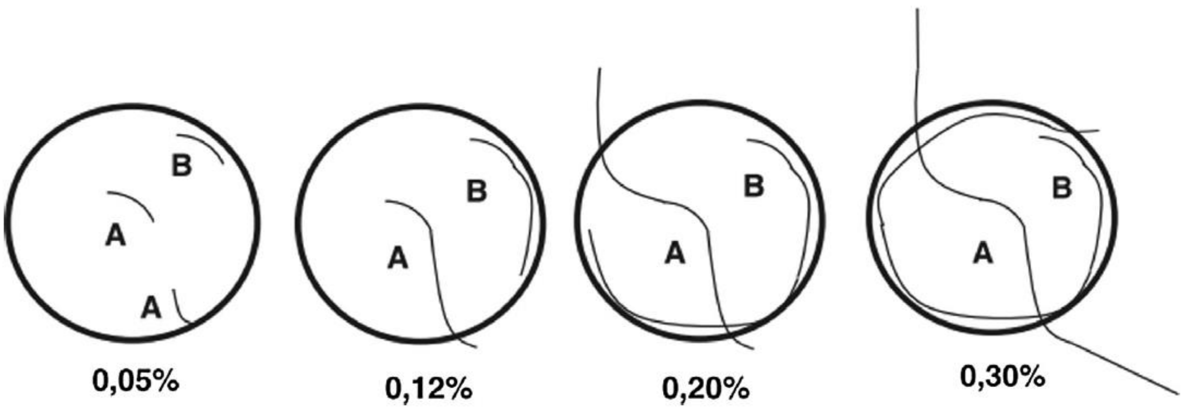

Figure 6.1: Qualitative damage model based on levels of expansion [13]

6.2 AAR-induced expansion and damage on Shear strength

6.2.1 Reactive coarse aggregate effect on shear strength

Figure 5 illustrates the shear strength reductions as a function of ASR-induced development for samples made of a reactive coarse (i.e. Springhill) and fine (i.e. Texas) aggregates. Evaluating the plot above, one notices that the shear strength lessens as a function of ASR progress. Yet, the reductions are not similar whether the reactive aggregate is a coarse or fine. In the case of Springhill specimens and as reported by Sanchez et al [13 – Figure 6.1], the cracks are mainly found within the aggregate particles at low expansion levels. Therefore, the aggregates can still be considered with almost the same "interlock effect", since under a stress-state very likely new cracks will be formed at the ITZ and outline the aggregate particles instead of going through and splitting them. This phenomenon would cause debonding of the aggregates while a shear failure using the proposed setup, which is exactly what has been verified as per Figure 6.1(a). At moderate expansion levels, some of the cracks developed within the aggregates reach the cement paste. The latter decreases the interlock effects of the aggregates and upon shear failure, some particles are expected to be split, as illustrated by Figure 6.1(b). Finally, for high expansion levels and onwards (i.e. > 0.20%), most of ASR cracks are expected to be in the cement paste, which might reflect in an important loo in shear but also in the majority of aggregates particles being broken while a failure in shear. This is very well visualized in Figure 6.1(c).

6.2.2 Reactive sand aggregate effect on shear strength

Although the qualitative and descriptive model proposed by Sanchez et al. [13] is still valid for ASR generated by reactive fine aggregates, the impact of ASR coming from a reactive sand on the shear failure of affected samples is expected to be slightly different from a reactive coarse due to the cracks generation within the system.

For samples made of the reactive Texas sand, it is verified that for low expansion levels (i.e. 0.05%), the cracks are still in the fine aggregates, yet, these aggregates are embedded in the so-called cement matrix (comprised of cement paste and sand). Thus, if new cracks are generated in the system at the ITZ while the shear test, very likely these cracks will take advantage (and shortcuts) of the pre-existing cracks in the matrix and thus the shear capacity of affected specimens should be reduced from the beginning of the chemical reaction. The latter is illustrated by the 20% loss observed by Texas sand samples at 0.05% expansion (Figure 5.3). Conversely, as ASR progresses and for moderate and high expansion levels (i.e. 0.12 and 0.20%), since the coarse aggregates used in the mix are non-reactive and do not present cracks until this stage, the reduction in shear tends to level off. This is explained by the matrix, which is expected to be leading the shear failure process, be already mostly deteriorated. Finally, at very high damage levels (i.e. 0.30%) some cracks may be observed within the non-reactive coarse aggregate particles. These may impact indeed on the shear capacity of affected specimens and are likely the cause of further shear strength reduction at this very high expansion level.

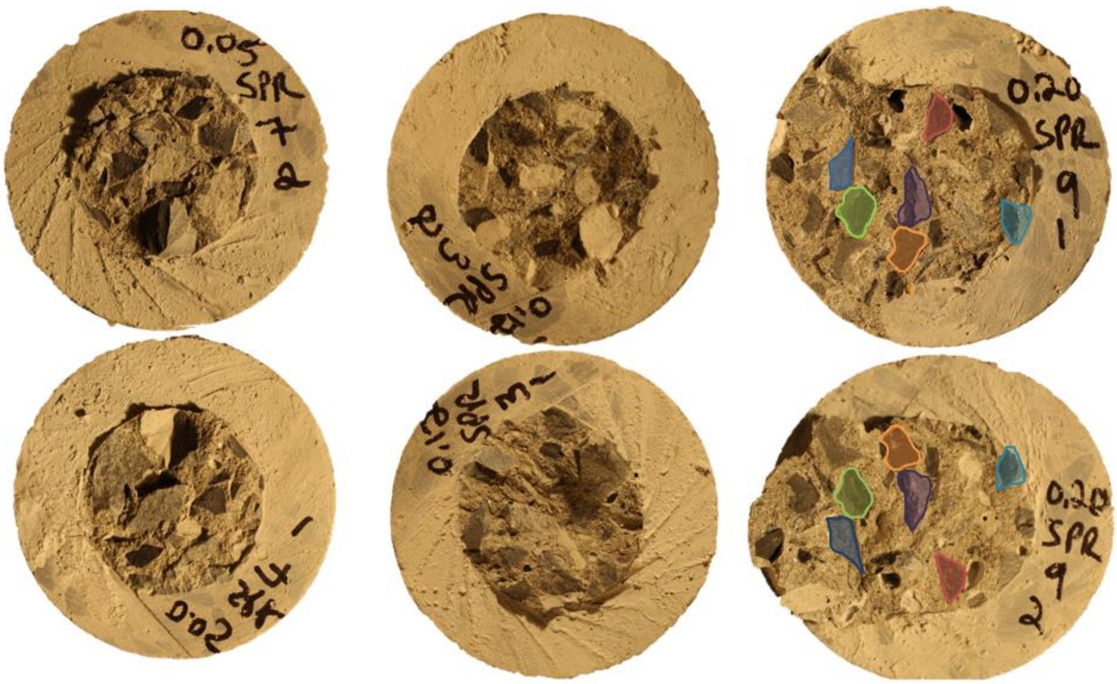

Figure 6.2 Shear failure of ASR affected Specimens where the mechanism is triggered by reactive coarse aggregate.

7. CONCLUSIONS AND RECOMMENDATION

The objective of this study was to validate the previous work performed by De Souza et al. [9] and compare how ASR-induced expansion and damage influences on the shear strength of ASR affected concrete comprised of reactive coarse and fine aggregates. From the results obtained, the following conclusions may be drawn:

- The higher the ASR-induced expansion and deterioration, the lower the direct shear strength of affected samples. Moreover, although the shear strength mechanism of concrete incorporating reactive coarse and fine aggregates is slightly different, the results seem to indicate that most of the shear strength reduction of ASR-affected samples happens in the early stages of the chemical reaction (i.e. 0.05%, 0.12%);

- The results obtained in this work seem to be in accordance with the data previously reported by De Souza et al.[9]. The latter emphasizes that the proposed direct shear test setup is a simple, yet reliable tool for appraising ASR-induced expansion of affected concrete;
- An image analysis conducted on the shear failure plane (Figure 8) was useful to understand the mechanism of failure generated by ASR coming from reactive coarse and fine aggregates as a function of its induced development;
- For a better assessment through the use of the proposed shear strength setup, it is recommended that at least 3, but ideally 6 samples shall be tested per concrete mix, per expansion level. The latter may help increasing reliability of the obtained results.

8. IMPORTANT DEFINITIONS AND ACRONYMS

DRI (Damage Rating Index) = a microscopic technique to appraise damage in concrete.

SDT (Stiffness Damage Test) = a mechanical protocol to appraise damage in concrete.

ITZ (Interfacial Transition Zone) = the interface between the aggregates and cement paste in conventional concrete.

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