Materiales de Construcción
Vol. 72, Issue 346, April-June 2022, e280
ISSN-L: 0465-2746
https://doi.org/10.3989/mc.2022.17621

Assessment of effects of ASR-induced cracking on direct shear strength of recycled concrete

R. Ziapour, C. Trottier, A. Zahedi, L.F.M. Sanchez ✉

Department of Civil Engineering, University of Ottawa, (Ottawa, Canada)
✉: Leandro.Sanchez@uottawa.ca

Received 28 November 2021
Accepted 2 March 2022
Available on line 6 May 2022

ABSTRACT: Recycled concrete aggregates (RCA) have been adopted as one of the most efficient methods to reduce the carbon footprint of the concrete industry. However, the performance of recycled concrete mixtures made of Alkali-silica reaction (ASR)-affected RCA is primarily unknown. In this work, two types of RCA were produced from ASR-affected concrete with distinct levels of deterioration (i.e., slight and severe). Three levels of secondary damage (i.e., expansion levels of 0.05%, 0.12%, and 0.20%) were selected and evaluated through the direct shear test. Results revealed that RCA concrete's shear strength depends on the severity of the RCA's past deterioration. Moreover, the performance of the concrete specimens subjected to direct shear are in accordance with the cracks features formed in the microstructure of the recycled concrete as a function of ASR-induced secondary expansion observed through the damage rating index (DRI).

KEYWORDS: Alkali-silica reaction (ASR); Direct shear test; Microscopic assessment; Damage rating index (DRI); Recycled concrete aggregate (RCA).

Citation/Citar como: Ziapour, R.; Trottier, C.; Zahedi, A.; Sanchez, L.F.M. (2022) Assessment of effects of ASR-induced cracking on direct shear strength of recycled concrete. Mater. Construcc. 72 [346], e280. https://doi.org/10.3989/mc.2022.17621.

RESUMEN: *Evaluación de los efectos de la fisuración inducida por ASR en la resistencia a cortante directa del hormigón reciclado.* Los áridos reciclados de hormigón (RCA) están siendo utilizados como uno de los métodos más eficientes para reducir la huella de carbono de la industria del hormigón. Sin embargo, el desempeño de las mezclas de hormigón reciclado hechas de RCA afectado por la reacción álcali-sílice (ASR) es en su mayoría desconocido. En el presente trabajo se produjeron dos tipos de RCA a partir del hormigón afectado por ASR con distintos niveles de daño (leve y severo). Se seleccionaron tres niveles de daño secundario (niveles de expansión de 0,05 %, 0,12 % y 0,20 %) y se evaluaron mediante el ensayo a cortante directo. Los resultados revelaron que la resistencia a la cizalladura del hormigón con RCA depende de la severidad de su daño anterior. Además, el comportamiento del hormigón sometido a cortante directo está en acuconcordancia con las características de las fisuras formadas en la microestructura del hormigón reciclado en función de la expansión secundaria inducida por ASR por el índice de clasificación de daños (DRI).

PALABRAS CLAVE: Reacción álcali-sílice; Ensayo de cortante directo; Evaluación microscópica; Índice de clasificación de daños (DRI); Áridos reciclados de hormigón.

This article was selected among the papers presented at the 2022 *International Conference on Alkali-Aggregate Reaction in Concrete* (16th ICAAR)

1. INTRODUCTION

Concrete is the most commonly used construction material worldwide due to the availability of its ingredients, economic benefits, and outstanding mechanical and durability-related properties. However, in 2018, the *International Energy Agency (IEA)* linked concrete production to approximately 7% of the global carbon dioxide emissions, mainly due to Portland cement production and aggregates processing (1). In light of the current urgency to adopt new measures to reduce the environmental impact of the production of concrete, recycling and reusing concrete can help reduce the consumption of non-renewable aggregates by transforming them into recycled concrete aggregates (RCA) while utilizing the adhered residual cement paste to reduce the new cement demand. However, there are still doubts on the material's variability and quality, especially concerning alkali-silica reaction (ASR), one of the most damaging distress mechanisms impacting concrete, which significantly reduces the service life of affected structures, leading to early demolition thus creating large amounts of waste.

Recent studies have evaluated the potential for "secondary" induced expansion of ASR-affected recycled concrete made of reactive coarse and fine RCA (2–7); these studies found that the source of the reaction (i.e., reactive coarse or fine aggregates) significantly affects the deterioration mechanism through its crack generation and propagation, kinetics, and potential of secondary expansion (6, 7). Nevertheless, very few works appraised the impact of ASR on the mechanical properties of RCA concrete (8). This work aims to evaluate the influence of ASR on the direct shear strength of RCA-affected concrete to better understand the role of the aggregate in such concrete mixtures. Moreover, correlations with microscopic analysis are also conducted to enhance understanding of the findings (6, 7). It is worth noting that to improve the text's readability, a description of all acronyms (in order of appearance) used in this work is presented in Table 1.

Table 1. Description of acronyms used.

Acronyms	Description
ASR	Alkali-silica reaction
RCA	Recycled concrete aggregate
DRI	Damage rating index
CC	Conventional concrete
OVA	Original virgin aggregate
RM	Residual mortar
EV	Equivalent volume mix design method
CCA	Closed crack in the aggregate
OCA	Open crack in the aggregate
OCAG	Open crack in the aggregate with gel
DAP	Disaggregated particles
CCP	Crack in the cement paste
CCPG	Crack in the cement paste with gel
CAD	Debonded aggregate
CPT	Concrete prism test
RH	Relative humidity
ITZ	Interfacial transition zone
NCP	New cement paste
RCP	Residual cement paste

2. BACKGROUND

2.1. Alkali-silica reaction (ASR)

Alkali-silica reaction (ASR) is a reaction between the alkalis from the cement paste (i.e., Na^+, K^+,OH^-) and uncrystallized silica within the aggregates. ASR is one of the leading causes of early concrete deterioration in Canada and worldwide (9). Concrete expansion levels are generally used to reflect ASR-induced damage. Figure 1 shows a qualitative crack propagation model in ASR-affected conventional concrete (CC), presenting A) sharp cracks and B) onion skin type cracks (10). Sharp cracks are generally initiated within the aggregate particles at a slightly damaged degree (i.e., 0.05% expansion level). As the reaction continues to a moderate expansion level (i.e., 0.12%), the previously generated sharp cracks propagate towards the aggregate's edges. At high expansion levels (i.e., 0.20%), the sharp cracks begin to extend into the cement paste. At very high expansion levels (i.e., 0.30%), the sharp cracks formed in the aggregates and the cement paste form an extensive cracking network and decrease the physical integrity of the material. Meanwhile, onion skin type cracks follow the aggregate's edge, elongating with increasing expansion until entering the cement paste. Mechanical properties (i.e., compressive strength tensile strength, and modulus of elasticity) of concrete affected by ASR are therefore reduced as a function of the expansion level, regardless of the aggregate type (i.e., coarse vs. fine aggregates) and nature (i.e., mineralogy) (10, 11). De Souza et al. (12) observed that the direct shear strength

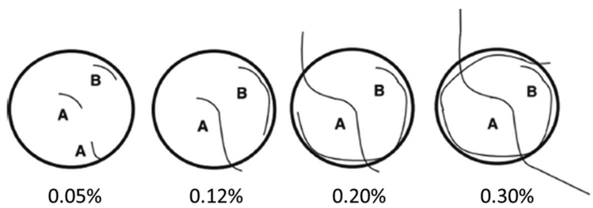

Figure 1. A qualitative model of crack propagation in ASR-affected CC (10).

of ASR-affected specimens reduces as a function of ASR expansion, observed even at low expansion levels, which was attributed to the adverse effect of ASR on the aggregate interlock of the concrete specimens.

2.2. Recycled concrete aggregate (RCA)

Recycled concrete aggregate (RCA) is a multiphase material composed of original virgin aggregate (OVA) and residual mortar (RM). RCA is often considered a lower quality material (i.e., presence of residual mortar - RM, impurities, deterioration, and high variability, among many others), resulting in lower concrete performance. Several mix-design procedures have been developed to increase the overall performance of recycled concrete. Among these mix-design techniques, the Equivalent Volume (EV) method (5) improves the hardened and fresh state properties and results in a more sustainable concrete mixture. The EV method is based on the mix-design technique developed by Fathifazl et al. (3) and its modified version (4). The EV mix-design technique aims to proportion recycled concrete mixtures with the same volume of aggregates (coarse and fine) and cement paste as a companion CC. Indeed, there are concerns regarding the use of RCA due to the presence of past deterioration such as ASR (12, 13), which can be influenced by the RCA production (i.e., aggregate crushing, washing, and storage) and the remaining reactivity potential (14–18). Trottier et al. (6, 7) found that the kinetics and deterioration process (i.e., crack width, crack length, and propagation path) are affected by the severity of initial damage and its location (i.e., OVA or RM). However, the influence of this type of aggregate on the aggregate interlock, determined through the direct shear test, remains unknown. Techniques used to assess ASR damage in concrete.

2.2.1. Damage Rating Index (DRI)

The damage rating index (DRI) is a microscopic tool developed (19) and further modified (10, 20) to appraise damage in ASR-affected concrete. After polishing the surface of a concrete section (i.e., cut longitudinally), distress features are counted with the help of a stereomicroscope (15 to 16x magnification) in a 1 cm^2 grid drawn on the reflective surface. The distress feature counts are then weighted according to their location and importance (i.e., 0.25 for closed cracks in the aggregate – CCA; 2 for open cracks in the aggregate without and with gel and disaggregated particles – OCA, OCAG, and DAP, respectively; and 3 for cracks in the cement paste without and with gel and debonded aggregate – CCP, CCPG, and CAD, respectively). The overall assessment is then normalized to 100 cm^2 resulting in the DRI number. This microscopic tool is an effective technique for assessing the degree of damage of ASR-affected concrete regardless of the aggregate type and concrete strength (10, 20, 21), as well as for recycled mixtures (6–8). Furthermore, the extended version of DRI, presenting characteristics in absolute (counts/100 cm^2) and relative (%) values without the weighting factors, gives a more thorough evaluation and comprehension of the ASR-induced damage development. (8, 10).

2.2.2. Direct shear setup test

The direct shear strength of concrete measures the material's aggregate interlock.; compression and tension are the governing forces in measuring the latter. The transfer of shear forces across inner cracks occurs through two mechanisms: a) dowel effect and b) shear friction (22). While the dowel effect is related to reinforcement used in concrete, shear friction is the frictional resistance of cracks to sliding (22) used in reinforced concrete design known as aggregate interlock (23). Barr and Hasso (24) proposed a setup using a modified cylindrical concrete specimen, where a semi-circular notch was applied on each side, expected to ensure a shear failure at this location. Gao et al. (25) introduced a new setup to evaluate the brittle fracture of reinforced concrete composites. The setup proposed by Gao et al. (25) was adopted by Barr and Hasso (26) for further analysis in 100 by 200 mm cylindrical specimens, using a circumferential notch of 20-25 mm in depth (Figure 2). Ultimately, De Souza et al. (27) utilized the last version of the setup proposed by Barr and Hasso (26) to evaluate the effects of ASR on the direct shear strength of affected concrete specimens.

3. SCOPE OF WORK

As aforementioned, only a few works have evaluated the impact of RCA's initial damage on the mechanical properties and deterioration of concrete made of ASR-affected RCA, while the influence of ASR on the mechanical properties of CC is somewhat well understood. This work aims to assess the influence of previ-

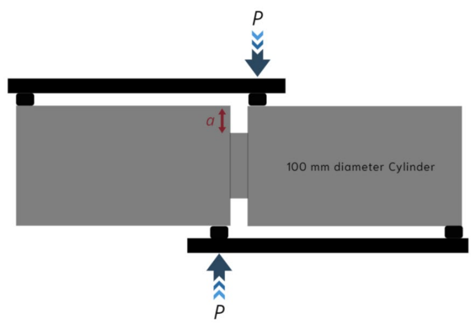

Figure 2. Shear setup for concrete specimens (26).

ously damaged RCA and its severity on the aggregate interlock captured by the direct shear strength test. As such, CC specimens incorporating a reactive coarse aggregate (i.e., Springhill - Greywacke) were manufactured in the laboratory and stored under conditions enabling ASR-induced expansion and deterioration. The specimens were split into two groups: slightly deteriorated (i.e., 0.05%) and severely deteriorated (i.e., 0.30%) concrete; upon reaching the above expansion levels, the specimens were crushed, and RCA material was obtained. RCA concrete specimens made of slightly and severely ASR-deteriorated coarse aggregates were fabricated and stored at conditions enabling secondary ASR-induced development. Secondary damage (i.e., expansion levels) was monitored over time to compare the ASR kinetics of recycled concrete with a companion CC affected by ASR. The direct shear test was then conducted on specimens reaching expansion levels of 0.05%, 0.12% and 0.20%, followed by complementary microscopic analysis (i.e., damage rating index) on a separate set of specimens at each expansion level to better understand the role of the RCA in concrete affected by ASR.

4. MATERIALS AND METHODS

4.1. Concrete manufacturing

To fabricate the control CC specimens (i.e., 100 mm by 200 mm, 35 MPa concrete cylinders) and concrete specimens to be used to produce the RCA, a highly reactive coarse aggregate (i.e., Springhill – Greywacke) was combined with natural non-reactive sand sourced locally in Ottawa. All concrete specimens were mix-proportioned following the concrete prism test (CPT) as per ASTM C1293 (28); CSA general use (ASTM type 1) Portland cement was used in the mixture. To accelerate ASR development, the total alkali content of the mixture was raised to 1.25% $Na_2O_{eq.}$ by cement mass after adding reagent grade NaOH. The specimens were moisture-cured in 100% relative humidity (RH) and 20°C, and then de-moulded after 24 hours. Holes of 5 mm in diameter by 15 mm in depth were then drilled in both ends of the specimens, and stainless-steel gauge studs were glued using a fast-setting cement paste slurry on both ends for the length change measurements. The specimens were left to moist-cure for an additional 24 hours before the initial reading. The specimens were then stored over a film of water in 22-litre plastic containers lined with an absorbent cloth and then placed in an environmental chamber (i.e., 100% RH and 38°C). The abovementioned absorbent cloth was installed on the lid and inside the buckets to prevent the formation of droplets and minimize the effect of leaching. Prior to the periodic monitoring of the length change measurements, the containers were removed from the environmental chamber and cooled down to 20°C for 16 ± 4 hrs. The specimens were taken out one by one during the measurement period, and buckets were returned to the environmental chamber immediately after each measurement. Two levels of expansion representing distinct damage degrees were selected to produce the RCA: 0.05% and 0.30% (i.e., slight and severe, respectively). The specimens were then jaw crushed to produce reactive coarse RCA ranging from 4.75 mm to 19 mm in size. After crushing, the RCAs were stored in sealed buckets in conditions preventing further ASR development (12°C). The RM content of slightly damaged RCA and severely damaged RCA were 46% and 51.5%, respectively. The RM content was determined following the procedure proposed by Abbas et al. (29), which involves five cycles of freezing and thawing. All recycled mixtures were proportioned using the EV method (5) while keeping the total cement content of the system equal to 420 kg/m^3 (i.e., using the CPT mixture proportions as the companion mixture) as presented in Table 2. To raise the alkali content, the recycled mixtures also incorporated reagent grade NaOH and were cast, cured, prepared, stored, and monitored over time, following the same procedures as aforementioned for the CC. It is worth noting that to assess the effect of initial damage on the future performance of the RCA concrete, only the alkali contribution from the new cement paste was considered. The total alkalis of the system was kept constant, and the stage of the initial reaction was not considered in the total alkali content calculation.

Table 2. Conventional and RCA mix proportioning.

Raw materials	Springhill CC	Slightly damaged RCA-concrete (0.05% -SPR-RCA)	Severely damaged RCA-concrete (0.30% -SPR-RCA)
Coarse aggregate-highly reactive (kg/m^3)	934	1040	1048
Sand-non reactive (kg/m^3)	823	774	791
Cement (kg/m^3)	420	340	331
Water (kg/m^3)	189	153	149

4.2. Experimental procedures

4.2.1. Direct shear test

The direct shear test was used to evaluate the direct shear strength (i.e., aggregate interlock) of the recycled mixtures. Three specimens per concrete mixture (i.e., CC, slightly and severely damaged recycled mixtures) and expansion level selected for this study (i.e., 0%, 0.05%, 0.12% and 0.20%) were prepared for the direct shear test. A circumferential 22 mm deep (26) and 5 mm wide (i.e., the width of the diamond blade on the masonry saw) notch at the center of the specimens was cut to ensure a shear failure at the notch. The specimens were then tested in accordance with the setup and procedure proposed by Barr and Hasso (26), as shown in Figure 2. A loading rate of 100 N/s was selected for this study. The following Equation [1] was then used to calculate the direct shear strength:

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

Where denotes the failure load (N), denotes the cylinder diameter (mm), and denotes the depth of the notch (mm).

4.2.2. Damage Rating Index (DRI)

One specimen per mixture (i.e., CC, slightly and severely damaged recycled mixture) and expansion level (i.e., 0%, 0.05%, 0.12% and 0.20%) was cut in half longitudinally and polished with diamond-impregnated rubber disks of successive grits (i.e., 30, 60, 140, 280, 600, 1200, 3000) through the use of a mechanical polishing machine prior to conducting the microscopic assessment. A grid of 1 cm by 1 cm was drawn on the reflective surface, and each square was observed through a stereomicroscope at 16x magnification. Distress features were then counted in each square while applying a weighting factor to each feature as per (20). The sum of the weighted counts was normalized to 100 cm^2 to obtain a DRI number. Moreover, the extended version of the DRI (i.e., without the application of the weighting factors) was also performed as per Sanchez et al. (10).

5. RESULTS AND DISCUSSION

5.1. ASR development and kinetics

Figure 3 illustrates ASR-induced average expansion levels as a function of time. A standard deviation of 0.01%-0.04%, 0.02%-0.04% and 0.02%-0.03% was obtained for the CC and recycled mixtures made of slightly damaged and severely damaged RCA, respectively. Expansion measurements were carried out for 150 days on the CC at which an expansion level of 0.31% was reached, whereas after 188 days, levels of expansion of 0.24% and 0.28% were obtained for the slightly and severely damaged recycled mixutres, respectively. A similar trend is observed at the beginning from 0-0.03% of expansion (i.e., 29 days), after which both recycled mixtures increase in expansion up to 0.09% and 0.06% at 51 days for the severely and slightly damaged RCA, respectively, while the CC attains only 0.05% at 52 days. After approximately 63 days, the CC swelled at a faster rate when compared to both recycled mixtures. The severely and slightly damaged recycled mixtures, as well as the CC, reached an expansion level of 0.05% at 36, 44 and 49 days, and an expansion level of 0.12% at 79, 94 and 75 days, respectively. Meanwhile, an expansion of 0.20% was observed after 94, 128, 157 days for the CC, severely and slightly dam-

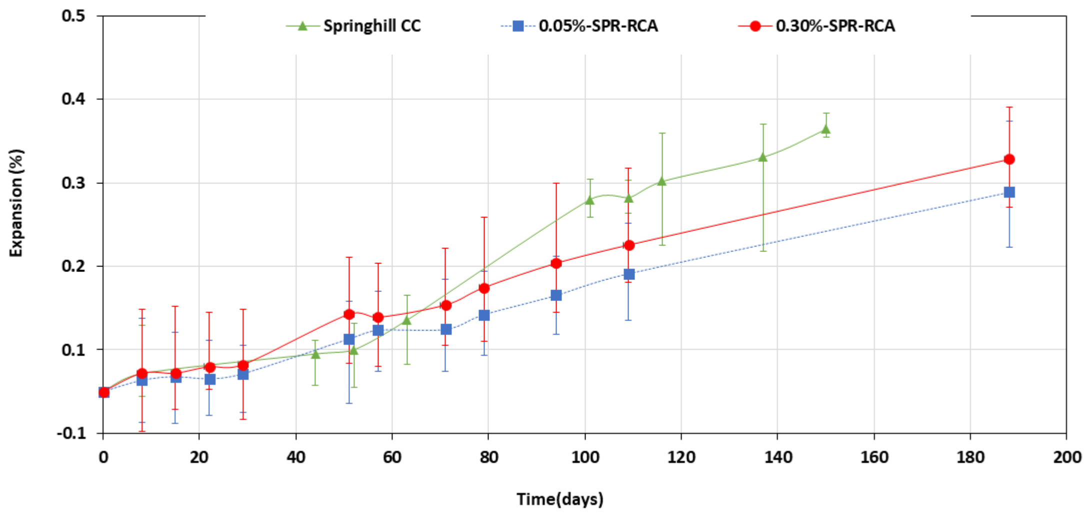

Figure 3. Expansion as a function of time for concrete mixtures (6).

aged recycled mixtures, respectively.

5.2. Direct shear test

The direct shear strength and reductions at distinct expansion levels of the CC and recycled concrete mixtures are presented in Figures 4a and 4b, respectively. Results indicate that the direct shear strength of all mixtures lessens as a function of induced expansion and ASR development. The CC's direct shear strength begins to decrease only after 0.05% of expansion (i.e., initially at 8.81 MPa) which can be attributed to the cracks being present within the aggregates as presented in Figure 1; thus, cracks propagating through the interfacial transition zone (ITZ) during shear failure. Hereafter, the decrease in direct shear strength is linear for the CC, reaching 5.82 MPa at 0.20% of the expansion. The recycled mixtures on the other hand, present a lower initial shear strength when compared to the CC. The slightly damaged RCA displayed an initial direct shear strength of 7.2 MPa. As expansion advanced, at low and moderate expansion levels (i.e., 0.05% and 0.12%, respectively), the direct shear strength reduced to 5.81 MPa and 5.44 MPa (i.e., losses of 20% and 24%, respectively). At an expansion level of 0.20%, a significant loss is observed (i.e., loss of 44%), reducing the direct shear strength to 4.02 MPa. Likewise, the severely damaged RCA with an initial direct shear strength of 6.8 MPa presented a similar trend through the low and moderate expansion levels (i.e., losses of 20% and 29%, respectively). Interestingly, no significant loss was observed at a high expansion level (0.20%), unlike the slightly damaged RCA (i.e., from 29% to 34%).

5.3. Microscopic assessment

The result from another study by Trottier et al. (6) with the same RCA particles and mixture proportions, was used to complement the results obtained through the direct shear test and understand the role of the RCA particles. Due to the multi-phase nature of the aggregates, the cracks observed in the cement paste were classified into two categories: a) cracks in new cement paste (NCP) and b) cracks in the residual cement paste (RCP). It should be noted that the crushing and weathering of the aggregates could result in closed cracks inside the aggregates, and these cracks are not necessarily attributed to ASR (30). However, a decrease in such cracks is a result of closed cracks in the aggregates opening due to the expansion of silica gel within these sites. As such, the CC mixture shows an increase in the proportions of *open cracks in the aggregates* (from 12% to 40%), as well as *cracks in the cement paste* (from less than 1% to 10%) up to moderate expansion level (i.e., 0.12%). Afterwards, their proportions remain constant (Figure 5a) although the number of cracks keeps increasing, as shown in Figure 5b. The severely damaged mixture (i.e., 0.30%-SPR-RCA) displays a significantly higher portion of *open cracks in the aggregate with and without gel* when compared to the slightly damaged mixture (i.e., 0.05% -SPR-RCA) before being subjected to secondary damage (28% and 10%, respectively). The proportion of *open cracks in the aggregate without and with gel* increases up to 45% for slightly damaged RCA and 36% for the severely damaged RCA concrete at 0.20% of expansion (Figure 5a). Meanwhile, the cracks in the cement paste present a significantly smaller proportion overall yet, similar proportions in both recycled mixtures are observed, increasing with expansion (i.e., from 5% to 20%).

The DRI numbers generally increase with increasing expansion, as presented in Figure 5b. The CC mixture displays the highest DRI values, followed by the severely then slightly damaged RCA mixtures. Before being subjected to ASR, only a negligible level of damage was observed for all concrete mixtures (i.e., DRI values of 138, 73, and 171, for CC, slightly and severely damaged RCA, respectively). At 0.05% and 0.12% of expansion levels, the CC mixture presents the highest DRI numbers (i.e.,

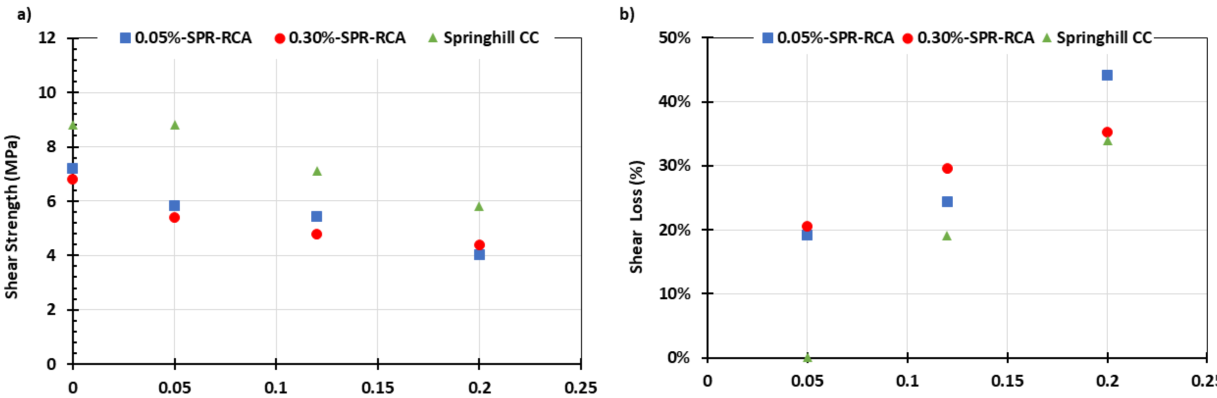

FIGURE 4. a) Direct shear strength of ASR affected specimens, and b) shear loss of ASR affected specimens at distinct expansion levels.

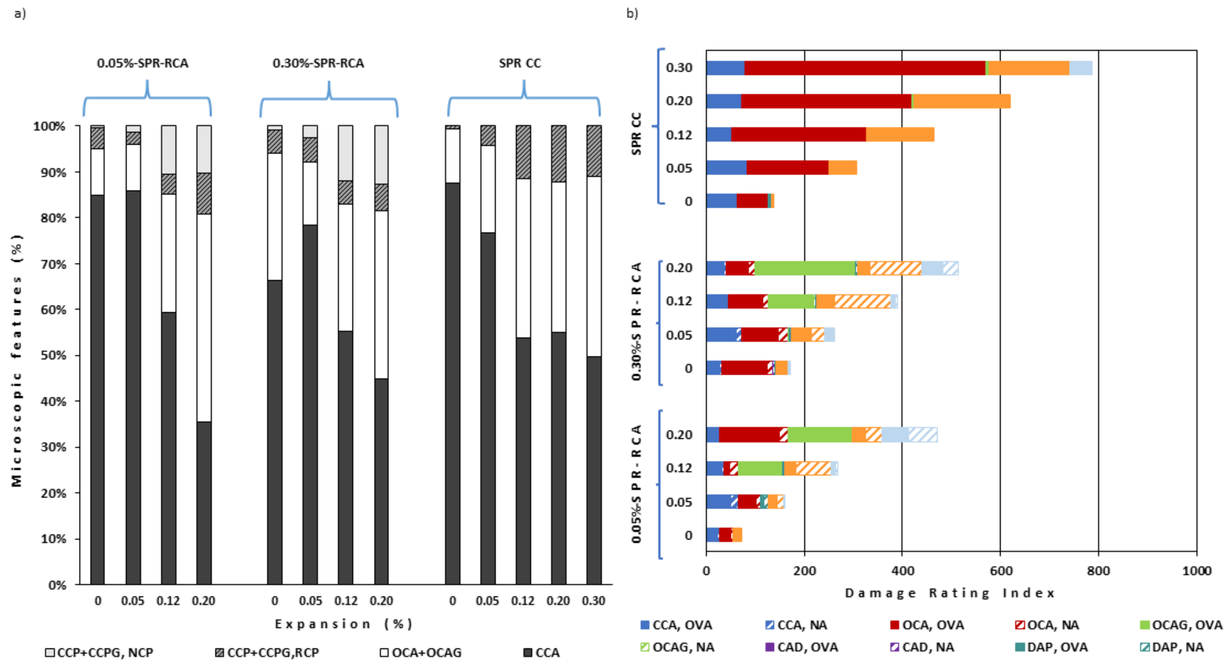

Figure 5. a) Percentage of distress features and b) DRI chart in CC and RCA concrete (6).

307 and 465, respectively) between all mixtures, while the slightly and severely damaged RCA mixtures achieve 161 and 261 for low (i.e., 0.05%) expansion and 268 and 390 for moderate (i.e., 0.12%) expansion, respectively. A significant increase in the DRI number is found for the slightly damaged RCA concrete at the expansion of 0.20%. (i.e., 470) whereas the severely damaged RCA and CC mixtures increased to 514 and 621.

5.4. Discussion and overall assessment

The shear strength of recycled mixtures presented interesting results when compared to the CC mixture. At low expansion levels (i.e., 0.05%), CC mixtures presented cracks mainly within the aggregates (10, 11, 21). This behaviour was well captured by the direct shear test (i.e., no reduction of the shear strength as per Figure 4) since no “aggregate interlock loss” is expected when cracks remain within the aggregate particles. Conversely, at moderate expansion levels (i.e., 0.12%), some of the cracks developed within the aggregates reached the cement paste (Figure 1), decreasing the aggregate interlock due to the splitting of the particles, which significantly reduces the shear strength of the affected material. In addition, the location of cracks (i.e., aggregate vs cement paste) and their severity (i.e., number, crack length and crack width) significantly affected the shear strength of CC (31). On the other hand, RCA mixtures showed a lower initial shear strength when compared to CC, likely due to: a) the distinct microstructure (i.e., multi-phase nature and increased number of ITZ) of RCA particles and, b) the crushing/processing inducing micro-cracks, which might have compromised the aggregate interlock capacity of RCA concrete as previously observed in the literature (22, 32, 33). Conversely to the CC mixtures where the shear strength remained constant from 0% to 0.05% of expansion, the recycled mixtures showed a 19% and 20% shear strength loss. This difference in the shear strength reduction in recycled mixtures compared to CC is likely due to the previous ASR damage, resulting in the secondary damage having a short initiation period leading towards cracks extending to the cement paste in recycled mixtures before such cracks are observed in CC (Figure 5b). Moreover, the influence of the previous ASR damaged was captured by the direct shear test where recycled mixtures made of slightly deteriorated RCA concrete displayed a greater initial shear strength when compared to RCA made of severely deteriorated particles. The DRI numbers obtained for the slightly and severely damaged recycled mixtures prior to being subjected to secondary ASR damage (i.e., 73 and 171, respectively) support the trend observed through the shear strength. Yet, a DRI number of 138 was reported for the CC, while a higher shear strength was observed at 0% of expansion. Therefore, the number of cracks does not necessarily govern the shear strength. Moreover, the open cracks in the aggregates are significantly lower in number for the slightly damaged RCA yet, similar numbers are observed for the severely damaged mixture and the CC. At 0.05% of expansion, although the shear strength in CC remains constant, the number of open cracks in the aggregate increases significantly while a smaller increase is observed in both recycled mixtures, highlighting the influence of the nature of the RCA presenting previous damage. Furthermore, the width of cracks may have played an essential role in the direct shear strength of recycled mixtures. Recycled mixtures at low expansion levels presented significantly wider cracks than CC (i.e., 0.15 mm and 0.10 mm, respectively) (7).

An interesting behaviour is observed at 0.20% of expansion for the slightly damaged recycled mixture observed through both the shear strength and the DRI number. The shear strength thus presents a higher loss for the slightly damaged mixture while the DRI number increases significantly with the number of open cracks in the aggregate being similar to that of the severely damaged mixture, further highlighting the difference between the RCA particles subjected to different levels of previous damage. In addition, at high expansions (i.e., 0.20%), cracks were widest in the slightly damaged RCA concrete reaching 0.25 mm, compared to 0.20 mm for severely damaged RCA concrete and CC as previously reported (7). The sudden loss of direct shear strength observed in the recycled concrete made of slightly damaged RCA at an expansion level of 0.20% may be linked to wider observed cracks. Nevertheless, the reactive potential of the RCA particles was captured by both tools used in this study. It is worth noting that it is generally agreed that the shear strength of concrete not only depends on the location and width of cracks, but the crack directionality could also play an important role in the shear strength of concrete specimens (34, 35), thus the impact of crack directionality on the shear strength of RCA concrete is recommended topics for future work.

6. CONCLUSIONS

This study aimed to appraise the direct shear strength reduction of concrete containing ASR reactive RCA while understanding its behaviour through a microscopic analysis. The results were compared with a companion CC, and the key findings of this study are presented below:

- The results gathered in this research indicate that the severity of past deterioration in RCA affects the shear strength of recycled concrete; it is worth noting that the location and type of these distress features are of great significance towards the shear strength of recycled concrete.
- Although severely damaged RCA displays a higher level of damage through the DRI number for all three secondary expansion levels selected in this study, slightly damaged RCA presented a significantly higher loss of direct shear strength and a significant increase in the DRI number at 0.20% of the expansion.
- The direct shear strength setup used in this study was able to capture the increase in ASR damage in CC and the recycled mixtures. The influence of the primary damage in the RCA particles was also highlighted through both the shear strength and DRI numbers which emphasizes the necessity to distinguish the type of RCA used in new concrete mixtures.
- Overall, the direct shear strength of RCA concrete depends on the original concrete properties and the secondary induced deterioration taking place in the RCA concrete. This was observed by Trottier et al. (7) when developing a qualitative model of crack generation and propagation of RCA. Further investigation of the mechanical properties is required to understand the effects of initial and secondary damage on RCA concrete.
- The overall crack width of the system plays an essential role in assessing the direct shear strength of ASR-affected specimens. This was clearly observed in this work, especially at high expansion levels.

AUTHOR CONTRIBUTIONS:

Conceptualization: R. Ziapour, L.F.M. Sanchez. Data curation: R. Ziapour. Formal analysis: R. Ziapour. Investigation: R. Ziapour, C. Trottier. Methodology: R. Ziapour, C. Trottier. Supervision: A. Zahedi, L.F.M. Sanchez. Validation: R. Ziapour, L.F.M. Sanchez. Writing, original draft: R. Ziapour, C. Trottier, A. Zahedi, L.F.M. Sanchez. Writing, review & editing: R. Ziapour, C. Trottier, A. Zahedi, L.F.M. Sanchez.

REFERENCES

1. International Energy Agency (2018) Cement technology roadmap plots path to cutting CO2 emissions 24% by 2050 - News - IEA. *Iea* [April], 1–3.
2. Abbas, A.; Fathifazl, G.; Isgor, O.B.; Razaqpur, A.G.; Fournier, B.; Foo, S. (2009) Durability of recycled aggregate concrete designed with equivalent mortar volume method. *Cem. Concr. Comp.* 31 [8], 555–563. https://doi.org/10.1016/j.cemconcomp.2009.02.012.
3. Fathifazl, G.; Abbas, A.; Razaqpur, A.G.; Isgor, O.B.; Fournier, B.; Foo, S. (2009) New mixture proportioning method for concrete made with coarse recycled concrete aggregate. *J. Mater. Civ. Eng.* 21 [10], 601–611. https://doi.org/10.1061/(asce)0899-1561(2009)21:10(601).
4. Hayles, M.; Sanchez, L.F.M.; Noël, M. (2018) Eco-efficient low cement recycled concrete aggregate mixtures for structural applications. *Constr. Build. Mater.* 169, 724–732. https://doi.org/10.1016/j.conbuildmat.2018.02.127.
5. Ahimoghadam, F.; Sanchez, L.F.M.; de Souza, D.J.; Andrade, G.P.; Noël, M.; Demers, A. (2020) Influence of the recycled concrete aggregate features on the behavior of eco-efficient mixtures. *J. Mater. Civ. Eng.* 32 [9], 04020252. https://doi.org/10.1061/(asce)mt.1943-5533.0003323.
6. Trottier, C.; Zahedi, A.; Ziapour, R.; Sanchez, L.; Locati,

F. (2021) Microscopic assessment of recycled concrete aggregate (RCA) mixtures affected by alkali-silica reaction (ASR). *Constr. Build. Mater.* 269, 121250. https://doi.org/10.1016/j.conbuildmat.2020.121250.
7. Trottier, C.; Ziapour, R.; Zahedi, A.; Sanchez, L.; Locati, F. (2021) Microscopic characterization of alkali-silica reaction (ASR) affected recycled concrete mixtures induced by reactive coarse and fine aggregates. *Cem. Concr. Res.* 144, 106426. https://doi.org/10.1016/j.cemconres.2021.106426.
8. Zhu, Y.; Zahedi, A.; Sanchez, L.F.M.; Fournier, B.; Beauchemin, S. (2021) Overall assessment of alkali-silica reaction affected recycled concrete aggregate mixtures derived from construction and demolition waste. *Cem. Concr. Res.* 142, 106350. https://doi.org/10.1016/j.cemconres.2020.106350.
9. Sims, I.; Poole, A.B. (2017) Alkali-aggregate reaction in concrete: A world review. Taylor and Francis, London (2017). https://doi.org/10.1201/9781315708959.
10. Sanchez, L.F.M.; Fournier, B.; Jolin, M.; Duchesne, J. (2015) Reliable quantification of AAR damage through assessment of the Damage Rating Index (DRI). *Cem. Concr. Res.* 67, 74–92. https://doi.org/10.1016/j.cemconres.2014.08.002.
11. Sanchez, L.F.M.; Drimalas, T.; Fournier, B.; Mitchell, D.; Bastien, J. (2018) Comprehensive damage assessment in concrete affected by different internal swelling reaction (ISR) mechanisms. *Cem. Concr. Res.* 107, 284–303. https://doi.org/10.1016/j.cemconres.2018.02.017.
12. Barreto Santos, M.; de Brito, J.; Santos Silva, A.; Hawreen, A. (2020) Effect of the source concrete with ASR degradation on the mechanical and physical properties of coarse recycled aggregate. *Cem. Concr. Comp.* 111, 103621. https://doi.org/10.1016/j.cemconcomp.2020.103621.
13. Peng, Z.; Shi, C.; Shi, Z.; Lu, B.; Wan, S.; Zhang, Z.; Chang, J.; Zhang, T. (2020) Alkali-aggregate reaction in recycled aggregate concrete. *J. Clean. Prod.* 255, 120238. https://doi.org/10.1016/j.jclepro.2020.120238.
14. Shehata, M.H.; Christidis, C.; Mikhaiel, W.; Rogers, C.; Lachemi, M. (2010) Reactivity of reclaimed concrete aggregate produced from concrete affected by alkali-silica reaction. *Cem. Concr. Res.* 40 [4], 575–582. https://doi.org/10.1016/j.cemconres.2009.08.008.
15. Ideker, J.H.; Adams, M.P.; Tanner, J.; Jones, A. (2013) Durability assessment of recycled concrete aggregates for use in new concrete: Phase I-Revised. *TREC Final Reports*. https://doi.org/10.15760/trec.15.
16. Johnson, R.; Shehata, M.H. (2016) The efficacy of accelerated test methods to evaluate alkali silica reactivity of recycled concrete aggregates. *Constr. Build. Mater.* 112, 518–528. https://doi.org/10.1016/j.conbuildmat.2016.02.155.
17. Mukhopadhyay, A.K.; Geiger, B.J.; Button, J. (2010) Use of alkali-silica reaction-affected recycled concrete aggregate in hot-mix asphalt. *Transp. Res. Rec.* 2179, 1–9. https://doi.org/10.3141/2179-01.
18. Li, X.; Gress, D.L. (2006) Mitigating alkali-silica reaction in concrete containing recycled concrete aggregate. *Transp. Res. Rec.* 1979, 30–35. https://doi.org/10.3141/1979-06.
19. Grattan-Bellew, P.E. (1995) Laboratory evaluation of alkali-silica reaction in concrete from Saunders generating station. *ACI Mater. J.* 92 [2], 126–134. https://doi.org/10.14359/9763.
20. 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 ICAAR, Austin, TX.
21. Sanchez, L.F.M.; Fournier, B.; Jolin, M.; Bedoya, M.A.B.; Bastien, J.; Duchesne, J. (2016) Use of Damage Rating Index to quantify alkali-silica reaction damage in concrete: Fine versus coarse aggregate. *ACI Mater. J.* 113 [4], 395–407. https://doi.org/10.14359/51688983.
22. Haskett, M.; Oehlers, D.J.; Mohamed Ali, M.S.; Sharma, S.K. (2011) Evaluating the shear-friction resistance across sliding planes in concrete. *Eng. Struct.* 33 [4], 1357–1364. https://doi.org/10.1016/j.engstruct.2011.01.013.
23. Concrete design handbook (1985). Canadian Portland Cement Association, Canada (1985).
24. Barr, B.I.G.; Hasso, E.B.D.; Liu, K. (1985) Shear strength of FRC materials. *Comp.* 16 [4], 326–334. https://doi.org/10.1016/0010-4361(85)90285-X.
25. Gao, H.; Zhiqiang, W.; Chengshou, Y.; Aihua, Z. (1979) An investigation on the brittle fracture of KI-KII composite mode crack. *Acta Metall. Sin.* 15 [3], 380–391.
26. Barr, B.; Hasso, E.B.D. (1986) Development of a compact cylindrical shear test specimen. *J. Mater. Sci. Lett.* 5, 1305–1308. https://doi.org/10.1007/BF01729401.
27. de Souza, D.J.; Sanchez, L.F.M.; de Grazia, M.T. (2019) Evaluation of a direct shear test setup to quantify AAR-induced expansion and damage in concrete. *Constr. Build. Mater.* 229, 116806. https://doi.org/10.1016/j.conbuildmat.2019.116806.
28. ASTM C1293 - 20a standard test method for determination of length change of concrete due to alkali-silica reaction. https://www.astm.org/Standards/C1293.
29. Abbas, A.; Fathifazl, G.; Burkan Isgor, O.; Razaqpur, A.G.; Fournier, B.; Foo, S. (2008) Proposed method for determining the residual mortar content of recycled concrete aggregates. *J. ASTM Int.* 5 [1], 1–12. https://doi.org/10.1520/JAI101087.
30. McCarthy, M.J.; Csetenyi, L.J.; Halliday, J.E.; Dhir, R.K. (2015) Evaluating the effect of recycled aggregate on damaging AAR in concrete. *Mag. Concr. Res.* 67 [11], 598–610. https://doi.org/10.1680/MACR.14.00260.
31. Ziapour, R.; Trottier, C.; Sanchez, L. (2020) Assessment of AAR-induced expansion and damage through the direct shear test. Proceedings of the 16th ICAAR. LX, Portugal.
32. Rahal, K.N.; Al-Khaleefi, A.L. (2015) Shear-friction behavior of recycled and natural aggregate concrete-An experimental investigation. *ACI Struc. J.* 112 [6], 725–734. https://doi.org/10.14359/51687748.
33. Hayles, M. (2018) Investigation into the mechanical properties and structural behaviour of recycled concrete members. [MSc Thesis] Civil Engineering Department, University of Ottawa, Ottawa (2018). https://doi.org/10.20381/ruor-22063.
34. Tanaka, Y.; Kishi, T.; Maekawa, K. (2005) Experimental research on the structural mechanism of RC members containing artificial crack in shear. *Doboku Gakkai Ronbunshu.* [802], 109-122. https://doi.org/10.2208/jscej.2005.802_109.
35. Pimanmas, A.; Maekawa, K. (2001) Shear failure of RC members subjected to pre-cracks and combined axial tension and shear. *J. Materials. Conc. Struct. Pavem.* 53 [690], 159–174. https://doi.org/10.2208/jscej.2001.690_159.