Sliping of Single Crystal and Texture Materials

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Abstract

Alkali-aggregate reactions (AAR) represent a significant durability challenge in concrete. This issue arises when alkali hydroxides interact with reactive components such as silica, dolomite, and other aggregates. This interaction forms gel-like substances that possess a high capacity for absorbing water, leading to expansion within the concrete structure. This expansion can reach levels of up to 3%, causing substantial cracks to appear. Consequently, comprehending AAR and adopting preventive measures is imperative in concrete formulation and manufacturing.

While extensive research exists on AAR in conventional concrete, the comprehension of AAR in recycled concrete aggregates (RCA) - which substitutes original aggregates (OA) to recycle construction and demolition debris - remains limited. AAR in RCA is more intricate due to the diverse origins, non-uniformity, manufacturing processes, and utilization conditions of RCA. This variety arises from the OA, which varies in alkali reactivity and AAR extent. The production process, involving various crushing stages, results in RCA of varying size, density, residual mortar (RM) content, and adherence to the initial cement paste. These factors can influence the AAR behavior of recycled concrete. Additionally, RCA conditions, including cement alkali content in recycled concrete, pre-washing of RCA, and water saturation, impact the AAR in recycled concrete. The combination of these factors in recycled concrete complicates its AAR performance and its correlation with the parent concrete's performance.

Aggregate reactivity significantly influences AAR in recycled concrete. Therefore, appropriate handling of RCA, particularly RM, could offer potential strategies to mitigate AAR in recycled concrete. Pre-treatment measures such as carbonation treatment and incorporating fine pozzolanic powders into RM can help alleviate or minimize the effects of AAR in RCA. The use of supplementary cementitious materials like fly ash, ground granulated blast furnace slag, metakaolin, and silica fume also serves as a method to counteract AAR in RCA. Furthermore, several researchers have identified lithium salts as potential agents for mitigating AAR.

Keywords: recycled concrete aggregates (RCA), Alkali-aggregate reactions (AAR), carbonation, pozzolanic powders, humidity, adhered mortar.

1. Introduction

Damage (crack) due to AAR in concrete occur because of the reaction between alkali hydroxides like NaOH which are produced from cement hydration, and reactive components in aggregates. Alkalis can also enter the concrete from mix water, admixtures, curing water, deicing salts, ground water, sea water, and industrial wastewater as well other than cement. For the reaction to start, humidity must be 85% at 20 Celsius. Reaction can also start at higher temperatures with lower humidity.

In general, there two types of AAR which are Alkali – carbonate reaction (ACR) and Alkali – silica reaction (ASR). It is also not certain that all these reactions will bring negative effects on concrete.

For the problem of AAR there still is no exact practical or economical solution. One of the methods to prevent ASR is to use limestone aggregates that do not contain silica. However, if the aggregates that contains reactive silica is necessary to be used in the mixture, it is proposed to use pozzolanic material in the binder.

Carbonate reactions occur when calcite limestone, dolomite limestone or calcite dolomite limestone that contains fine grained clay react with alkali hydroxides in concrete.

Equation 1 below indicates the reaction with dolomite and sodium oxide.

$$CaMg(CO_3)_2 + 2NaOH \rightarrow Mg(OH)_2 + CaCO_3 + Na_2CO_3 \quad (1)$$

As a result of this reaction Mg (OH)2 (brucite) is created as a product. This compound has high capacity of water absorption that can lead to volumetric expansion and thus cracks in concrete. Figure 1 demonstrates the cracks occur due to ACR.

Figure 1 Cracks in concrete due to ACR

ASR is more common than ACR. Also, expansion due to ASR is generally much greater than expansion due to ACR. ASR is typically a slow reaction, and its effects are seen a few years later. As the alkalinity of concrete increases potential of ASR also increases. Because alkali hydroxide solution can easily react with reactive aggregates. Equation 2 below indicates the reaction with silicate and sodium oxide.

$$SiO_2 + 2NaOH + H_2O \rightarrow Na_2SiO_3.2H_2O \quad (2)$$

As a result of this reaction alkali – silica gel occurs as a product. This gel is capable of absorbing great amount of water that can lead 2-3% volumetric expansion in concrete and thus cracks. Figure 2 demonstrates the cracks occurred due to ASR.

Figure 2 Cracks in concrete due to ASR

For ASR which causes expansion, to occur, apart from the reactive silica forms in the aggregate, there must be enough alkalis such as Na2O and K2O in the cement and the environment must be moist.

$$(Na_2O)_{eq} = Na_2O + (0.658)K_2O \quad (3)$$

As seen in the Equation 3, if the equivalent sodium percent in cement is lower than 0.6% even if the reactive aggregate is used ASR do not occur. Also, ASR occur in high pH values since reactive silica dissolves in high pH values. At every point where the Ca (OH)2 balance is established in concrete, the pH is generally at least 12.5 and if a highly alkaline cement is used pH cam be up to 13.5. This 1.0 degree of pH difference increases the OH- 10 times. This is the reason why reactive aggregates must be used with cement that contains low amount of alkaline.

Expansion in ASR is related to the aggregate size as well. As the size of the aggregate increases the expansion rate decreases but it continues for a long time. As the size of the aggregate decreases the rate of expansion increases in early stages.

2. Methodology

The experiments conducted to determine the existence of AAR in concrete are done for aggregates and mortars. Investigation of mineral structure (ASTM C295) and chemical method (TS 2517 – ASTM C289) are experiments done on aggregates. Long-term experiments (ASTM C227 – ASTM C1293) and short-term experiments (ASTM C1260) are done on mortars.

2.1 AAR in Recycled Concrete Aggregate

Construction and demolition waste is an important component that needs to be considered with high priority for waste management. Therefore, use of recycled concrete as aggregate (RCA) is a significant and efficient strategy for sustainable development of construction industry. However, several studies showed that the recycled concrete exhibited poorer durability performance compared to original concrete with respect to impermeability, chloride resistance, carbonation resistance, frost resistance and alkali-aggregate reaction. Durability of RCA concrete is mainly determined by the adhered mortar of RCA. High RCA content and higher amount of adhered mortar can result in higher porosity, water absorption, leading to poorer durability performance.

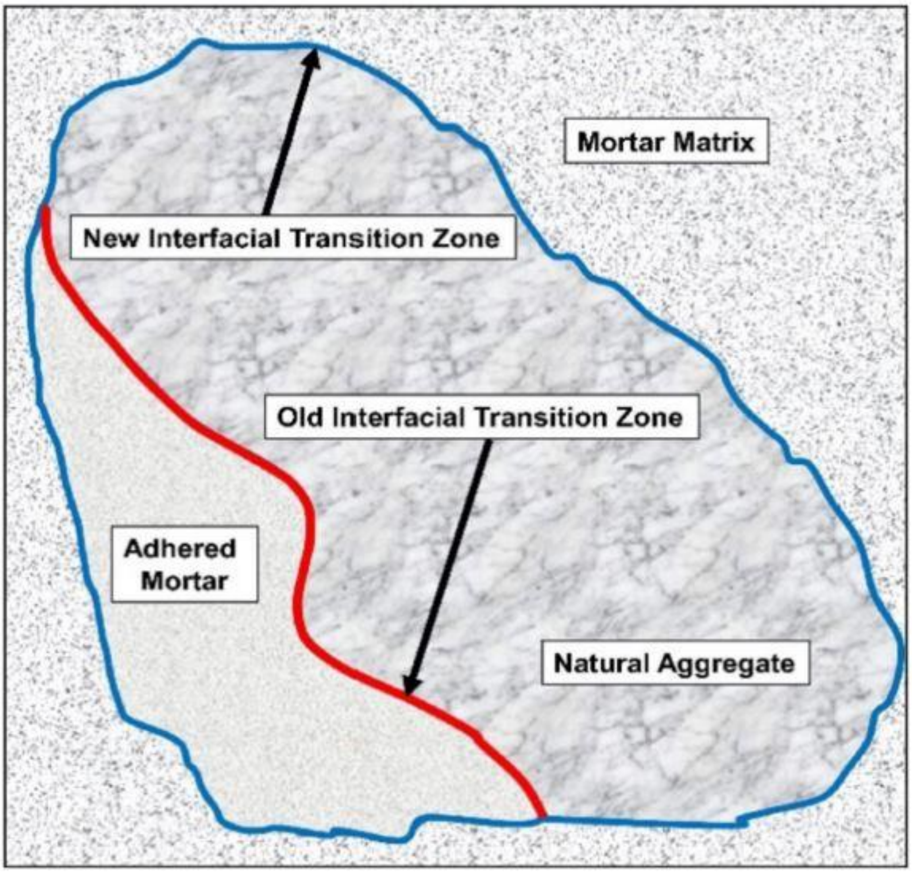

Figure 3 Schematic diagram of recycled concrete aggregate

OA aggregate doesn't have an adhered mortar like in RCA as seen in Figure 3. The residual mortar is normally more porous than OA which can lead to high water absorption and considerably affect the hardened properties of RCA concrete as summarized in Table 1. Moreover, the presence of residual mortar can also release some alkalis into pore solution and increase the risk of AAR.

Table 1 Effect of RCA on the hardened properties of concrete in comparison to OA

Properties	Range of changes
Dry density	5–15% less
Compressive strength	0–30% less
Splitting tensile strength	0–10% less
Flexural strength	0–10% less
Bond strength	9–19% less
Modulus of elasticity	10–45% less
Porosity	10–30% more
Permeability	0–500% more
Water absorption	0–40% more
Chloride penetration	0–30% more
Drying shrinkage	20–50% more
Creep	30–60% more
Thermal expansion	10–30% more

2.2 Effect of Alkali Content

AAR in RCA concrete mainly controlled by the content of alkali reactive component available to reaction. For the RCA concretes, the AAR expansion is higher when the OA has high alkali reactivity.

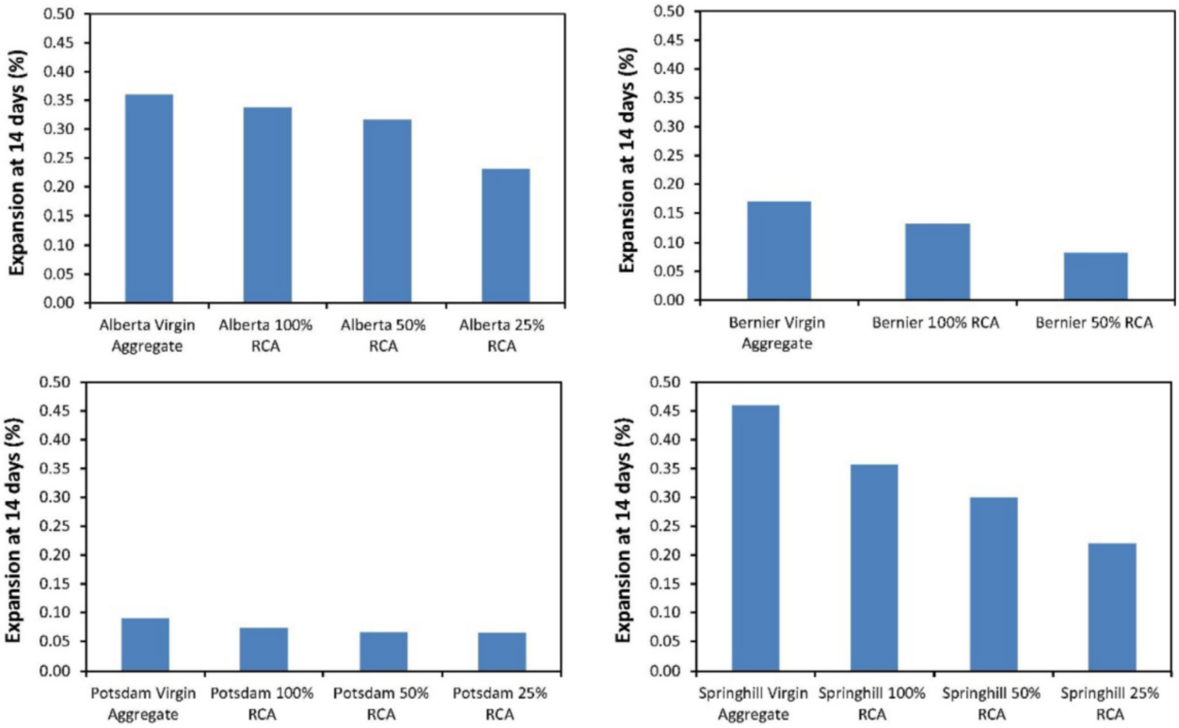

Figure 4 Expansion of OA with various sources and RCA generated from concrete containing the same aggregate.

Figure 4 demonstrates the effect of alkali content in aggregate. For instance, Alberta and Spinghill Virgin aggregate have high alkali reactivity, therefore the AAR potential of their corresponding RCA is higher in comparison to the RCA made from Bernier or Potsdam concrete at similar replacement level of RCA.

2.3 Effect of Reactivity and Reaction Extent of OA on the Expansion

Both the reactivity of OA and its reaction extent in parent concrete could pose an effect on the AAR expansion.

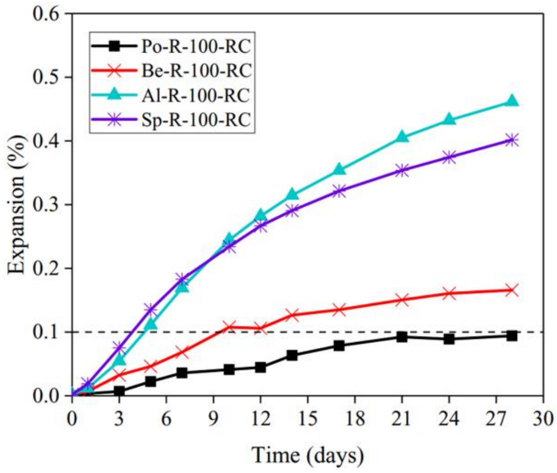

Figure 5 Effect of reactivity of OA on the expansion of RCA

In Figure 5, Al-R is mixed mineralogy gravel with high reactive OA, Sp-R is greywacke with the most reactive OA, Po-R (sandstone) and Be-R (Argillaceous limestone) are less reactive OA. However, the recycled aggregate concrete containing RCA with the most reactive OA (i.e., Sp-R, greywacke) showed a slightly lower expansion. This is because OA containing Sp-R was older than the concrete containing Al-R, such that a large fraction of the reactive silica may have been consumed.

2.4 AAR expansion of RCA and RM

The influence of RM on the ASR expansion of RCA concrete is more complicated, since it is affected by both the reactive silica and alkali content in RM. Despite the importance of RM, it is difficult to accurately quantify its amount. If the fine OA is non-reactive, the expansion caused by RM would be limited and the total expansion would be lower. Once the reactive substance in OA had been largely consumed, the change in the content of RM only was not enough cause a significant difference in the extent of AAR.

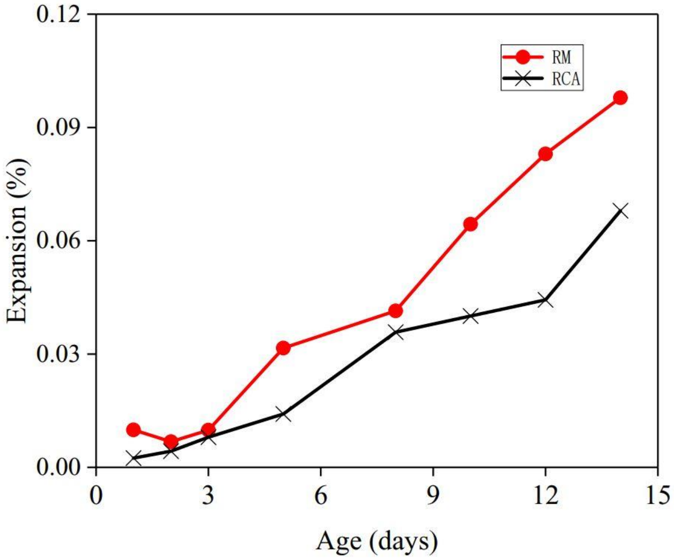

Figure 6 AAR expansion of RCA and RM

2.5 The Size Effect of RCA on the AAR Expansion

For the RCA with smaller size, the expansion is slightly higher when mixed with reactive aggregate in recycled concrete under the high alkaline environment.

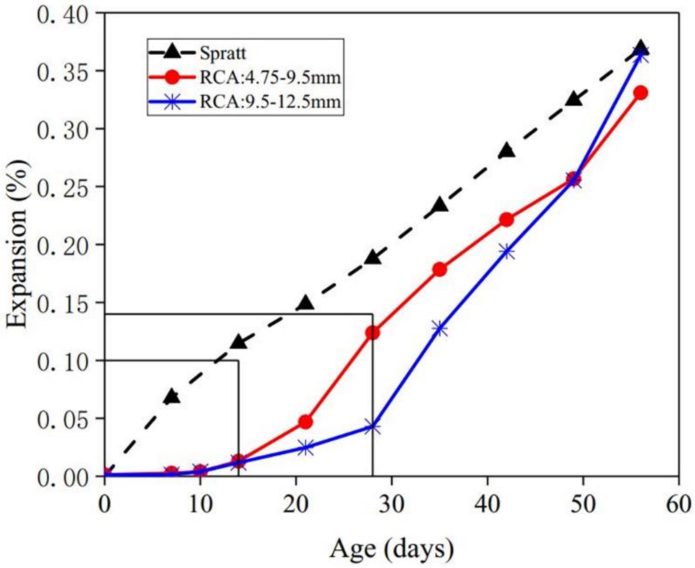

Figure 7 The AAR expansion of coarse RCA with different size

As seen is Figure 6 AAR expansion of RCA with larger size (9.5 - 12.5 mm) is generally lower than that with smaller size (4.75 - 9.5 mm) within 28 days. Coarser size of aggregate has smaller reactive surface area of the particles, thus requires more time for the reaction to proceed.

Also, for very large and very small aggregates, the effect of angularity on AAR expansion is negligible.

2.6 Crushing Effect on AAR Expansion of RCA

As seen in Figure 7, RCA subjected to secondary crushing stage has a significantly higher expansion at 14th day than the RCA only with primary crushing stage. This could be attributed to the fact that secondary crushing stage allows more reactive components to be involved in the AAR.

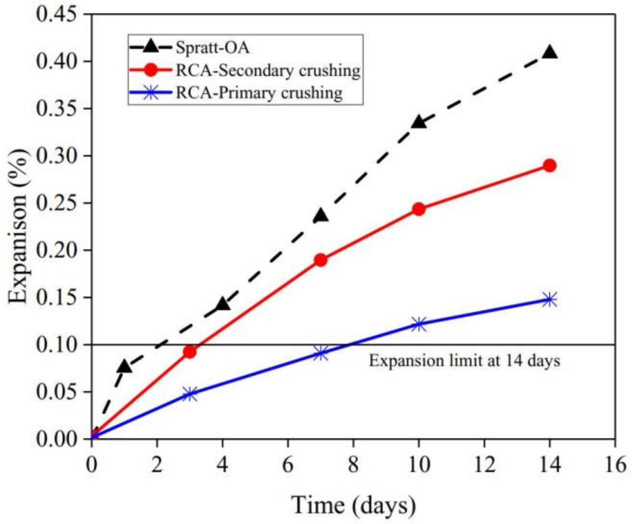

Figure 8 AAR expansion of RCA with different crushing stages

2.7 Replacement Ratio of RCA Effect on AAR Expansion

The Figure 8 represents the replacement ratio of RCA in concrete on AAR expansion. The first five types of RCA were all obtained from outdoor exposure block made from four different reactive OA, but without any expansion damage and the last two type of RCA was produced by AAR-affected concrete. A continuous increase in AAR expansion is observed with the increase of proportions of RCA from 25 to 100% in the concrete mixtures for the first five specimens. Most important inference from Figure 8 is increase of RCA content causes the increase of AAR expansion for RCA concrete whose OA did not show any deterioration of AAR.

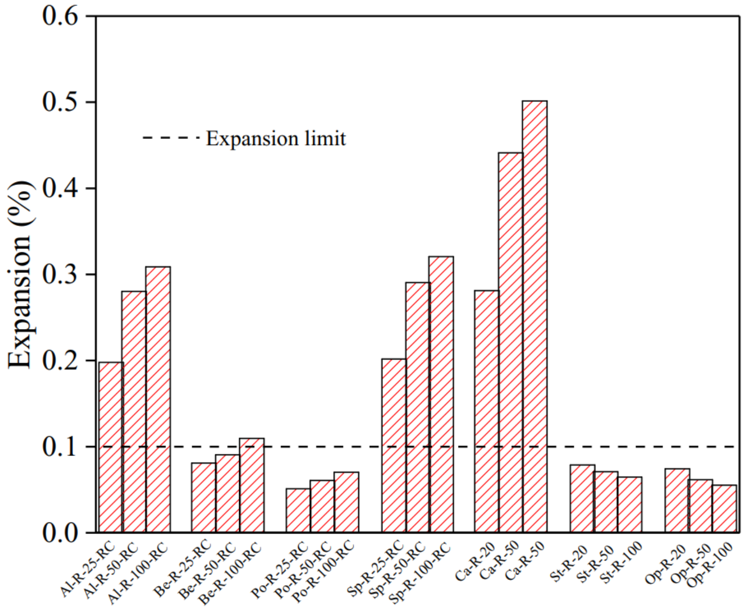

Figure 9 AAR expansion of concrete with different replacement ratio of RCA

2.8 Washing Effect on AAR Expansion

As demonstrated in Figure 9 the expansion of specimens casted with unwashed RCA is obviously higher than those using washed RCA.

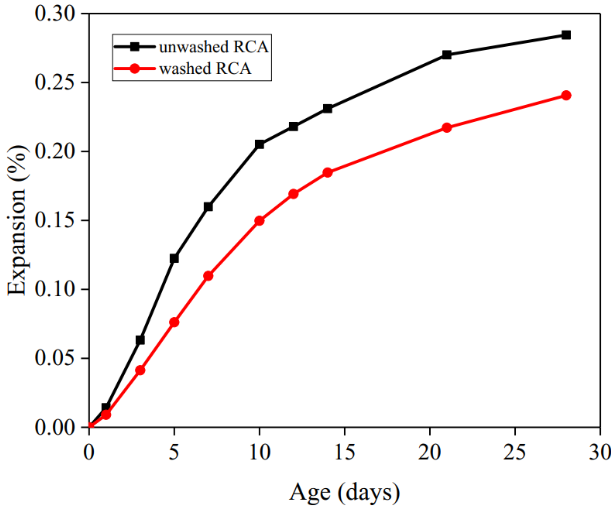

Figure 10 Effect of washing on the expansion of RCA mortar bars

The low expansion of the concrete with washed RCA can be attributed to the loss of alkalis during washing.

2.9 Na_2O_e of PC Effect on AAR expansion of RCA

As seen in Figure 11 AAR expansion of RCA is higher than that of the natural Spratt aggregate when cement alkali content is lower than 0.8 wt %.

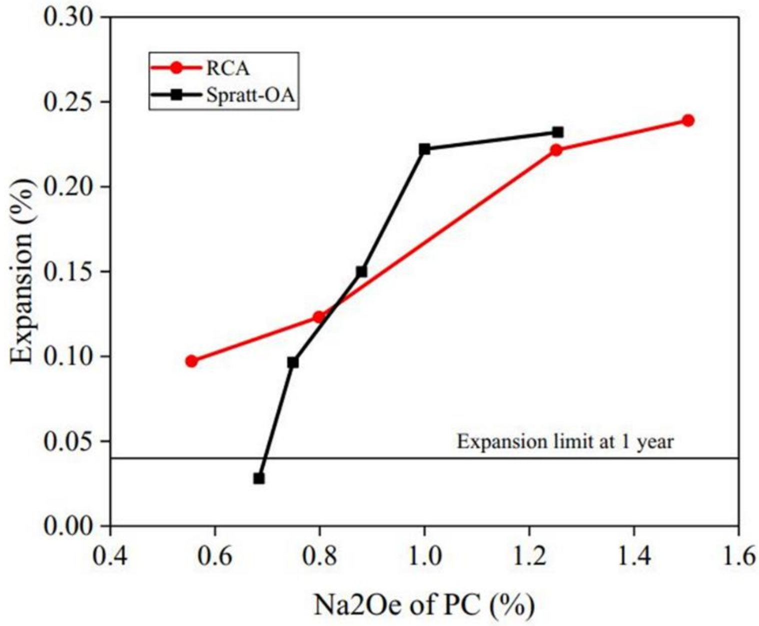

Figure 11 AAR expansion of RCA concrete with different Na_2O_e of PC used in new concrete

2.10 Effect of Saturation

In Figure 12 the RCAs were produced from the demolition of the foundation blocks (DVb) and the bridge deck (DVd). S1: RCA in a dry condition, S3: RCA in saturated condition.

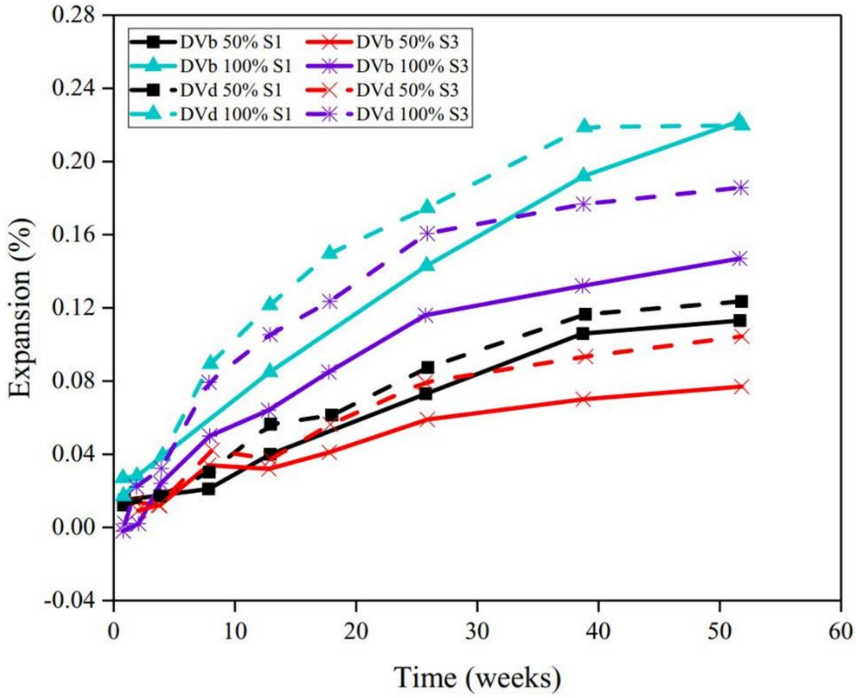

Figure 12 AAR expansion of dry and water-saturated RCA with different parent concrete

The results indicate that expansion of concrete with RCA under water saturation is lower than that with dried RCA. Because high water absorption could induce more pore solution to enter the RCA. For original concrete, the low water absorption of the OA has little influence on the effective water content, the amount of water absorbed by OA can be neglected. The water absorption cannot be neglected for recycled aggregate concrete containing reactive RCA as it may affect the measured AAR expansion. It was reported that the concrete made from dried RCA occurred a more significant AAR expansion than those pre-saturated with water. This was mainly attributed to the fact that RCA with high water absorption could induce more pore solution to enter the RCA.

3. Discussion of the results

The reactivity of aggregate plays the dominate role in ASR of recycled concrete. Thus, proper treatment of RCA especially the RM could potentially provide measures for mitigating AAR in the recycled concrete.

3.1 Carbonation Treatment of RCA

Improvement of RM is the key to enhance the performance of RCA; and carbonation is an efficient and environmentally friendly way to treat the RM.

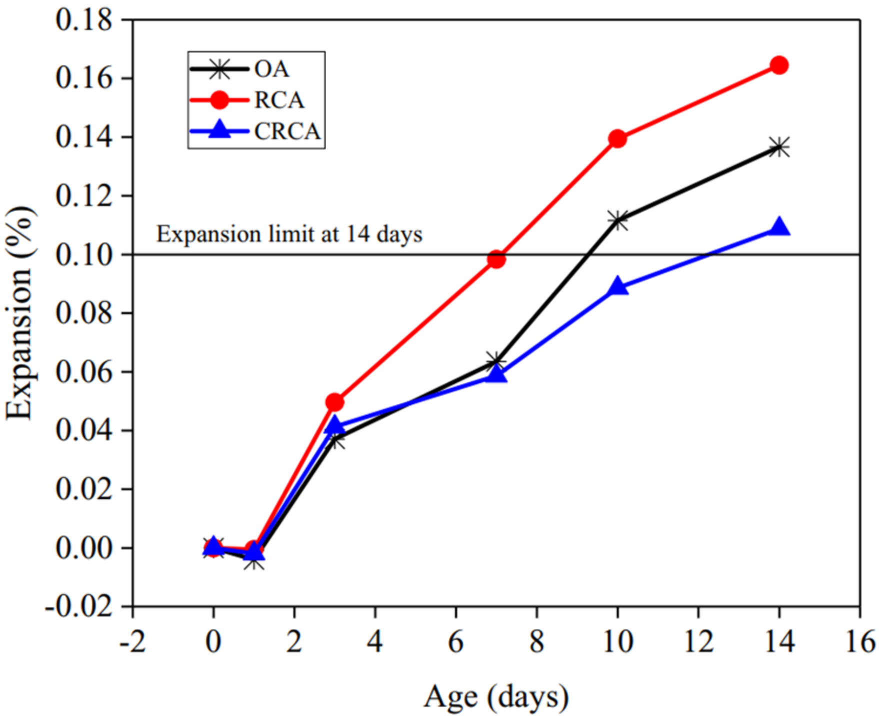

Figure 13 Effect of carbonation on AAR expansion of mortar bar made by RCA

The RCA in Figure 13 was carbonated in a carbonation chamber at 20% CO_2, 60% relative humidity and 20 Celsius. The results show that carbonated RCA expansion is reduced by approximately 30%.

3.2 Suction of fine pozzolanic powders into residual mortar

There is also a method to enhance the quality of RCA by sucking the silica fume slurry into RM of RCA. The specific procedure can be divided into the following steps:

- Crushing and sieving the recycled concrete according to the gradation of ASTM C1260.
- Preparing the silica fume slurry with different water to powder ratios.
- Soaking the RCA in the silica fume slurry and putting them together in a vacuum environment under pressure of 0.08e0.10 MPa.
- Filtering excessive silica fume slurry and drying the RCA, and then sieving the extra silica fume.
- Testing the expansion according to ASTM C1260.

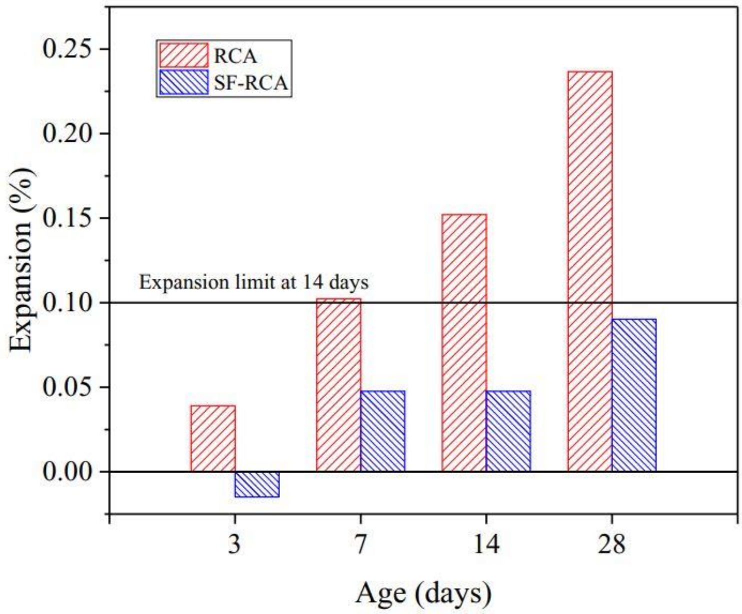

Figure 14 Mitigation of AAR expansion of RCA by sucking fine pozzolanic material into RM

The reduction in expansion as seen in Figure 14 could be attributed to the fact that the reactive substance, such as SiO_2, could react with Ca $(OH)_2$ to form C-S-H gel, which provide a barrier for AAR to take place by reducing the pH in the RM.

3.3 Use of SCMs

Researchers investigated AAR in recycled concrete containing three types of SCMs, i.e., class F fly ash, ground granulated blast furnace slag (GGBFS) and silica fume.

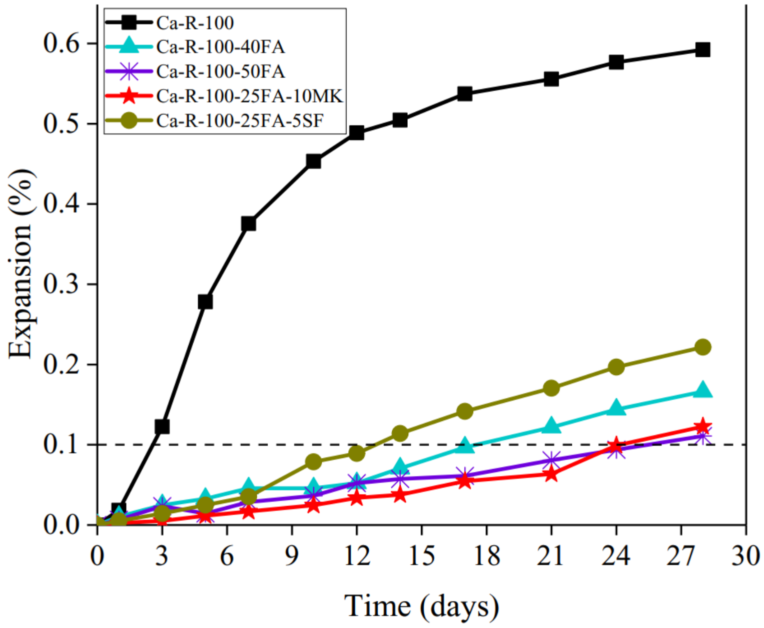

Figure 15 Expansions of RCA with various cementitious material blends

The results in Figure 15 show that that 25% fly ash could reduce the ASR expansion of RCA below the threshold. At the same replacement level, i.e., 25%, GGBFS could hardly mitigate the expansion of AAR in recycled concrete containing reactive RCA. Instead, at least 55% of GGBFS was required to control the expansion below the threshold. Using 8% silica fume could not effectively reduce the AAR expansion. Even the 12% silica fume was still unable to suppress the AAR expansion in recycled concrete. Compared to various methods of AAR mitigation in RCA concrete with SCMs, the class F fly ash was an effective approach at a relatively low level of usage than others.

3.4 Use of Lithium salt

Figure 16 demonstrates the effect of lithium on AAR expansion of concrete with RCA. As seen in the figure pre-soaking of the RCA in $LiNO_3$ in half of the mixing water prior mixing does not show any advantages in comparison to direct addition of LiNO3 to the mixing water. Combination of 20% fly ash with LiNO3 can effectively reduce the AAR expansion. The AAR expansion of RCA with 100% lithium nitrate mitigation is far lower than the threshold, especially, the expansion was kept a quite low level within 28 days.

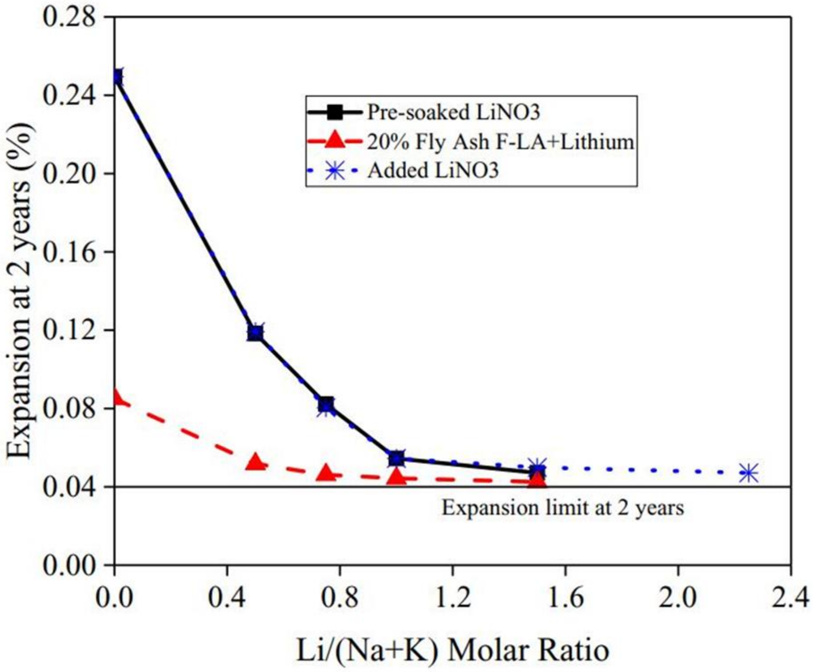

Figure 16 Effect of lithium on the expansion of concrete with RCA

3.5 Test Methods to Evaluate the Reactivity of RCA

Accelerated mortar bar test (AMBT) and concrete prism test (CPT) are the most prevalent methods to evaluate the reactivity of aggregate. According to AMBT the average expansion of less than 0.10% in 14 days is generally considered as non-reactive aggregate. Figure 17 demonstrates the correlation between AMBT and CPT. However, these tests might not always be reliable to assess RCA because of the existence of old paste. Because the variation in this proportion between OA and RM could further influence the AAR expansion and the water absorption of RCA. Further investigation and modification of the current methods need to be adapted using more sources of aggregates and for OA with different reaction extent.

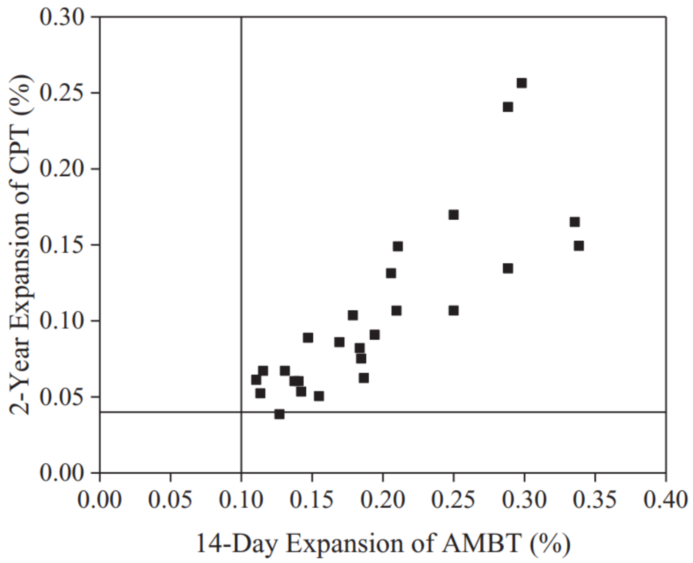

Figure 17 Correlation between AMBT and CPT

4. Conclusion

AAR is an important phenomenon in concrete design and production. Because it significantly affects the durability of concrete negatively. That is why necessary precautions must be taken during the design and production stages to prevent or reduce AAR.

AAR in recycled concrete is more complicated than the AAR of its original concrete since it is affected by many factors such as alkali reactivity of OA, reaction extent of OA, presence of RM and production procedure. Although, there is a controversy in literature about the current test methods for evaluating the reactivity of RCA there are still some useful methods to mitigate or reduce expansion due to AAR in RCA. Pre-treatment of RCA, use of supplementary cementing materials and use of lithium salt can significantly lower the expansion due to AAR in concrete with RCA.

References

- Peng, Ziyi, et al. "Alkali-aggregate reaction in recycled aggregate concrete." Journal of cleaner production 255 (2020): 120238.

- Dealing with Alkali-Aggregate Reaction in Hydraulic Structures (renewableenergyworld.com).

- By US Department of Transportation – Federal Highway Administration: Dr. P.E. Grattan-Bellew. Publication No. FHWA-HRT-06-069 - From: Figure 1. Extensive map cracking in several concrete barriers along State Highway 2 near Leominster, MA. In TechBrief: Selecting Candidate Structures for Lithium Treatment: What to Provide the Petrographer Along with Concrete Specimens Publication No. FHWA-HRT-06-069 February 2006.

- Yıldız Technical University, Durability of Concrete Course, Lecture Notes.

- Astm, C. "ASTM standards." Philadelphia: American Society for Testing Materials.