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Systematic review on alkali-aggregate reactions: comparative overview of studies carried out in Canada and Brazil

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ABSTRACT
The objective of this research is to compare the performance of Canada and Brazil in studies related to alkali aggregate reaction (AAR) in concrete, through a qualitative, quantitative and systematic review of the literature, in addition to using the VOSviewer software for co-analysis, citation and bibliographic coupling. The collected data indicate that Canada is the country that most stands out in terms of AAR research in the world, and Brazil is in seventh place. The work presented the research centers of the two countries, the existing methodologies for assessing AAR and the panorama of research on the subject in Brazil. Finally, the work showed the emerging themes about AAR and knowledge gaps.
Keywords: alkali-aggregate reaction; durability; expansive reactions; Canada; Brazil.

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Contribution of each author
In this work, the first author contributed with a bibliographic review, applied methodology, research, discussion of results and conclusions with a percentage of 80%. The second and third authors contributed with the bibliographic review and revision with a percentage of 20% and the fourth author contributed with the original idea, direction and revision of the text.

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Revisión sistemática de la reacción álcali-agregado: resumen comparativo de estudios realizados en Canadá y Brasil

RESUMEN

El objetivo de esta investigación es comparar el desempeño de Canadá y Brasil en estudios relacionados con la reacción de agregado alcalino (AAR) en el concreto, a través de una revisión cualitativa, cuantitativa y sistemática de la literatura, además de utilizar el software VOSviewer para el co-citación y acoplamiento bibliográfico. Los datos recopilados indican que Canadá es el país que más se destaca en cuanto a investigaciones sobre RAA en el mundo, Brasil se encuentra en la séptima posición. El trabajo presentó los centros de investigación entre los dos países, las metodologías existentes para evaluar AAR y el panorama de la investigación sobre el tema en Brasil. Finalmente, el trabajo mostró que entre los temas emergentes sobre RAA y lagunas de conocimiento.

Palabras clave: reacción álcali-árido; durabilidad; reacciones expansivas; Canadá; Brasil.

Revisão sistemática sobre reação álcali-agregado: panorama comparativo dos estudos realizados no Canadá e no Brasil

RESUMO

O objetivo desta pesquisa é comparar à atuação do Canadá e do Brasil em estudos relacionados a reação álcali agregado (RAA) no concreto, por meio de uma revisão qualitativa, quantitativa e sistemática da literatura, além de utilizar o software VOSviewer para analise de co-citação e acoplamento bibliográfico. Os dados levantados indicam que o Canadá é o país que mais se destaca em termos de pesquisa sobre RAA no mundo, o Brasil encontra-se na sétima posição. O trabalho apresentou os núcleos de pesquisa entre os dois países, as metodologias existentes para avaliação da RAA e o panorama da pesquisa sobre o assunto no Brasil. Por fim, o trabalho mostrou os temas emergentes sobre RAA e as lacunas de conhecimento.

Palavras-chave: reação álcali-agregado; durabilidade; reações expansivas; Canadá; Brasil.

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1. INTRODUCTION

The alkali-aggregate reaction (AAR) is one of the most harmful deterioration mechanisms that affects the durability and service life of concrete structures in the world. AAR can be divided into two main types of reaction: alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR) (Fournier and Bérubé, 2000). ASR, most commonly found in concrete structures, is characterized by the chemical reaction between the unstable silica minerals present in the aggregates and the alkaline hydroxides (Na+, K+, OH-) arising primarily from the hydration of Portland cement while dissolved in the concrete pore solution. On the other hand, ACR is a much less common type of reaction, whose mechanism is still largely unknown. ACR is seen by many researchers as a reaction that occurs between alkaline hydroxides and certain types of dolomitic limestones (Fournier and Bérubé, 2000; Beyene et al., 2013). In general, it is ordinarily accepted that ACR is accompanied by a process of dedolomitization and calcite and brucite formation (Thomas and Folliard, 2007), although different studies consider ACR as a form of ASR (Katayama et al., 2012, 2016). However, the microscopic characteristics of expansion and deterioration induced by ACR were separated from the ASR because they are quite different (Sanchez et al., 2017), which justifies the distinction of terms. Independently, both deterioration mechanisms (ASR and ACR) are present in concrete structures all over the world and are responsible for the generation of secondary products that cause expansions in the presence of moisture. With the expansion, which occurs as a consequence of AAR, the durability and mechanical properties of concrete are impaired, with the appearance of microcracks in the affected structure (Fournier and Bérubé, 2000; Bérubé et al., 2005; Fournier et al., 2010; Naar, 2010; Kubo and Nakata, 2012; Zhu et al., 2021; Fiset et al., 2021).
Studies related to this type of expansive reaction seek to assess the degree of reactivity of the aggregates present in different regions (Lu et al., 2006a; Lu et al., 2006b, Drolet et al., 2017a and Drolet et al., 2017b, Santos and Ribeiro, 2021). Others seek to identify mineral additions that can mitigate the effects of this reaction (Duchesne and Berubè, 2001 and Grattan-Bellew et al., 2003; Gallo et al., 2007; Adorno et al., 2018; Adorno et al., 2020) and evaluative methodologies in order to correlate techniques of accelerated tests and field tests (Ideker et al., 2010; Sanchez et al., 2014; Sanchez et al., 2015; Sanchez et al., 2016; Lindgard et al., 2016; Sanchez et al., 2017; Martin et al., 2017). In addition, there are studies aimed at correlating the alkalinity of the cementing matrix with the development of AAR (Shehata et al., 2000; Shehata et al., 2002; Shehata et al., 2006; Shehata et al., 2010).
Evaluating and studying AAR is of paramount importance in order to characterize and identify factors that influence the useful life of concrete structures. Researchers in several countries have sought to understand the effects of AAR since it was first identified. Among the countries that most publish articles in journals of high scientific impact on AAR is Canada. Brazilian researchers have an important history of partnerships and research interactions on this topic with researchers working in Canada. In this context, the present research consists of carrying out a bibliographical survey in order to analyze the main themes of studies related to AAR developed by Canadian and Brazilian authors, as well as the evaluative methodologies and rising themes. The importance of developing this work is to produce an overview in order to better understand trends related to alkali-aggregate reaction studies in the scientific environment of the two countries involved. In addition, the work presents an important discussion about the use of the accelerated method of mortar bars for AAR research, in comparison with longer-term methods such as the concrete prism test, which is considered more realistic, and with methods of damage assessment such as the Damage Rating Index (DRI) and the Stiffness Damage Test (SDT).

2. METHODOLOGY

The research consists of carrying out a qualitative, integrative and systematic review in order to compare the studies and evaluation methods of the alkali-aggregate reaction in both countries, Canada and Brazil.
First, the search term "Alkali-aggregate reaction" was defined and later the keyword was searched in the Web of Science (WoS) and Scopus databases. Both present an excellent temporal coverage, with records from the years 1945 and 1970, respectively, until the present. In addition, these databases include a large number of journals, events and publishers with a peer review system, which contributes to the variety and quality of publications. The search period considered was the entire available temporal space of the databases, considering all registered research areas. Data collection was carried out on January 13, 2022.
Related analyses were carried out regarding the number of publications in each country, main authors on the subject and number of citations. Finally, we sought to detail the publications and validate the evidence based on co-citation analyses and bibliographic coupling, which allows identifying the relationship between authors and references, as developed by Mariano and Rocha (2017). The VOSviewer 1.6.10 software was used to form the networks, which reads the data and uses clustering algorithms, separating them into groups according to the study areas.

2.1 Number of Publications - Brazil and Canada

Figure 1 identifies the number of publications found in the Web of Science (WoS) and Scopus databases in high-impact journals using the term "Alkali-aggregate reaction" and the contribution of each country on the topic. Figure 1 shows the publications of the 10 most prominent countries in the world's scientific production on the topic of aggregate alkali reaction.
Observing Figure 1, adding the number of publications from the two databases, and excluding repeated works, it is possible to rank the countries. Thus, it is noted that the country that most contributed to research related to AAR was Canada with 215 publications, followed by the United States and China with 170 and 167 publications, respectively. Brazil ranks seventh, contributing with 50 publications.
A total of 727 records on AAR were found in the WoS database, with 113 of these publications being Canadian and 33 being Brazilian. In the Scopus database, 1096 records were obtained, where Canada contributed with 173 publications and Brazil with 46. In general, based on the information obtained, it appears that Canada is the country that most contributes to studies related to AAR, representing about 22% of the total, while Brazil represents 5.7%. Thus, the number of studies published on "Alkali-aggregate reaction" in Canada is almost four times greater than in Brazil.

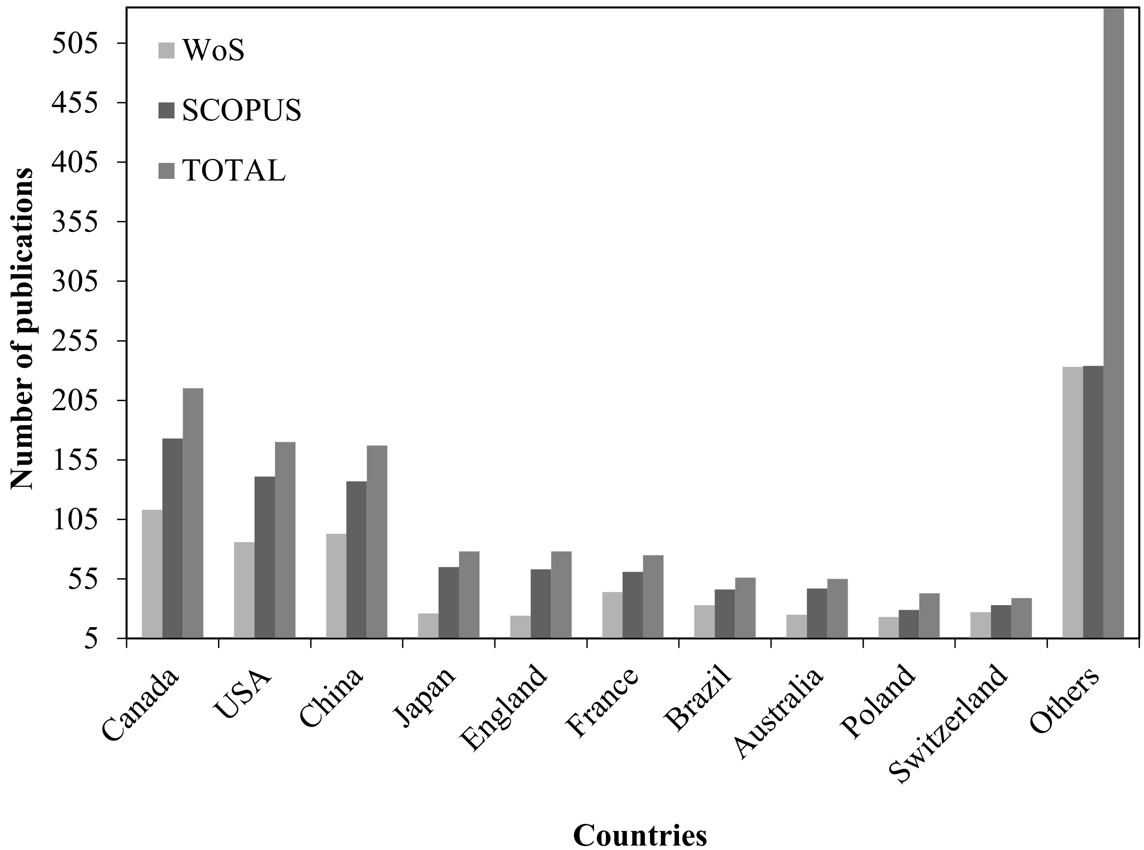


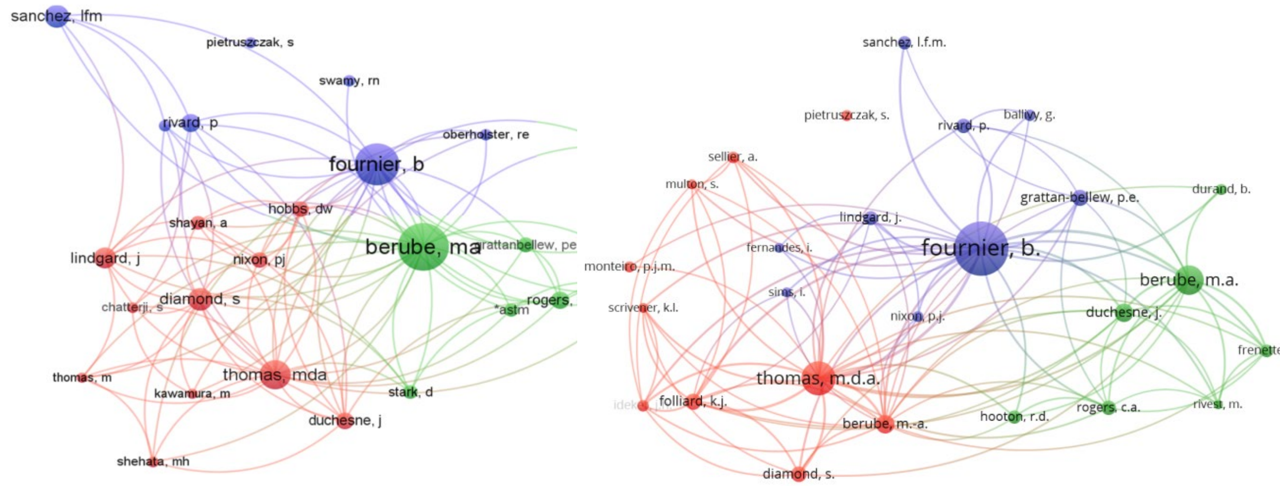
Figure 1. Number of publications in the WoS and Scopus databases with the term "Alkali-aggregate reaction" in the title.

2.2 Co-citation analysis – Brazil and Canada

Co-citation analysis is based on how often two authors or papers are cited together in subsequent articles. This indicates a proximity between the research themes addressed and the researchers. Thus, it is possible to distinguish a domain of knowledge through iterative analyses (Hjorland, 2013).

The interconnection of citations characterizes the research according to its social, historical and dynamic nature and helps to identify the dependence on academic literature, which allows the determination of the main research groups related to the study topics and their publications with the greatest impact (Glänzel, 2003).

Figures 2 show the links between the main research groups and authors related to AAR in Canada and Brazil, extracted from the WoS and Scopus databases, respectively.



(a) (b)

Figure *2*. Link between the main research groups focused on investigating the alkali-aggregate reaction, with data obtained from WoS (a) and Scopus (b).

Analyzing Figure 2, one can observe three major research themes led by Fournier, Thomas and Berubè with 29, 21 and 14 publications by each author, respectively, for the WoS database and Scopus, excluding repeated works.
The three major groups of researched themes are led by Canadian authors, and in these lines of research, Brazilian authors such as Sanchez and Monteiro share similar themes, relating mainly to AAR assessment techniques. The first author is a professor at the University of Ottawa, Canada, and has interaction with the research of Professor Fournier's group, located at the University of Laval, Quebec City, also in Canada. The second author is currently a professor at the University of California in Berkeley, USA. He is also part of a research group led by Hasparyk at Furnas Centrais Elétricas, Department of Concrete & Quality Control in Aparecida de Goiânia, GO, Brazil and with partnerships with Professor Dal Molin from the Federal University of Rio Grande do Sul in Porto Alegre, RS, Brazil. The approaches researched by Monteiro significantly interact with the subjects studied by Thomas.
The following chapter seeks to go deeper into the subject of the works developed by the authors cited above, based on a selection of the articles with the highest number of citations.

3. RESULTS AND DISCUSSIONS

3.1 Themes of greatest relevance among the most cited articles

The connection network between the authors identifies the similarity of the themes studied. Thus, publications released from the year 2000 onwards were chosen, with more than five citations of each author listed above, for analysis of the lines of research.
Several studies carried out together with other researchers encompass a series of subjects related to the alkali-aggregate reaction, becoming an international reference on the subject.
Studies related to AAR evaluative methodologies were carried out by Ideker et al. (2010), Lindgard et al. (2012), Sanchez et al. (2014), Sanchez et al. (2015a), Sanchez et al. (2015b), Sanchez et al. (2016a), Sanchez et al. (2016b), Lindgard et al. (2016), Sanchez et al. (2017) and Martin et al. (2017).
Studies have indicated that the Stiffness Damage Test (SDT) can be used as a way to assess AAR and evaluate the damage related to the expansion of the concrete (Martin et al., 2017). However,

parameters such as environmental conditions, sample characteristics and sample conditioning history seem to significantly influence the results of the cyclic loading test. On the other hand, different types of surface preparation and sample size do not seem to modify the test analyses (Sanchez et al., 2014; Sanchez et al., 2015a; Sanchez et al., 2016a and Sanchez et al., 2017).
The Damage Rating Index (DRI), a microscopic and semi-quantitative petrographic tool, also proved to be effective for the assessment of AAR (Martin et al., 2017), and from the analyses with various reactive aggregates, a quantitative model was developed for this assessment (Sanchez et al., 2015b and Sanchez et al., 2016b).
In addition, studies evaluating the reliability and comparisons between expansion tests in mortar bars and field tests indicate that the accelerated method in mortar, despite being used for more than 15 years worldwide, still needs to be better calibrated to transpose or approach the reality of the structures. This is true for all types of aggregates and binders, as they can present false negative and false positive results. In addition, parameters such as temperature, pH and concentration of alkali in the exposure solution must be considered, as they influence the performance of the tests (Jason et al., 2010; Lindgard et al., 2012; Lindgard et al., 2016).
As for the reactivity tests of the aggregates, studies indicate that the finer the particles and the higher the temperature, the greater and faster the release of alkalis. Furthermore, thermal activation has the greatest effect on gneiss and a smaller and similar effect on granite and feldspar (Lu et al., 2006a, Lindgard et al., 2013a and 2013b). It was also observed that, when exposed to $Ca(OH)_2$, NaOH and KOH solutions, the test on mortar bars showed more alkalis released in the solutions (with NaOH and KOH) compared to the solution saturated with $Ca(OH)_2$ (Berubè et al., 2002).
Berubè et al. (2003a), Rivard et al. (2007) and Shehata et al. (2010) investigated the effects of alkaline content in cement and found that the alkali content in cement has a significant effect on the expansion of concrete prisms and mortars and depends on the proportion and aggregate used. Furthermore, Berubè et al. (2003b) indicated that low-alkali concretes are a good choice for marine exposure conditions or de-icing salts.
To mitigate the effects of AAR in concrete, researchers evaluated the effect of mineral additions to it and found that the presence of some additions significantly reduces the expansions generated by AAR (Duchesne and Berubè, 2001; Grattan-Bellew et al., 2003). Other studies show that cement-silica fume mixtures were not efficient in retaining alkalis in their hydration products, although cement mixtures with silica fume and fly ash have the ability to agglomerate and retain alkalis (Shehata et al., 2000; Shehata et al., 2002 and Shehata et al., 2006, Xue et al., 2021, Andrade Neto et al., 2021).
Skolu et al. (2007) and Feng et al. (2010) investigated the influence of lithium nitrate on expansions in mortars and concrete. The results obtained indicated that the lithium salt reduced the occurrence of expansions due to the formation of late ettringite, forming a protective barrier that prevents the reactive silica from being attacked by alkalis.
Munhoz et al. (2021) evaluated the effect of self-healing of improved autogenous mortar on the alkali-aggregate reaction (AAR). The results showed that the reference mortar and the mixture with 1% polypropylene microfiber showed the highest and lowest levels of expansion, respectively.
The themes developed by Brazilian researchers deal with the investigation of the characteristics of materials that influence the development of AAR (Tiecher et al., 2012; Tiecher et al., 2017), as well as the characterization of the gel produced by AAR (Johnson et al., 2017), from the investigation of works with signs of AAR (Hasparyk et al., 2009; Prado et al., 2019) and analysis of the behavior of new materials subjected to AAR (de Carvalho et al., 2009).
Tiecher et al. (2012) studied the mesostasis material present in the interstices of volcanic rocks, with results that indicated that the mesostasis in the interstitials of volcanic rocks generally consists of micro to cryptocrystalline mineral phases of quartz, feldspar and clay. Mesostasis has been identified as having different characteristics and therefore this new characterization calls for a

reassessment of its influence on the reactivity of volcanic rocks. Tiecher et al. (2017) presented research on the influence of quartz deformation in aggregates on the development of the alkali-silica reaction in concrete and its relationship with the dissolution of silica. The results indicated that the presence of slightly deformed quartz indicates the presence of internal pathways available to react with alkaline solutions in the concrete pores and points to the potential development of an alkali-silica reaction. Using the visible spectrophotometer test, it was possible to evaluate the dissolution potential of different samples of deformed quartz, which confirmed that the reactivity of quartz increases as the deformation of the crystalline structure increases.

Johnson et al. (2017) evaluated the fracture properties of the gel produced by the alkali-silica reaction in concrete. The researchers used the scanning electron microscopy technique and a fracture mechanics model and estimated that the fracture energy of the gel is $G_f = 11.2$ J/m^2.

At the Furnas Hydroelectric Plant in Brazil, already identified with the presence of AAR, Hasparik et al. (2009) investigated the properties of the affected concrete. The ultrasonic results showed that the pulse velocity is sensitive to different degrees of deterioration due to AAR and correlates with the modulus of elasticity of the investigated concretes. Furthermore, the modulus of elasticity was the main property affected by AAR.

Carvalho et al. (2009) investigated the effect of using steel fibers in mortars subjected to AAR, and the results showed that the addition of steel fibers reduced the expansion by AAR. The most expressive benefit corresponded to the addition of 13.0 mm fibers in the mixture containing 2% fibers.

Most works (13 articles) are related to methodologies for assessing damage caused by alkali-aggregate reactions. This refers to the attempts to standardize the tests used worldwide and the correlation between accelerated and field methods (Lindgard et al., 2016). Furthermore, most of these investigations were led by Fournier's Canadian research group, with significant contributions from Brazilian Sanchez, Professor at the University of Ottawa.

Research related to the use of pozzolans totals 10 works, while the subjects reactivity of aggregates and alkalinity of Portland cement present proportions of similar studies, 7 and 6, respectively.

3.2 Testing methods

Accurately analyzing samples of concrete and mortar subject to AAR provides reliability and safety related to the conditions of use of certain materials in reinforced concrete structures. Thus, the standardization of the methods of carrying out tests allows the efficient comparison of the conditions of accelerated and field tests, aiming to simulate reality more accurately. Furthermore, understanding how much deterioration in existing structures has affected or will affect their performance is another difficulty to be mastered in the field of alkali-aggregate reaction research.

Within this context, the main evaluation methods for diagnosing AAR and the degree of concrete deterioration as a result of the generated expansion are presented below.

3.2.1 Petrographic Analysis

Petrographic analysis is used to identify and classify the aggregates according to their mineralogical, structural and chemical characteristics, in order to determine their possible reactive potential.

Based on the petrographic analysis of the rock, it is possible to classify the aggregate according to the AAR as potentially innocuous or potentially reactive. The maximum limits of reactive phases generally adopted to classify an aggregate as potentially innocuous are: 5% (deleterious quartz), 3% (chalcedony), 1% (tridymite or cristobalite), 3% (volcanic glass) and 0.5% (opal). However, based on the experience of the petrographer, as well as on the present features, slightly different limits can be admitted. In Brazil, the standard that establishes a method for performing petrographic analysis of representative samples of rocks for use as aggregates in concrete, with emphasis on the

conditioning factors for the occurrence of the alkali-aggregate reaction (AAR), is NBR 15577 (2018) part 3.
In recent decades, researchers have sought to develop this technique, increasing diagnostic evaluation procedures and potential for expansion in structures subject to the development of AAR (Sanchez et al., 2015). In this context, several petrographic methods were developed worldwide (Blight et al., 1981; Sims and Miglio, 1992, Salomon and Panetier, 1994; Clemena et al., 2000; Rivard et al., 2000; Broekmans, 2002; Lindgard et al., 2004), but the most used is the Damage Rating Index (DRI), improved by Grattan-Bellew and colleagues (Grattan-Bellew and Danay, 1992; Dunbar and Grattan-Bellew, 1995; Grattan-Bellew and Mitchell, 2006; Sanchez, 2014).
In 2017, a Brazil-Canada collaboration work (Sanchez et al., 2017) was published to disseminate the AAR assessment by the Damage Rating Index (DRI), which is an important milestone for the insertion of the method in Brazil. Currently, the Damage Rating Index (DRI) test is registered as a FURNAS Technical Instruction document, authored by renowned Brazilian researchers Nicole Hasparyk and Leandro Sanchez (Hasparyk and Sanchez, 2021). This fact is a breakthrough such that Brazilian research should start to use this technique more frequently to investigate AAR and other expansive reactions.

3.2.2 Damage Rating Index (DRI)

The Damage Rating Index (DRI) technique is a semi-quantitative petrographic analysis performed with the aid of a stereomicroscope with 15 to 16x magnification (Figure 3), where the deterioration characteristics of the samples are accounted for through small areas with dimensions of 1 cm x 1 cm marked on the polished surface of the sample (Grattan-Bellew, 1995; Villeneuve et al., 2012). It is important to point out that in addition to quantifying the cracks found, their petrographic characteristics are also identified (Figure 3 and Table 1), which are multiplied by important factors, seeking to balance the influence of the types of cracks with respect to the resulting impact on losses of mechanical properties (Table 1) (Sanchez et al., 2015). The number obtained by the DRI is normalized to an area of 100 cm^2 (Villeneuve, 2011; Sanchez, 2014; Waidner, 2016; Sanchez et al., 2017).

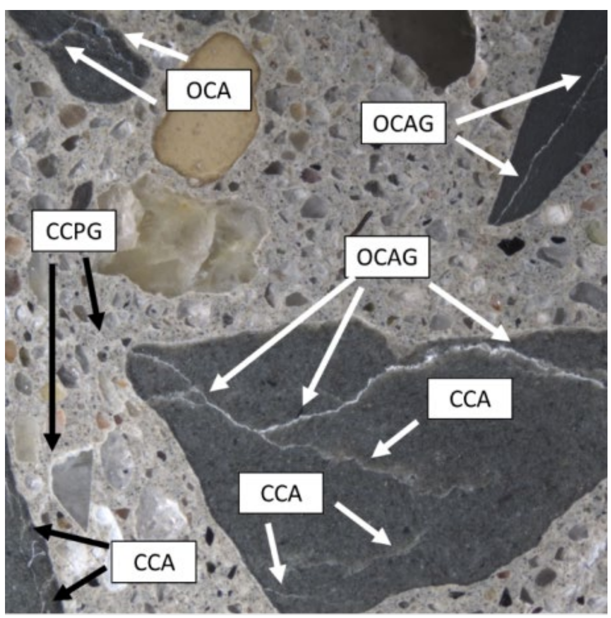


Figure 3. Image of the Damage Rating Index (DRI) technique performed at the Materials and Structures Laboratory of the Federal University of Paraná (LaME-UFPR).

Table 1. Weighted characteristics for DRI analysis.

Petrographic Characteristics	Abbreviation	Weight	Group
Closed cracks in the aggregate	CCA	0.25	I
Open cracks in the aggregate	OCA	2.00	II
Cracks in the aggregate with the presence of gel	OCAG	2.00	II
Disaggregated aggregate	CAD	3.00	-
Disaggregated/shattered aggregate particle	DAP	2.00	II
Cracks in the cement paste	CCP	3.00	III
Cracks in the cement paste with the presence of gel	CCPG	3.00	III

Classification of Groups:
Group I: closed cracks (opening ≤ 0.1 mm) in coarse aggregate particles or in the coarse fraction of sand particles (1 to 5 mm) (CCA);
Group II: open cracks (opening ≥ 0.1 mm) in the coarse aggregate particles or in the coarse fraction of sand particles (1 to 5mm), with or without reaction products (OCA + OCAG);
Group III: cracks in the cement paste, with or without reaction products (CCP + CCPG) (Sanchez et al., 2015) adapted from (Villeneuve, 2011).

The method proposes the classification of cracks into groups. Group I presents great variability in the number of cracks according to the aggregate used, showing values proportional to the increase in expansion. However, it should be noted that the aggregate crushing process also causes variations in the results, since the energy applied in the process can lead to the formation of small cracks inside the aggregate particles. On the other hand, groups II and III present open cracks that tend to propagate towards the transition zone of the aggregate with the cement paste. In addition to the varying appearance of cracks, it is interesting to add that the density and amount of them per cm^2 follow the increasing trend due to the development of expansion of the concrete samples (Sanchez et al., 2015).
Based on the various DRI observations, Sanchez et al. (2015) proposed an interesting model that relates concrete expansion with the development of cracks generated by AAR, as shown in Figure 4 and exemplified below. At the beginning of the physical-chemical reaction (concrete expansions smaller than 0.05%), cracks caused by AAR, type A or B, are commonly found within the reactive aggregate particles. As expansion progresses to moderate levels (approximately 0.12%), new cracks continue to develop within the reactive particles. However, there is also progress in the development of pre-existing cracks, which are able to cross the transition zone and progress towards the cement paste. For high expansion levels (approximately 0.20%), most previously formed cracks in the aggregates tend to be found already propagated within the cement paste. Furthermore, at this stage of deterioration, the "law of least energy" tends to govern crack progression. In other words, there is a greater tendency for existing cracks to continue to propagate, rather than a continuous generation and appearance of new cracks. Finally, at very high expansion levels (equal to or greater than 0.30%), the cracking is seen as very intense, since there is a tendency for interconnection between the cracks formed in different aggregate particles. At this point, it is worth mentioning that the mechanical properties of concrete are extremely reduced and affected, especially the compressive strength of concrete.

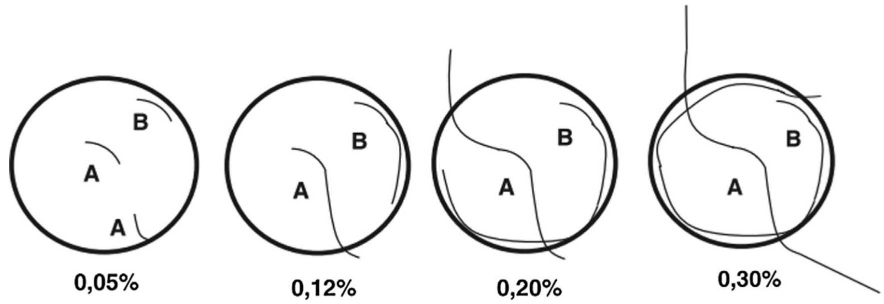


Figure 4. Qualitative model of damage due to AAR versus levels of expansion (Sanchez et al., 2015).

3.2.3 Stiffness Damage Test (SDT)

The SDT method was initially developed by Walsh (1965); the author detected an interesting correlation between the internal cracking density of rock samples and the stress/strain behavior provided by their cyclic loading. In the early 1990s, in research led by Crouch, the use of SDT was proposed for the evaluation of concrete samples affected by the alkali-aggregate reaction. As a result, Chrisp et al. (1993) predicted the application of a fixed cyclic load (five cycles), from 0 to 5.5 MPa, at a rate of 0.10 MPa/s. The authors indicate that the modulus of elasticity and the area of hysteresis (J/m^3) are good parameters for verifying the AAR, in addition to not being a destructive test and being able to reuse the samples in other analyses. The results show that the modulus of elasticity decreases, while the hysteresis area increases due to the plastic deformation generated when the cyclic load is applied (Smaoui et al., 2004a).

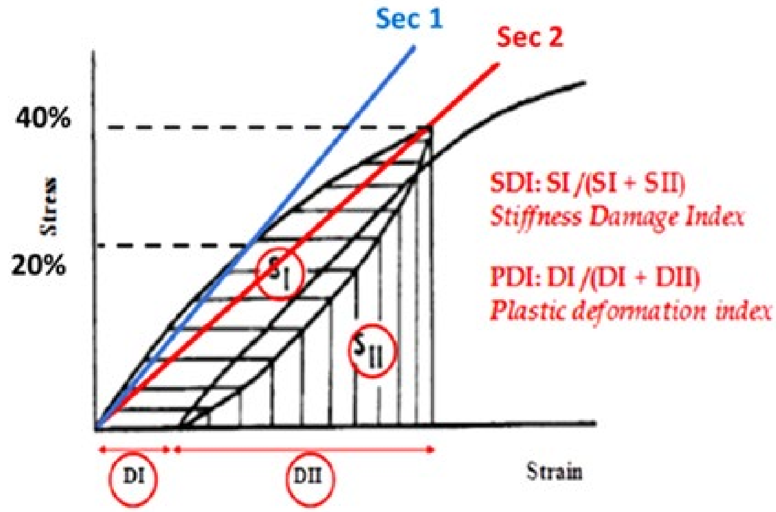
This method has already been studied by several authors, who aimed to identify test characteristics that influenced the results (Smaoui et al., 2004a; Sanchez et al. 2014; Sanchez et al. 2015; Sanchez et al. 2017a; Sanchez et al., 2017b). Smaoui et al. (2004a) tested other load application rates such as maximum, 5, 10 and 15 MPa, so that the load of 10 MPa showed the best results in general.

Sanchez et al. (2014a), Sanchez et al. (2015a), Sanchez et al. (2017) studied the application of techniques in various concrete mixtures with different aggregates and also in testimonies extracted from structures affected by AAR. The results showed that the use of an application load of 40% of the concrete strength at 28 days showed better performance to diagnose the degree of AAR damage. Sanchez et al. (2016a and 2017) indicate a strong correlation between the SDT and DRI tests, as both measure damage caused by AAR in a similar way and can complement each other and show the same trends in relation to expansion.

The SDT numbers express the mechanical characteristics of the concrete; that is, as the expansions caused by the AAR progress, the cracks also increase, decreasing the modulus of elasticity and tensile strength (Sanchez et al., 2017). Figure 5a shows the SDT test being performed at LaME-UFPR, while Figure 5b shows an output result of the SDT test, where the parameters called Stiffness Damage Index (SDI) and Plastic Deformation Index (PDI) are identified. They are translated as the ratio of dissipated energy over the total energy applied to the sample and the ratio of plastic deformation to the total strain applied to the system, respectively. Finally, the modulus of elasticity and the Non-Linear Index (NLI) can also be obtained from the test.

In Brazil, this evaluation technique was published by Sanchez et al. (2017) in a Brazil-Canada collaboration and, currently, the Stiffness Damage Test (SDT) is registered as a Technical Instruction document by FURNAS (Hasparyk and Sanchez, 2021). This is yet another national advancement such that Brazilian research should apply SDT more frequently in research on expansive reactions in concrete.

a)



b)

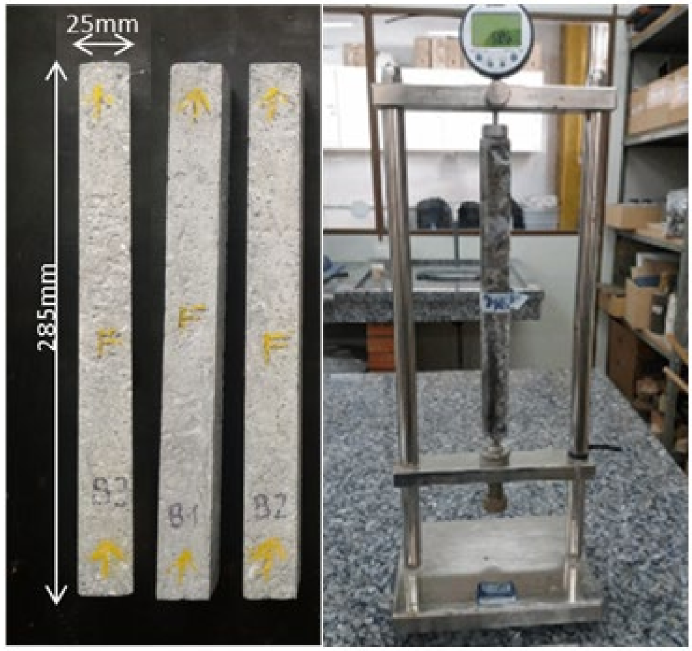
Figure 5. a) performance of the SDT test at the Laboratory of Materials and Structures of the Federal University of Paraná (LaME-UFPR); b) stress-strain behavior for concrete samples affected by AAR (Sanchez et al., 2017)

3.2.4 Accelerated Mortar Bar Method

The accelerated mortar bar test (AMBT) is standardized in Brazil by NBR 15577: 2018 – part 4 and in Canada by CSA A23.2-25A.

This is one of the most widespread tests in the world and consists of evaluating the variation in length of the mortar bars in order to verify a potential expansion due to the occurrence of the alkali reaction in a short period of time (16 and 30 days in the case of NBR 15577:2018 – part 4 and 14 days in the case of CSA A23.2-25A). Because it is an accelerated test, it occurs under severe exposure conditions (high temperature, 80ºC, and immersion in an alkaline 1N NaOH solution), which generates several criticisms regarding its use and variations in results.

Figure 6a shows the mortar specimens that are submitted to the expansion test by AAR and Figure 6b shows the measurement of the dimensional variation being performed in AMBT.



a) b)

Figure 6. a) mortar specimens for the expansion test, b) mortar expansion test.

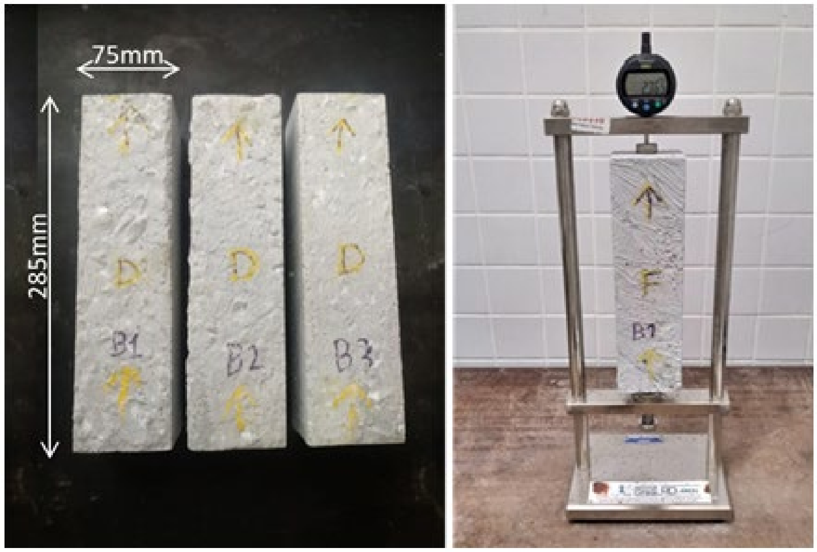
Several authors use this method to assess reactivity in aggregates (Fournier and Bérubé, 2000; Thomas et al., 2006; Alaejos et al., 2014; Golmakani; Hooton, 2016) and indicate that it can generate false positive and false negative results. Aggregates that result in false negatives may initially appear as harmless, but over time have reactive potential. It is also possible to obtain results of aggregates that can be used in concrete without damage, but the AMBT results discard them, generating false positives.

Several researchers seek to improve the AMBT method in order to remedy existing problems (Shon et al., 2002; Thomas et al., 2006; Sanchez et al., 2011; Alaejos et al., 2014), but it remains a highly criticized test due to its drastic conditions of acceleration of expansions by AAR, as reported (Thomas et al., 2006; Alaejos et al., 2014; Golmakani; Hooton, 2016; Fournier; Bérubé, 2000).

3.2.5 Concrete Prism Method

The Concrete Prism Test (CPT) is generally considered the best indicator of field performance when studying the alkali-aggregate reaction, and consists of measuring expansions of concrete prisms subjected to an environment of high humidity (95%) at a temperature of 38^0C. However, it requires an evaluation period of one year for studies of aggregate reactivity and two years for the use of reaction mitigating materials (Ideker et al., 2010). The fact that it only generates results in the long term is one of the reasons why many studies and companies tend not to follow this test method, even though it is considered more appropriate than the AMBT (accelerated mortar bar test) method. Figure 7a shows the concrete prisms used for the expansion test and Figure 7b shows the test being carried out.

In Brazil, NBR 15577-6 (2018) establishes the necessary procedures for the evaluation of AAR in concrete prisms. It is indicated to determine the reactive potential of the aggregates in comparison with concrete with standard cement, with the addition of sodium hydroxide, for a period of 365 days. As for the evaluation of supplementary materials or AAR inhibitors, the investigation period extends over 2 years.



a) b)

Figure 7. a) Concrete specimens for expansion testing, b) Expansion testing of concrete prisms.

It is worth noting that although the CPT is considered to be the most reliable test procedure in existence, a major disadvantage of the method is its long test period (1-2 years). In an attempt to solve this problem, accelerated CPT procedures were proposed in the 1990s (Ranc and Debray, 1992). Notable among them was an accelerated CPT version (i.e., ACPT) performed at 60ºC, showing promising results worldwide. It was found that reliable results can be achieved within 3-4 months or 6-8 months to assess the potential reactivity of aggregates or the efficiency of preventive measures, respectively.

This method has been standardized in Europe by RILEM (Lindgård, 2011), although in North and South America it is currently not a standard, as some problems related to alkali leaching and important variability in test results have been observed (Kermit, 2017).

The literature also suggests a test period of 3 months for the ACPT method to determine the reactivity of the aggregates (Degrosbois and Fontaine, 2000; Touma et al., 2001; Fournier et al., 2004) and six months for the determination of effectiveness of supplementary cementitious materials (Touma et al., 2001). In Brazil, NBR 15577-7 (2018) indicates the use of the accelerated concrete prism test (ACPT), which establishes a temperature of 60ºC for a period of 140 days with humidity above 95%.

It is worth mentioning that Sanchez (2008) and Sanchez, Kuperman and Helene (2011) studied another accelerated method with the objective of reducing the problems resulting from leaching that exist in the ACPT method and to seek a balance between the internal environment (test specimen) and the external one (solution in which the specimens are immersed); that is, a solution with less NaOH is used at a temperature of 80ºC and carried out for a period of four weeks. It is called the accelerated Brazilian concrete prism test (ABCPT). The results obtained using this method were satisfactory compared to the CPT (89% correlation).

3.2.6 Comparison between the evaluation methods of expansion by AAR

Many AAR research tests were identified, some standardized and others not, some more consistent with field conditions and others not. Thus, in this section we chose to show an overview of the frequency of use of the test methods covered between the years from 2000 to 2022. In this context, Figure 8 presents a comparison of the frequency of use of the types of expansion monitoring methods applied to assess AAR. The survey was carried out from the systematic search of studies published in the WoS and SCOPUS databases from the year 2000 onwards, with more than 5 citations from both countries (Brazil and Canada).

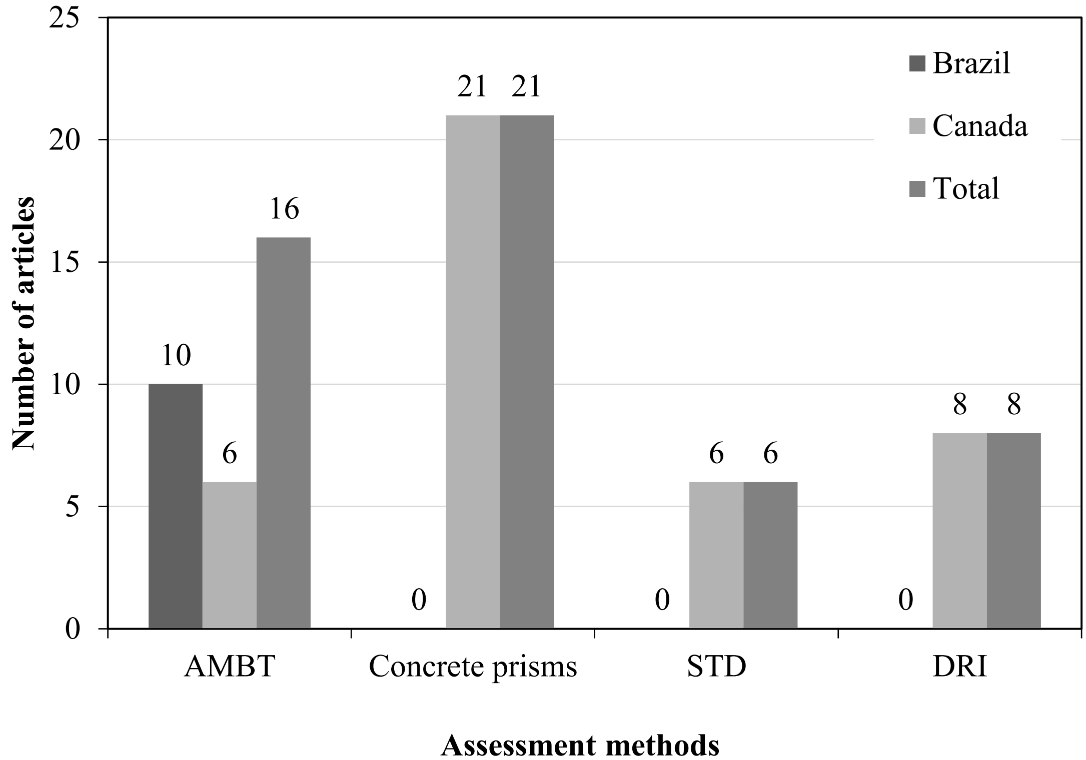


Figure 8. Methods for evaluating the expansion caused by AAR applied in research in Canada and Brazil.

It is observed that the accelerated mortar bar test (AMBT) is the one that predominates in studies related to AAR in Brazil. It should also be noted that, in Brazil, the other methods (CPT, SDT and DRI) were not used in the articles consulted in the survey carried out for this research. This fact is explained by the time and ease of execution of AMBT (results in 4 weeks) compared to concrete prisms (results in 1 to 2 years). It is worth mentioning that this research does not consider Brazilian journals with great relevance in the country, so works that use other evaluation methods may have been published nationally. In this context, the publication by Sanchez et al. (2017) and the FURNAS Technical Instruction document (Hasparyk and Sanchez, 2021) are important recent works that should make these methods of assessing damage by AAR applied more in research carried out in Brazil.

Thus, the little use of SDT and DRI analyses is due to the little knowledge and diffusion related to them in Brazil. In addition, they are methods for evaluating the state of deterioration in concrete test specimens that were not found in the articles in the survey of this research, with the published works coming from Brazilian research based only on mortars (AMBT).

On the other hand, in Canada, the concrete prism test is used more frequently than in Brazil. Figure 8 also shows that the SDT and DRI are frequently used tools to measure the extent of damage caused by AAR in Canada. The frequent use of these methods (CPT, SDT and DRI) in research in Canada is based on the fact that the AMBT has a dubious reliability. In addition, the SDT and DRI are useful to understand the present deterioration of concrete by AAR and to determine whether the expansion by AAR has affected the concrete structure and its mechanical properties.

3.3 Overview of AAR research in Brazil

In Brazil, the first registered studies addressing the AAR problem occurred in 1963, when the characterization of the aggregates that would be used in the construction of the Jupiá dam, located between the states of São Paulo and Mato Grosso do Sul, was carried out. The study was carried out by Gitahy and Ruiz in partnership with IPT – Instituto de Pesquisa e Tecnologia (Research and Technology Institute), and Centrais Elétricas de Urubupungá S.A. and found that the aggregates had reactive elements in their composition that could react like the alkalis present in cement, as Stanton published in 1940 (Lima, 2009; Priszkulnik, 2005).

According to Hasparyk (2005), since the discovery of AAR, several studies have focused on understanding the chemical process and characterization of reactive minerals, as well as the causes and consequences in works affected by this deterioration process. Haspariryk (2005) indicated that at least 19 dams in Brazil were identified with signs of AAR, which compromises the durability of the structures, in addition to the impact on the country's economy caused by the malfunction or suspension of activities.

With regard to the characterization of materials, data collected by the Brazilian Association of Portland Cement (ABCP) in 2015 indicate that of the aggregates already analyzed, 36% have reactive potential. In addition, the number of civil construction companies that seek to analyze the materials used in their works has been increasing every year, where most requests refer to the states of São Paulo and Pernambuco (Battagin et al., 2016).

Regarding the state of Pernambuco, in 2004 there was a milestone regarding the occurrence of AAR in Brazil, which was the first national proof of AAR in building constructions. This occurred in the Metropolitan Region of Recife (RMR), state of Pernambuco, with the expert investigation of the collapse of the Areia Branca residential building. Cracks due to AAR were concentrated in the foundation blocks of the Areia Branca building, but it is worth noting that the building did not collapse due to the deterioration process caused by AAR (Silva et al., 2021). In the following years, with inspection work led by Dr. Tibério Andrade, Professor at the Federal University of Pernambuco (UFPE), several residential buildings were found with foundation blocks cracked by AAR. These facts resulted in very important discussions for the technical and scientific environment, so that inspection procedures and recovery methods developed specifically for the solution of these cases emerged.

The growing concern with the subject has increased the number of studies related to AAR in Brazil. Figure 9 shows the growth of Brazilian publications related to the subject in high-impact journals, in the WoS and Scopus databases.

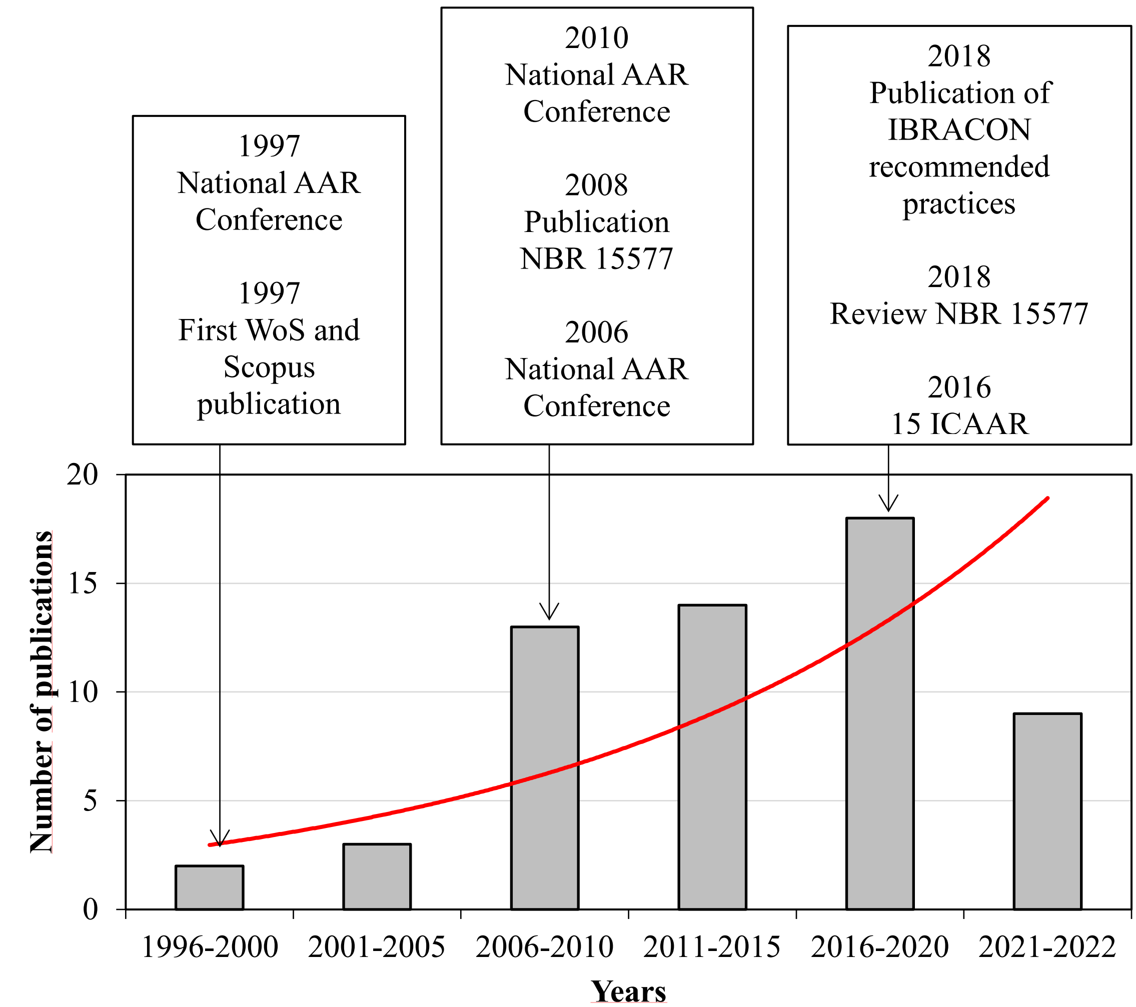


Figure 9. Growth of publications related to AAR in Brazil in high-impact journals present in the WoS and Scopus databases.

It can be seen from Figure 9 that publications related to AAR in Brazil, in addition to having increased over the years, show a leap from 2007. This fact coincides with the studies developed for the publication of the Brazilian regulatory standard in 2008, NBR 15577, which is divided into 7 parts and refers to the test procedures for the characterization of aggregates and binding materials subject to AAR. It was revised and updated in 2018.

Concomitantly with the publication of NBR 15577:2018, the Alkali-Aggregate Reaction Prevention Guide – Recommended Practices by IBRACON (Brazilian Institute of Concrete) was launched in 2018. The work was developed by the Alkali-Aggregate Reaction Technical Committee from IBRACON, with the coordination of researchers Cláudio Sbrighi Neto, Eduardo Quitete and Arnaldo Battagin.

With regard to Brazil's performance as a host and organization of events in the field of research on AAR, in 1997, the 1st Symposium on Alkali-Aggregate Reactivity in Concrete Structures took place, which was a landmark incentive for Brazilian research on AAR. It should be noted that 1997 also coincides with the first records of Brazilian research (article publication) in international databases, as can be seen in Figure 9.

In 2006, the 2nd Symposium on Alkali-Aggregate Reaction in Concrete Structures was held, at which time Brazil was already at a higher level in research on AAR and the verification of the reaction in the foundation blocks that occurred in buildings in Pernambuco was evidenced in Brazil.

It should be noted that shortly after this event, Brazil launched its first standard on AAR, the aforementioned NBR 15577/2008. It should also be noted in Figure 9 that the participation of Brazilian researchers in publications in high-impact national journals grew a lot after the 2nd Symposium on Alkali-Aggregate Reaction in Concrete Structures.

In 2016, another Brazilian landmark on research on AAR occurred when Brazil hosted the 15th International Conference on Alkali-Aggregate Reaction (15th ICAAR), considered the most important conference in the world on research and development on AAR. This is a merit of the national researchers and the editors of the annals of this event, Dr. Haroldo de Mayo Bernardes and Dr. Nicole Pagan Hasparyk. Figure 9 also shows an increase in the participation of Brazilians in publishing articles in high-impact journals from 2016, when ICAAR was held in São Paulo, Brazil. Thus, it is evident that Brazil plays an important global role in advancing research related to AAR, participating and encouraging national and international discussions provided by its specialists who discuss knowledge in specific committees on the subject.

3.4 Future approaches and knowledge gaps

The publications of the last three years in Brazil and Canada, referring to the researched topic, amount to 19 articles. With these works, a bibliographic coupling analysis was carried out, which measures the relationship between two articles based on the number of common references cited (correlations), in order to define similar areas of research that are on the rise, as indicated in the work of Lucas; Garcia-Zorita, Sanz-Casado (2013).

Of these 19 articles, those with at least two citations from the two databases under study were selected and the research themes were correlated between them. These works are presented in Table 2.

Among the works presented, two large groups of research can be observed, which are related according to the studied themes. The largest group identified refers to the study of alkali-aggregate reactions in general, as well as their implications for reinforced concrete structures. Within this group are the works by Campos et al. (2018) and Gorga et al. (2018) with 21 and 26 correlations, respectively. This group indicates that the theme related to AAR is still on the rise, as well as the various parameters related to tests and the forms of deterioration observed with attempts to model the behavior of concrete with AAR. It is important to highlight that the two works cited as outstanding in this group, Campos et al. (2018) and Gorga et al. (2018), present Brazilian researchers as first authors.

The other group is represented by the works by Angulo-Ramirez et al. (2018) with three correlations and Tiecher et al. (2018), with 5 correlations. These papers refer to alkali-aggregate reactions in alternative cementitious systems, such as alkali-activated cements and the use of pozzolanic additions. This study group seeks a better understanding of the durability of cements with low clinker content and sees it as a theme of greater originality with few bibliographies available so far, and which should be studied more in-depth over the next few years. These two works also present the performance of Brazilians in the development of research, which shows Brazil's participation at the forefront of research on AAR.

In general, works related to AAR deal mainly with the characterization of materials, forms of AAR mitigation, evaluation methods and identification of works with a deleterious reaction. Despite the topic being recent and most works referring to the implications of AAR in concrete structures, among the gaps in knowledge on the subject, the study of reaction mechanisms in aggregates of volcanic and dolomitic igneous origins can be mentioned, as well as the characterization of AAR in alternative cements. In addition, emphasis should be given to the development of methodologies to recover or contain the effects caused by AAR.

Table 2. Correlation analysis between the topics studied regarding AAR in Canada and Brazil.

Themes	Authors	Year	Citations	Correlations
Alternative cements				
Alkali-activated Portland blast furnace slag cement mortars: Performance to alkali-aggregate reaction	Angulo-Ramirez et al.	2018	17	3
Alkali-Aggregate Reaction: A study of the influence of the petrographic characteristics of volcanic rocks	Tiecher et al.	2018	2	5
Alkali-aggregate reaction and structural implications				
Effects of an internal sulfate attack and an alkali-aggregate reaction in a concrete dam	Campos et al.	2018	12	21
Deterioration Assessment of Infrastructure Using Fuzzy Logic and Image Processing Algorithm	Pragalath et al.	2018	9	0
FE approach to perform the condition assessment of a concrete overpass damaged by ASR after 50 years in service	Gorga et al.	2018	6	26
Impact of pore solution concentration on the accelerated mortar bar alkali-silica reactivity test	Golmakani and Hooton	2019	5	1
Structural implications of internal swelling reactions in concrete: review and research needs	Noel et al.	2018	2	12
Material, structural and modelling aspects of alkali aggregate reaction in concrete	Ferche et al.	2019	2	10

4. CONCLUSIONS

The analysis carried out from the systematic review shows that Canada is the country that most stands out in the publication of scientific articles in high impact journals internationally in the scope of the alkali-aggregate reaction. It is also evidenced in this work that Brazil is the seventh country in this classification ranking. The comparison between published research of Canadian and Brazilian origin indicates that Canada produces three times more works of international scope than Brazil related to the AAR theme.

It was also evident that several of these Canadian studies are carried out jointly with Brazilian authors. The interconnection between citations and authors indicated that the works carried out between the two countries are divided into three large groups of researchers led by Fournier, Thomas and Berubè, thus identifying the correlation between the topics studied.

Regarding the thematic categories, four main areas of research were identified, namely: AAR evaluation methodologies, use of cement additions, aggregate reactivity, and cement alkalinity. The topic with the highest number of publications refers to the various methodologies applied to the assessment of AAR, led by the Canadian Benoit Fournier, with significant contributions from the Brazilian Leandro Sanchez.

Regarding the AAR detection methods, it was noted that in Brazil, the concrete prism test is little used in the evaluated studies, despite being standardized. In addition, SDT and DRI analyses are not widespread in the country, although there are national publications in recent years that tend to change this context.

With the criterion and procedure of bibliographic survey applied in this research, it was demonstrated that the AAR studies developed in Brazil are based on AMBT, with no detection of the use of more reliable tests such as: concrete prism test (CPT), Stiffness Damage Test (SDT) and Damage Rating Index (DRI).

Despite this, Brazil presents an advance in the number of studies related to the theme of AAR, in order to identify, mitigate and solve the pathological manifestations resulting from it. In the country there are many specialists dedicated to the subject, having organized several specific conferences on AAR, indicating the national protagonism in this field of research.

As for future studies, there is a trend related to AAR and its structural implication and the effect of AAR in alternative cements without the use of clinker. There are efforts in search of a better understanding of the reaction mechanisms in distinct aggregates and innovative materials, as well as ways of recovering structures already affected by the reaction.

Brazil shows an increase in publications on AAR in high-impact journals over the years and showed a preponderant presence when it came to future approaches and the knowledge gap.

Through a project funded by Capes and the National Water Agency (ANA), and in partnership with the University of Ottawa (Canada), the Materials and Structures Laboratory (LaME) at the Federal University of Paraná (UFPR) began to develop research applying the mentioned methods. In the near future, it is intended to publish many studies including results of CPT, SDT and DRI in experimental programs developed in Brazil.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Associação Brasileira De Normas Técnicas. (2018). *NBR 15577: Agregados — Reatividade álcali-agregado Parte 7: Determinação da expansão em prismas de concreto pelo método acelerado.* Rio de Janeiro.

Associação Brasileira De Normas Técnicas. (2018). *NBRE15577: Agregados — Reatividade álcali-agregado Parte 6: Determinação da expansão em prismas de concreto.* Rio de Janeiro.

Adams, D. F., Walrath, D. E. (1987). *Current status of the Iosipescu shear test method,* J. Compos. Mater. 21: 494–507. https://doi.org/10.1177/002199838702100601

Adorno, C. S., Langaro, E. A., Medeiros, M. H. F., Gobbi, A. (2020). *Teste acelerado de argamassas e a combinação de adições minerais ativas com agregado potencialmente reativo*. Journal of Urban Technology and Sustainability. 3: 36-50. https://doi.org/10.47842/juts.v3i1.23

Adorno, C. S., Medeiros, M. H. F., Filho, J. H., Réus, G. C. (2018). *Effects of the addition of red ceramic, limestone filler and rice husk ash in alkali silica reaction.* Journal of Building Pathology and Rehabilitation. 3: 1-11. https://doi.org/10.1007/s41024-017-0030-0

Alaejos, P., Lanza, V., Bermúdez, M. A., Velasco, A. (2014). *Effectiveness of the accelerated mortar bar test to detect rapid reactive aggregates (including their pessimum content) and slowly*

reactive aggregates. Cement and Concrete Research. 58: 13–19. https://doi.org/10.1016/j.cemconres.2014.01.001
Andrade Neto, J. S., França, M. J. S., Amorim Júnior, N. S., Véras Ribeiro, D. (2021). *Effects of adding sugarcane bagasse ash on the properties and durability of concrete.* Construction and Building Materials. 266: 120959. https://doi.org/10.1016/j.conbuildmat.2020.120959
Angulo-Ramírez, D. E., Gutiérrez, R. M., Medeiros, M. H. F. (2018). *Alkali-activated Portland blast furnace slag cement mortars: Performance to alkali-aggregate reaction.* Construction and Building Materials. 179: 49-56. https://doi.org/10.1016/j.conbuildmat.2018.05.183
Berubè, M. A., Dorion, J., Duchesne, J., Fournier, B., Vezinac, D. (2003b). *Laboratory and field investigations of the influence of sodium chloride on alkali–silica reactivity.* Cement and Concrete Research. 33: 77–84. https://doi.org/10.1016/S0008-8846(02)00926-2
Berubè, M. A., Duchesne, J., Dorion, J. F., Rivest, M. (2002). *Laboratory assessment of alkali contribution by aggregates to concrete and application to concrete structures affected by alkali–silica reactivity*. Cement and Concrete Research. 32: 1215–1227. https://doi.org/10.1016/S0008-8846(02)00766-4
Berubè, M. A., Duchesne, J., Ollivier, J. P., Ballivya, G. (2003). *Alkali mass balance during the accelerated concrete prism test for alkali–aggregate reactivity.* Cement and Concrete Research 33: 1147–1153. https://doi.org/10.1016/S0008-8846(03)00020-6
Bérubé, M. A., Smaoui, N., Bissonnette, B., Fournier, B. (2005). *Outil d'évaluation et de gestion des ouvrages d'art affectés de réactions alcalis-silice (RAS)*. Études et Recherches en Transport, Ministère des Transports du Québec.Canadá.
Beyene, M., Snyder, A., Lee, R. J., Blaszkiewicz, M. (2013). *Alkali Silica Reaction (ASR) as a root cause of distress in a concrete made from Alkali Carbonate Reaction (ACR) potentially susceptible aggregates.* Cem. Concr. 51: 85–95. https://doi.org/10.1016/j.cemconres.2013.04.014
Blight, G. E., Mciver, J. R., Schulte, W. K., Rimmer, R. (1981). "*The effects of alkali–aggregate reaction on reinforced concrete structures made with Witwatersrand quartzite aggregate*". 5th ICAAR — International Conference on Alkali–Aggregate Reaction in Concrete, Cape Town, South Africa.
Bolotte, B. (1992). "*Development of an accelerated performance test on concrete for evaluating its resistance to AAR*." The 9th International Conference on Alkali–Aggregate Reactivity in Concrete. United Kingdom, London.
Broekmans, M. A. T. M. (2002). "*The Alkali – Silica Reaction: Mineralogical and Geochemical Aspects of some Dutch Concretes and Norwegian Mylonites",* PhD Thesis, Utrecht University, The Netherlands.
Campos, A., López, C. M., Blanco, A., Aguado, A. (2018). *Effects of an internal sulfate attack and an alkali-aggregate reaction in a concrete dam.* Construction and Building Materials. 166: 668-683. https://doi.org/10.1016/j.conbuildmat.2018.01.180
Chrisp, T. M., Waldron, P., Wood, J. G. (1993). *Development of a non-destructive test to quantify damage in deteriorated concrete*. Magazine of Concrete Research. 45 (165): 247–256. https://doi.org/10.1680/macr.1993.45.165.247
Clemena, G. G., Lane, S., Freeman, T., Lozev, M. (2000). *Evaluation of Nondestructive Evaluation Methods for Application in Early Detection of Deterioration in Concrete Pavements*. VTRC 00-R13 Virginia Transportation Research Council, Charlottesville, USA.
Crouch, R. S., Wood, J. G. M. (1990). *Damage evolution in ASR affected concretes*. Eng. Fract. Mech. 35: 211–218.
De Carvalho, M. R. P., Faisbain, E. M. R., Filho, R. D. T., Cordeiro, G. C., Hasparyk, N. P. (2010). *Influence of steel fibers on the development of alkali-aggregate reaction.* Cement and Concrete Research. 40(4): 598-604. https://doi.org/10.1016/j.cemconres.2009.11.007

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. 116806.

Degrosbois, M., Fontaine, E. (2000). "*Performance of the 60 °C-Accelerated Concrete Prism Test for the evaluation of potential alkali–reactivity of concrete aggregates".* The 11th International Conference on Alkali–Aggregate Reactivity in Concrete. Quebec City, QC, Canada.

Drolet, C., Duchesne, J., Fournier, B. (2017). *Effect of alkali release by aggregates on alkali-silica reaction*. Construction and Building Materials. 157: 263–276. https://doi.org/10.1016/j.conbuildmat.2017.09.085

Drolet, C., Duchesne, J., Fournier, B. (2017). *Validation of the alkali contribution by aggregates to the concrete pore solution*. Cement and Concrete Research. 98: 10–23. https://doi.org/10.1016/j.cemconres.2017.04.001

Duchesne, J., Berubè, M. A. (2001). *Long-term effectiveness of supplementary cementing materials against alkali–silica reaction*. Cement and Concrete Research. 31: 1057–1063. https://doi.org/10.1016/S0008-8846(01)00538-5

Dunbar, P.A., Grattan-Bellew, P. E. (1995). "*Results of damage rating evaluation of condition of concrete from a number of structures affected by ASR".* CANMET/ACI International Workshop on Alkali–Aggregate Reactions in Concrete, Darmouth, Canada. pp. 257-266.

Feng, X., Thomas, M. D. A., Bremner, T. W., Folliard, K. J., Fournier, B. (2010). *Summary of research on the effect of LiNO3 on alkali–silica reaction in new concrete.* Cement and Concrete Research. 40: 636–642. https://doi.org/10.1016/j.cemconres.2009.08.021

Fiset, M., Sanchez, L. F. M., Bilodeau, S., Mitcell, D., Bastien, J. (2021). *Influence of Alkali-Silica reaction (ASR) on aggregate interlock and shear-friction behavior of reinforced concrete members.* Engineering Structures. 233: 111890. https://doi-org.ez48.periodicos.capes.gov.br/10.1016/j.engstruct.2021.111890

Fournier, B., Bérubé, M.-A. (2000). *Alkali-aggregate reaction in concrete: a review of basic concepts and engineering implications.* Canadian Journal of Civil Engineering. 27(2): 167–191. https://doi.org/10.1139/l99-072

Fournier, B., Bérubé, M. A., Folliard, K., Thomas, M. D. A. (2010). *Report on the diagnosis, prognosis, and mitigation of alkali-silica reaction (ASR) in transportation structures.* US Department of Transportation, Federal Highway Administration, Publication FHWA-HIF-09-004.

Fournier, B., Chevrier, R., Degrosbois, M., Lisella, R., Folliard, K., Ideker, J., Shehata, M., Thomas, M., Baxter, S. (2004*). "The accelerated concrete prism test (60 °C): variability of the test method and proposed expansion limits"*. The 12th International Conference on Alkali–Aggregate Reaction in Concrete, Beijing China.

Gallo, G., Sanchez, L., Medeiros, M. H. F., Andrade, T. (2007). *Medidas preventivas para a reação álcali-agregado (RAA) no concreto.* Concreto & Contruções. 46: 22-28.

Glänzel, W. (2003). "*Bibliometrics as a research field: a course on theory and application of bibliometric indicators". Course handouts* .Bélgica.

Golmakani, F., Hooton, R. (2016). "*Comparison of laboratory performance tests used to assess alkali-silica reactivity".* Proceedings, Annual Conference - Canadian Society for Civil Engineering. 2: 1–7.

Grattan-Bellew, P. E., Cybanski, G., Fournier, B., Mitchell, L. (2003). *Proposed Universal Accelerated Test for Alkali-Aggregate Reaction The Concrete Microbar Test.* Cement. Concrete, and Aggregates. 25: 2.

Grattan-Bellew, P. E., Danay, A. (1992). "*Comparison of laboratory and field evaluation of AAR in large dams Proc. of the International Conference on Concrete AAR in Hydroelectric".* Plants and Dams, Canadian Electrical Association & Canadian National Committee of the Int. Commission on Large Dams, Fredericton New Brunswick, Canada.

Grattan-Bellew, P. E., Mitchell, L. D. (2006*). "Quantitative petrographic analysis of concrete — The Damage Rating Index (DRI) method, a review Proc".* Marc-André Bérubé Symposium on AAR in Concret. CANMET/ACI Advances in Concrete Technology Seminar, Montréal, Canada, 1: 321-334.
Gorga, T., Sanchez, L. F. M., Martín-Pérez, B. (2018). *FE approach to perform the condition assessment of a concrete overpass damaged by ASR after 50 years in service.* Engineering Structures. 177: 133-146. https://doi.org/10.1016/j.engstruct.2018.09.043
Golmakani, F. R., Hooton, D. (2019). *Impact of pore solution concentration on the accelerated mortar bar alkali-silica reactivity test*. Cement and Concrete Research. 121: 72-80. https://doi.org/10.1016/j.cemconres.2019.02.008
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: 1357–1364. https://doi.org/10.1016/j.engstruct.2011.01.013.
Hasparyk, N. P., Monteiro, P. J., Molin, D. C. C. (2009). *Investigation of mechanical properties of mass concrete affected by alkali-aggregate reaction.* Journal of Materials in Civil Engineering. 21: 294:297. https://doi.org/10.1016/j.cemconres.2009.11.007
Hasparyk, N. P., Sanchez, L. F. M. (2021).*"SDT – Método de ensaio para a determinação do índice de dano de rigidez (SDI) e índice de deformação plástica (PDI) em concretos".* Instrução técnica ITDSBE001. FURNAS. Gôiania. Brasil. p. 19.
Hjørland, B. (2013). *Citation analysis: A social and dynamic approach to knowledge organization.* Information Processing and Management. 49: 1313–1325. https://doi.org/10.1016/j.ipm.2013.07.001
Ideker, J. H., East, B. L., Folliard, K. J., Thomas, M. D. A., Fournier, B. (2010). *The current state of the accelerated concrete prism test.* Cement and concrete research. 40(4): 550-555. https://doi.org/10.1016/j.cemconres.2009.08.030
Johnson, C. V., Chen, J., Hasparyk, N. P., Monteiro, P. J. M., Akono, A. T. (2017). Fracture properties of the alkali silicate gel using microscopic scratch testing. Cement and Concrete Composites. 79: 71-75. https://doi.org/10.1016/j.cemconcomp.2017.01.012
K. J. Murdock, K. J., Blanchette, A. (1994). *Rapid evaluation of alkali–aggregate reactivity using a 60 °C concrete prism test*. The 3 rd International Conference on Durability of Concrete. Nice, France.
Katayama, T., Grattan-Bellew, P. E. (2012). "*Petrography of the Kingston experimental sidewalk at age 22 years--ASR as the cause of deleteriously expansive, socalled alkali-carbonate reaction*". in: Proc. 14th Int. Conf. Alkali-Aggregate React. Concr. Austin, Texas, USA.
Katayama, T., Jensen, V., Rogers, C. A. (2016). *The enigma of the 'so-called' alkali-carbonate reaction.* Proc. Inst. Civ. Eng. Constr. Mater. 169(4): 223-232. https://doi.org/10.1680/jcoma.15.00071
Kermit, P. H. (2017). "*Determining alkali content in ASR performance-tested concrete".* Master of Science in Engineering and ICT. Norwegian University of Science and Technology. Department of Structural Engineering. p.72.
Kubo, Y., Nakata, M. (2012). "*Effect of reactive aggregate on mechanical properties of concrete affected by alkali-silica reaction"*. In: Proceedings of the 14th international conference on alkali-aggregate reaction in concrete. Austin. Texas. Electronic.
Lindgård, J. (2011). "*Literature survey on performance testing"*. RILEM TC 219-ACS-P. p. 164.
Lindgard, J., Andiç-Cakir, O., Fernandes, I., Ronning, T., Thomas, M. D. A. (2012). *Alkali–silica reactions (ASR): Literature review on parameters influencing laboratory performance testing.* Cement and Concrete Research. 42: 223–243. https://doi.org/10.1016/j.cemconres.2011.10.004

Lindgård, J., Fournier, B., Ronning, T. F., Thomas, M. D. A. (2016). *Alkali–aggregate reaction: performance testing, exposure sites and regulations Proceedings of the Institution of Civil.* Engineers Construction Materials. 169: 189-196. https://doi.org/10.1680/jcoma.15.00077
Lindgard, J., Sellevold, E. J., Thomas, M. D. A., Pedersen, B.; Justnes, H.; Ronning, T. (2013). *Alkali–silica reaction (ASR)—performance testing: Influence of specimen pre-treatment, exposure conditions and prism size on concrete porosity, moisture state and transport properties.* Cement and Concrete Research. 53: 145–167. https://doi.org/10.1016/j.cemconres.2013.05.020
Lindgard, J., Skjolsvold, O., Haugen, M., Hagelia, P., Wigum, B. J. (2004). "*Experience from evaluation of degree of damage in fluorescent impregnated plan polished sections of half-cores based on the "Crack Index Method"*. 12th ICAAR — International Conference on Alkali–Aggregate Reaction in Concrete. Beijing, China. pp. 939-947.
Lindgard, J., Thomas, M. D. A., Sellevold, E. J., Pedersen, B., Andiç-Cakir, O., Justnes, H., Ronning, T. (2013). *Alkali–silica reaction (ASR)—performance testing: Influence of specimen pre-treatment, exposure conditions and prism size on alkali leaching and prism expansion*. Cement and Concrete Research. 53: 68–90. https://doi.org/10.1016/j.cemconres.2013.05.017
Lu, D., Mei, L., Xu, Z., Tang, M., Fournier, B. (2006). *Alteration of alkali reactive aggregates autoclaved in different alkali solutions and application to alkali–aggregate reaction in concrete (I) Alteration of alkali reactive aggregates in alkali solutions*. Cement and Concrete Research. 36: 1176–1190. https://doi.org/10.1016/j.cemconres.2006.01.008
Lu, D., Zhou, X., Xu, Z., Lan, X., Tang, M., Fournier, B. (2006). *Evaluation of laboratory test method for determining the potential alkali contribution from aggregate and the ASR safety of the Three-Gorges dam concrete.* Cement and Concrete Research. 36: 1157–1165. https://doi.org/10.1016/j.cemconres.2006.01.004
Lucas, E. O., Garcia-Zorita, J. C., Sanz-Casado, E. (2013). *Evolução histórica de investigação em informetria: ponto de vista espanhol*. Liinc em Revista. 9 (1): 255-270. https://doi.org/10.18617/liinc.v9i1.509
Mariano, A. M., Rocha, M. S. (2017). "*Revisão da literatura: apresentação de uma abordagem integradora*". XXVI Congreso Internacional AEDEM. Reggio Calabria. Italia.
Martin, R. P., Sanchez, L., Fournier, B., Toutlemonde, F. (2017). *Evaluation of different techniques for the diagnosis & prognosis of Internal Swelling Reaction (ISR) mechanisms in concrete.* Construction and Building Materials. 156: 956–964. https://doi.org/10.1016/j.conbuildmat.2017.09.047
Munhoz, G. S., Dobrovolski, M. E. G., Pereira, E., Medeiros Junior, R. (2021). *Effect of improved autogenous mortar self-healing in the alkali-aggregate reaction*. Cement and Concrete Composites.117: 103905. https://doi.org/10.1016/j.cemconcomp.2020.103905
Naar, R. (2010). "*Modelisation du comportement mécanique du béton par approche multi-physique (couplage chimie-mécanique): application à la réaction alcalisilice*". Thèse de doctorat. École Nationale Supérieure des Mines de Paris (France).
Noel, M., Sanchez, L., Tawil, D. (2019). *Structural implications of internal swelling reactions in concrete: review and research needs.* Magazine of concrete research. 70(20): 1052-1063. https://doi.org/10.1680/jmacr.17.00383
Prado, R. J., Tiecher, F., Hasparyk, N. P., Dal Molin, D. C. C. (2019). *Structural characterization of alkali-silica reaction gel: Na x-ray absorption fine structure study.* Cement and Concrete Research. 123: 105774. https://doi.org/10.1016/j.cemconres.2019.05.019
Pragalath, H., Seshathiri, S., Rathod, H., Balasubramanian Esakki, S. M. A. S. C. E. (2018). *Deterioration Assessment of Infrastructure Using Fuzzy Logic and Image Processing Algorithm.* Journal of Performance of Constructed Facilities. 32: 1-13. 10.1061/(ASCE)CF.1943-5509.0001151

Ranc, R., Debray, L. (1992). "*Reference test methods and a performance criterion for concrete structures"*. The 9th International Conference on Alkali-Aggregate Reaction in Concrete. London.
Rivard, P., Berubè, M. A., Ollivier, J. P., Ballivy, G. (2007). *Decrease of pore solution alkalinity in concrete tested for alkali-silica reaction.* Materials and Structures. 40:909–921. https://doi.org/10.1617/s11527-006-9191-z
Rivard, P., Fournier, B., Ballivy, G. (2000). *Quantitative petrographic technique for concrete damage due to ASR: experimental and application.* Cem Concr Aggreg. 22 (1):63-72. https://doi.org/10.1520/CCA10465J
Salomon, M., Panetier, J. L. (1994). "*Quantification du degré d'avancement de l'alcali-réaction dans les bétons et de la néofissuration associée"*. 3rd CANMET/ACI International conference on durability of concrete. Nice, France. pp. 383-401.
Sanchez, L. F. (2014). "*Contribution to the assessment of damage in aging concrete infrastructures affected by alkali-aggregate reaction"*. Tese (Doutorado) — Université Laval. p. 377.
Sanchez, L. F. M., Fournier, B., Jolin, M., Bastien, J., Mitchell, D. (2017). *Tools for assessing damage in concrete affected by AAR coming from fine and coarse aggregates*. Revista Ibracon De Estruturas E Materiais. 10:84-91. https://doi.org/10.1590/S1983-41952017000100005
Sanchez, L. F. M., Fournier, B., Jolin,M., Mitchell, D., Bastien, J. (2017). *Overall assessment of Alkali-Aggregate Reaction (AAR) in concretes presenting different strengths and incorporating a wide range of reactive aggregate types and natures*. Cem. Concr. Res. 93: 17–31. https://doi.org/10.1016/j.cemconres.2016.12.001
Sanchez, L., Kuperman, S. C., Helene, P. (2011). *Uso do método acelerado brasileiro de prismas de concreto (ABCPT) para avaliação da reação álcali-agregado (RAA).* Revista Ibracon de Estruturas e Materiais (RIEM). 4(4):575–581. https://doi.org/10.1590/S1983-41952011000400004
Sanchez, L. F. M., Fournier, B., Jolin, M., Bastien, J. (2015). *Evaluation of the Stiffness Damage Test (SDT) as a tool for assessing damage in concrete due to alkali-silica reaction (ASR): Input parameters and variability of the test responses.* Construction and Building Materials. 77: 20–32. https://doi.org/10.1016/j.conbuildmat.2014.11.071
Sanchez, L. F. M., Fournier, B., Jolin, M., Bastien, J. (2014). *Evaluation of the stiffness damage test (SDT) as a tool for assessing damage in concrete due to ASR: Test loading and output responses for concretes incorporating fine or coarse reactive aggregates.* Cement and Concrete Research. 56: 213–229. https://doi.org/10.1016/j.cemconres.2013.11.003
Sanchez, L. F. M., Fournier, B., Jolin, M., Bastien, J., Mitchell, D. (2016). *Practical use of the Stiffness Damage Test (SDT) for assessing damage in concrete infrastructure affected by alkali-silica reaction.* Construction and Building Materials. 125: 1178–1188. https://doi.org/10.1016/j.conbuildmat.2016.08.101
Sanchez, L. F. M., Fournier, B., Jolin, M., Duchesne, J., Bedoya, M. A. B., Bastien, J. (2016). *Use of Damage Rating Index to Quantify Alkali-Silica Reaction Damage in Concrete: Fine versus Coarse Aggregate*. ACI MATERIALS JOURNAL. 113: 395-407. http://dx-doi.ez48.periodicos.capes.gov.br/10.14359/51688983
Sanchez, L. F. M., Fournier, B., Jolin, M., Duchesne, J. (2015). *Reliable quantification of AAR damage through assessment of the Damage Rating Index (DRI).* Cement and Concrete Research. 67: 74–92. https://doi.org/10.1016/j.cemconres.2014.08.002
Sanchez, L. F. M., Fournier, B., Jolin, M., Mitchell, D., Bastien, J. (2017*). Overall assessment of Alkali-Aggregate Reaction (AAR) in concretes presenting different strengths and incorporating a wide range of reactive aggregate types and natures.* Cement and Concrete Research. 93: 17–31. https://doi.org/10.1016/j.cemconres.2016.12.001
Sanchez, L. F. M., Fournier, B., Jolin, M., Bastien, J., Mitchell, D. (2017). *Tools for assessing damage in concrete affected by AAR coming from fine and coarse aggregates*. Rev. IBRACON Estrut. Mater. 10(1): 84-91. https://doi.org/10.1590/S1983-41952017000100005

Santos, B. S., Ribeiro, D. V. (2021). *Influence of granitic rock fines addition in the alkali-aggregate reaction (AAR) in cementitious materials.* Revista Ibracon De Estruturas E Materiais. 14: 14203. https://doi.org/10.1590/S1983-41952021000200003

Shehata , H. S. M., Thomas, M. D. A. (2006). *Alkali release characteristics of blended cements.* Cement and Concrete Research. 36: 1166–1175. https://doi.org/10.1016/j.cemconres.2006.02.015

Shehata , H. S. M., Thomas, M. D. A. (2002). *Use of ternary blends containing silica fume and fly ash to suppress expansion due to alkali–silica reaction in concrete*. Cement and Concrete Research. 32: 341–349. https://doi.org/10.1016/S0008-8846(01)00680-9

Shehata, H. S. M., Thomas, M. D. A. (2000). *The effect of fly ash composition on the expansion of concrete due to alkali–silica reaction.* Cement and Concrete Research. 30:1063– 1072. https://doi.org/10.1016/S0008-8846(00)00283-0

Shehata, H. S. M., Thomas, M. D. A. (2010). *The role of alkali content of Portland cement on the expansion of concrete prisms containing reactive aggregates and supplementary cementing materials.* Cement and Concrete Research. 40: 569–574. https://doi.org/10.1016/j.cemconres.2009.08.009

Shon, C. S. C.-S., Zollinger, D. G., Sarkar, S. L. (2002). *Evaluation of modified ASTM C 1260 accelerated mortar bar test for alkali-silica reactivity.* Cement and Concrete Research. 32(12):1981–1987. https://doi.org/10.1016/S0008-8846(02)00903-1

Silva, C. S., Santos, M., Monteiro, E. C. B.; Andrade, T. W. C. O.; Soares, W.; Neves, D. (2021). *Recovery procedures for foundation elements with alkali/aggregate reaction problems*. Documental research. Revista ALCONPAT. 11(2): 124–145. https://doi.org/10.21041/ra.v11i2.490

Sims, I., Hunt, B., Miglio, B. (1992). "*Quantifying microscopical examinations of concrete for AAR and other durability aspects".* Am Concr Inst. Idorn international symposium. Annual ACI convention. Toronto. Ontario. Canada. 131–114, pp. 267-287.

Skolu, S. O., Thomas, M. D. A., Hooton, R. D. (2007). *Dual effectiveness of lithium salt in controlling both delayed ettringite formation and ASR in concretes.* Cement and Concrete Research. 37: 942–947. https://doi.org/10.1016/j.cemconres.2007.01.014

Smaoui, N., Bérubé, M. A., Fournier, B., Bissonnette, B., Durand, B. (2004). *Evaluation of the xpansion attained to date by concrete affected by alkali-silica reaction. PartI: Experimental study.* Canadian Journal of Civil Engineering. 31(5): 826–845. https://doi.org/10.1139/l04-104

Thomas, M. D. A., Folliard, K. J. (2007). "*Concrete aggregates and the durability of concrete"*. Durab. Concr. Cem. Compos. 247–281. https://doi.org/10.1533/9781845693398.247

Thomas, M., Fournier, B., Folliard, K., Ideker, J., Shehata, M. (2006). *Test methods for evaluating preventive measures for controlling expansion due to alkali-silica reaction in concrete.* Cement and Concrete Research. 36,(10):1842–1856. https://doi.org/10.1016/j.cemconres.2006.01.014

Tiecher, F., Dal Molin, D. C. C., Gomes, M. E. B., Hasparyk, N. P., Monteiro, P. J. M. (2012). *Influence of mesostasis in volcanic rocks on the alkali-aggregate reaction*. Cement and Concrete Composites. 34(10): 1130-1140. https://doi.org/10.1016/j.cemconcomp.2012.07.009

Tiecher, F., Gomes, M. B., Dal Molin, D. C. C. (2018). *Alkali-Aggregate Reaction: A Study of the Influence of the Petrographic Characteristics of Volcanic Rocks.* Engineering, Technology & Applied Science Research. 8(1): 2399-2404. https://doi.org/10.48084/etasr.1731

Tiecher, F., Dal Molin, D. C. C., Gomes, M. E. B., Hasparyk, N. P., Monteiro, P. J. M. (2017). *Relationship between degree of deformation in quartz and silica dissolution for the development of alkali-silica reaction in concrete*. Materials. 10(9): 1022. https://doi.org/10.3390/ma10091022

Touma, W. E., Fowler, D. W., Carrasquillo, R. L. (2001). "*Alkali–silica reaction in portland cement concrete: testing methods and mitigation alternatives"*. Report ICAR 301–1F. International Center for Aggregates Research, Austin, Texas.

Walsh, J. B. (1965). *The effect of cracks on the uniaxial elastic compression of rocks*. J Geophys Res. 70:399–411. https://doi.org/10.1029/JZ070i002p00399

Xue, L., Zang, Z., Wang, H. (2021). *Hydration mechanisms and durability of hybrid alkaline cements (HACs): A review.* Construction and Building Materials. 266: Part A, 121039. https://doi.org/10.1016/j.conbuildmat.2020.121039

Zhu, Y., Zahedia, A., Sanchez, L. F.M., Fournier, B., Beaucheminc, S. (2021). *Overall assessment of alkali-silica reaction affected recycled concrete aggregate mixtures derived from construction and demolition waste.* Cement and Concrete Research. 142: 106350. https://doi.org/10.1016/j.cemconres.2020.106350