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*Review Article*

# Structural Behavior of Reinforced Concrete Beam Affected by Alkali Aggregate Reaction: A Systematic Review

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***Abstract*** *- Alkali-Aggregate Reaction (AAR) is a serious issue with Reinforced Concrete (RC) structures. The resulting expansion and cracking compromise the structural integrity. This systematic review aims to enhance the understanding of AAR and its influence on the structural behavior of RC beams, synthesizing the results of different studies in a comprehensive manner. A search strategy was conducted across databases, including Google Scholar, Library, Emerald Insight, Science Direct, and Wiley Online. The 1,387 studies found were reduced to 577 studies after 810 duplicates were removed. The titles and abstracts of 577 studies were screened, and 95 papers were subjected to full-text evaluation. Finally, 9 observational and retrospective studies were included in the systematic review. These studies were analyzed to assess the effects of AAR on the structural performance of RC beams. The review shows that AAR significantly reduces the shear capacity and overall load-carrying capacity of RC beams due to microcracking and decreased aggregate interlock. The same degradations are predicted correctly with finite element models and are also confirmed by experimental results. The network of cracks from AAR further facilitates the ingression of aggressive substances, leading to further deterioration. AAR seriously threatens the structural integrity and durability of RC beams. Effective mitigation strategies, early detection methods, and further research on advanced materials and modeling techniques are thus urgently needed to address these challenges and ensure the longevity of affected structures. Future research must target long-term field studies and novel mitigation strategies to ensure comprehensive solutions.*

***Keywords*** *- Alkali-aggregate, Concrete, Alkali-silica, Alkali-carbonate, Reinforced-concrete beams.*

## 1. Introduction

A multitude of modern residences are constructed utilizing Reinforced Concrete (RC) systems. A material of exceptional strength is produced by combining the compressive strength of concrete with the tensile strength of the steel reinforcement. It obtains its energy from this source. In the construction industry, RC is highly regarded for its long-lasting properties and high structural efficacy. Conversely, several degradation mechanisms may have an impact on the functionality and extensibility of RC structures. The Alkali Aggressive Reaction (AAR) is the mechanism that causes the most damage.

A cascade effect was initiated by multiple reaction accumulations within Rose City concrete, which were precipitated by the alkali hydroxides present in the substance. AAR is the designation for this domino effect. As a result of the formation of a substantial polymer, which induces internal complications, the concrete matrix fractures and endures a variety of painful manifestations. Principal subtypes of the Alkali-Acid Reaction (AAR) include the Alkali-Silica Reaction (ASR) and the Alkali-Carbonate Reaction (ACR). ASR, which is more prevalent, is characterized by the formation of a hygroscopic gel through the reaction of alkali hydroxides and amorphous or inadequately crystalline silica in the deposits. This gel absorbs water and undergoes expansion, resulting in substantial internal tension and eventual fracture (Fournier & Bérubé, 2000; Thomas, 2011).

On the other hand, ACR is characterized by a series of consequences that commence with the reaction between alkali hydroxides and the accumulation of specific dolomitic carbonate, subsequently leading to the formation of brucite and calcite and ultimately resulting in fractures (Swamy, 1992).

The structural impacts of ASR and ACR on RC beams are complicated and extensive. The polymers' increasing pressures during ASR and ACR manufacture cause small fractures in the concrete matrix. If these micro-fractures grow into bigger fissures, the reinforcing steel-concrete bond may be damaged. Rajabipour et al. (2015) say this degradation may reduce RC beam load-bearing capacity, ductility, and serviceability (Rajabipour et al., 2015). AAR-induced fractures in concrete allow pollutants to infiltrate, which may accelerate the degradation of the material and any reinforcing components (Chatterji, 2005; Neville, 2012). AAR cracks allow pollutants to enter the structure.

The architectural patterns of RC light beams that are affected by AAR must be understood to develop maintenance and reduction techniques that are both efficient and effective. In fundamental concrete investigations, particularly those focusing on RC beams, the outcomes of AAR are highly inconsistent, notwithstanding the wealth of literature on the subject.

The objective of this systematic review is to address this knowledge deficit through an examination of existing literature, a review of the current research landscape, the identification of crucial search terms, and the identification of areas that necessitate additional research (Malvar et al., 2001).

The objectives of this evaluation are as follows: first, to determine which components and devices influence ASR and ACR in RC light beams; second, to determine how these responses affect the architectural resilience and efficiency of RC light beams; and third, to assess the performance of various reduction and recovery strategies in addressing AAR-induced damages. This review may help researchers and designers create weather-resistant physical frameworks using AARs (Farny & Kosmatka, 1997; Thomas et al., 2006).

The AAR literature will be thoroughly reviewed to determine its development catalysts, chemical devices, impacts on mechanical homes, and structural integrity of RC light beams in architecture. Additionally, it will discuss new AAR mitigation efforts, such as chemical preservatives and supplemental cementitious materials (Huang et al., 2012).

The purpose of this testimonial is to enhance comprehension regarding AAR and its impact on the architectural behaviors of RC light beams through the provision of an exhaustive synthesis of the existing research. In the end, this will contribute to the development of more dependable methods for prevention and rectification.

## 2. Methodology

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, including planning and reporting, were followed at each stage of this systematic review. As this was a literature review, neither informed consent nor formal ethics approval was necessary (Page et al., 2021).

### *2.1. Searching Strategy*

Using the terms " reinforced concrete," "alkali," "alkali aggressive," "alkali-silica," "alkali-carbonate," "review," and "concrete beam," an extensive search on published literature was conducted. The keywords were searched using the "OR" and "AND" operators in combination.

In addition, for the accuracy of investigations, the references mentioned in the literature were evaluated to locate a relevant study that satisfied our inclusion criteria.

Meanwhile, the following factors were not considered: (1) articles that were not available for complete distribution and (2) publications in the form of conference proceedings, dissertations, surveys, protocols, or theses.

### *2.2. Screening of Articles*

To accomplish the filtration procedure, a variety of techniques were implemented. To fulfill the assignments, we conducted a comprehensive search across seven databases for pertinent keywords, selected abstract and title that satiated our present inclusion criteria, and verified the accessibility and suitability of the entire text.

In the event of a disagreement, an external reviewer will be engaged. Employing a third reviewer would resolve the dispute, ascertain the points of disagreement between the initial two reviewers, and validate the filtering efforts of the first two reviewers. Throughout the entirety of the screening procedure, abstract screeners must have confidence in reconciliation to validate their judgments (Polanin et al., 2019).

### *2.3. Data Extraction*

To determine which nine papers should be included, each reviewer implemented grid synthesis. The approach incorporated details pertaining to the authors, year of publication, geographical origin, objectives, design, outcomes, and other pertinent aspects concerning the reaction of alkali aggregates in reinforced concrete beams.

A summary of the articles that underwent the review procedure, as determined by the information provided, is presented in Table 1.

## 3. Results

Nine papers were considered when conducting this assessment. The researchers employed various criteria, including publication year, article type, subject matter, and open access, to eliminate 810 of the 1,387 publications discovered across five databases.

Following the abstract and title-based sifting of 577 papers, 95 were selected for review. Following the assessment of their suitability and incorporation of papers from the reference list, a total of nine publications were adopted for our investigation (Figure 1).

**Table 1. Summary of the included studies**

| Author & Year | Country | Objective | Methodology | Results |
|---|---|---|---|---|
| (Gencturk et al., 2021) | USA | Investigated the shear behavior of full-scale Reinforced Concrete (RC) beams affected by alkali-silica reactivity damage. | Experimental study (Finite element model) | The Finite Element (FE) study helped explain the ASR-affected RC beam failure mechanism and capacity deterioration with ASR growth. |
| (Kongshaug et al., 2021) | Norway | The constitutive model's impact on ASR-induced load effects in statically indeterminate beam constructions. | RC beams are modeled using Euler–Bernoulli beam theory and solved numerically using finite elements. | The stress dependence of the ASR expansion smooths the applied ASR strain field, reducing load effects, while cracking releases system stresses via crack/plastic hinges. |
| (Vo et al., 2021) | France | To evaluate a computational technique for assessing large, Reinforced Concrete (RC) structures, including nuclear power plants, dams, and bridges, that effectively manage concrete and reinforcement nonlinearity. | Incorporate big finite elements with nonlinear behavior rules, anticipate anisotropic swelling from homogenized rebars and external loadings, verify against RC beam testing, and parametrize finite element size. | The verified model predicts residual strength capacity, minimizes finite elements for computing time, maintains prediction accuracy with coarse mesh, and incorporates ASR-induced anisotropic swelling. |
| (Al-Rousan, 2022) | Jordan | Strengthening ASR-damaged RC beam-column junctions using external FRP composites. | Nonlinear Finite Element Analysis (NLFEA) | Cyclic performance improved in ASR-damaged RC B-C joint models reinforced with FRP. |
| (Ferche & Vecchio, 2021) | Canada | to better characterize the response of ASR-affected reinforced concrete. | Ten panels were constructed and tested under in-plane pure shear loading conditions. | The reactive panels had a 30% lower deformation capacity than the non-reactive panels of the same kind. |
| (Aryan & Gencturk, 2021) | USA | the shear response of full-scale ASR-damaged RC beams with minimum shear reinforcement. | Six RC beams with varied ASR susceptibilities were conditioned in various conditions with continuous expansion monitoring. | Beams with ASR expansions above 0.4% had 25% less rigidity, twice as many shear fractures and deformations at peak load, and 20% lower shear reinforcement yield than beams with expansions below 0.2%. |
| (Fiset et al., 2021) | Canada | ASR distressed reinforced concrete on aggregate interlock. | ASR reactive coarse aggregate was used to make push-off specimens with varied transverse reinforcement ratios. | The transverse reinforcement ratio affects ASR-induced expansion and damage. |
| (Gorga et al., 2022) | Canada | Create a simple finite-element model that accurately portrays AAR progression and degradation in reinforced concrete structures. | Finite-element modeling of AAR in concrete. | Accurate simulation of AAR expansion effects. |
| (Lacombe et al., 2024) | France | the coupling between AAR and creep in concrete. | Compression tests on AAR and non-reactive concrete. | 56.1% swelling resorption, deformation transferred. |

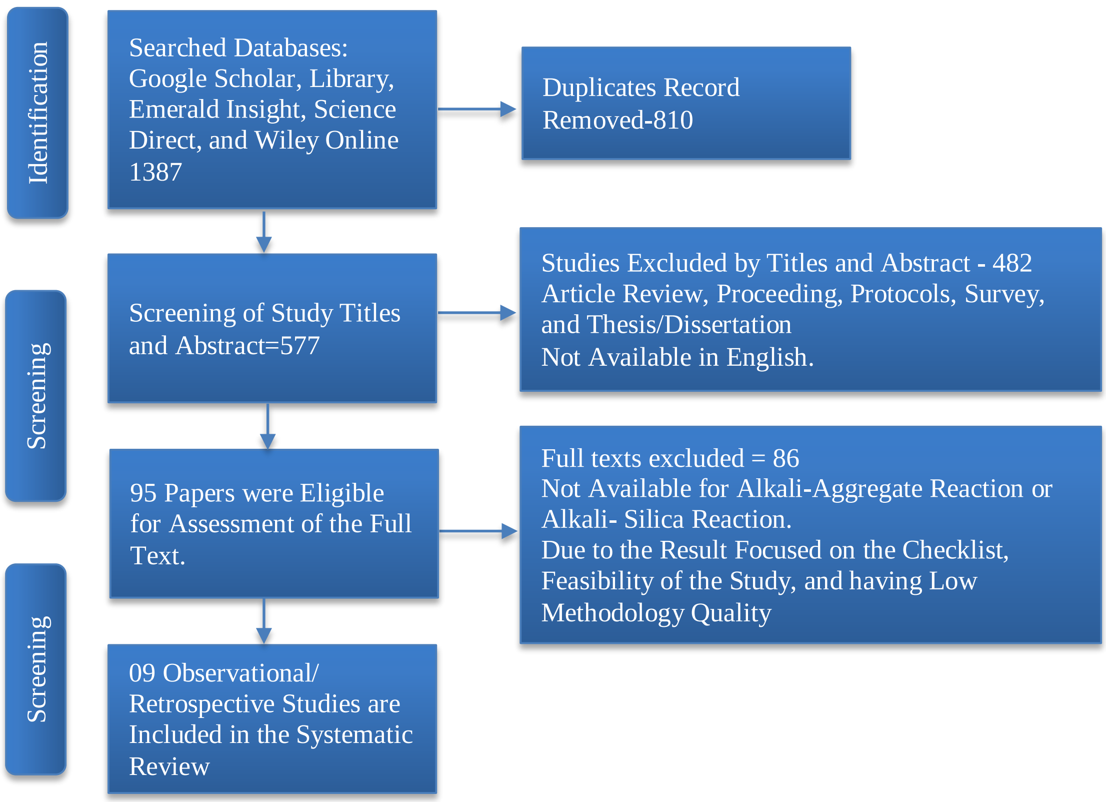


**Fig. 1 The PRISMA flow diagram for the selected studies**

## 4. Discussion

The consequence of Alkali-Aggregate Reaction (AAR) on the structural performance of Reinforced Concrete (RC) beams is serious in terms of both diagnosis and the safety of concrete structures in the long term. Since weak and bond failure modes are related highly to debonding, a systematic review is attempted here to synopsize the ongoing research to get a deeper insight into how AAR affects the structural behavior of RC beams. It was found that the mechanical properties and durability of concrete are both influenced largely by AAR, which results in changes to the behavior of RC beams under different loading conditions.

AAR, specifically ASR, provokes expansive gel formation in the matrix, resulting in internal stresses and cracking (Fournier & Bérubé, 2000). These cracks reduce the functional stiffness and ultimate strength, leading to lower load-carrying capacity and increased susceptibility to other forms of deterioration, such as frost-thaw cycling and chloride ingress (Lliso-Ferrando et al., 2023). Results from the reviewed papers show that the synthesis emphasized the need to manage AAR when planning and maintaining RC structures.

AAR has significant adverse effects on the shear strength of RC beams. Paul Kong noted that the interlock provided by the aggregates contributed considerably to the shear resistance (Kong, 1996). AAR-induced expansion of aggregates reduces the interlock between aggregate and concrete. As the interlock decreases decrease with the decrease of interlock, the shear strength of the beam decreases. As shown in the test results in this paper, the shear strength of RC beams with AAR damage is smaller than that of the same reinforcement ratio undamaged beam.

The FEM was utilized to model the responses of RC beams subjected to AAR, and insights provided by the model complement the test results. A finite element model with AAR expansion and associated microcracking was introduced by Takashi (2023) (Takahashi et al., 2023). FEM well predicted stiffness degradation and load capacity reduction with respect to experimental results. It would also be possible to predict behavior over a longer period and thus formulate maintenance strategies using FEM to do so.

Cracks in the affected beams can indicate the extent of the damage, which helps to determine the amount of time before action must be taken to strengthen a damaged structure. The orientation of the principal tensile stresses, as stated by Ahmed et al. (2003), is related to the direction of AAR cracking (Ahmed et al., 2003).

Cracks in the concrete matrix affected by AAR propagation formed a web that weakened the structure. This crack web reduced the load capacity and allowed the penetration of aggressive agents such as chlorides that further deteriorated the structure.

However, of great concern to civil engineers and infrastructure managers is the long-term behavior of RC beams affected by AAR. Fournier and Bérubé pointed out that AAR affects short-term structural performance and accelerates other mechanisms of degradation in the structures. For example, the presence of cracks increases concrete permeability, which makes the beam more vulnerable to frost-thaw cycles and to the penetration of chlorides that corrode the steel reinforcement. This effect has a direct impact on the corrosion rate of the embedded steel (Fournier & Bérubé, 2000). Thus, the dual action of AAR calls for timely detection and repair of the affected members. Due to the adverse effect of AAR, some proposals for mitigation and remediation have been put forward. Thomas and Matthews proposed the use of low-alkali cement and supplementary cementing materials, such as fly ash and slag, to reduce the possibility of AAR occurrence (Thomas, 2007). Some non-destructive testing techniques, such as ultrasonic pulse velocity and ground-penetrating radar, have been used to detect AAR damage early so that remediation may be taken accordingly.

The research in the area of AAR's effect on RC beams has shown some progress, though a number of gaps are required to be addressed in the future. For mitigation measures, long-term validity should be examined, especially for the environmental conditions that vary from site to site. On the remediation technique, more efficient FEMs should be developed that can catch the interaction of the damage induced by AAR with other types of deterioration for prediction.

The other promising future avenue of research involves new materials and technologies. Recent developments in self-healing concrete and the application of nanoengineered additives may be more effective for mitigating the effects of AAR. Field studies monitoring the long-term performance of structures affected by AAR would also be very beneficial since they would provide data to verify the laboratory test results and help to improve currently available models.

In summation, AAR poses a serious threat to the structural integrity and durability of RC beams. The systematic review shows the multifaceted way in which AAR acts to reduce shear capacity, compromise structural integrity, and speed up deterioration due to other environmental factors. Although various mitigation strategies have been proposed, continued research is necessary to come up with more effective solutions and improve the long-term performance of RC structures affected by AAR. The integration of advanced modeling techniques and novel materials holds promise for future advancements in this critical area of civil engineering.

## 5. Conclusion

The current systematic review synthesized existing research on the effect of Alkali-Aggregate Reaction (AAR) on the structural behavior of Reinforced Concrete (RC) beams, concluding that AAR significantly compromises structural integrity by the formation of expansive gel and microcracking, therefore reducing the load-carrying capacity and shear strength. The experimental studies and finite element models evidenced that AAR-induced damage reduces aggregate interlock and shear capacity, which demands early detection and effective mitigation strategies. The net of cracks allows the penetration of detrimental agents and accelerates the deterioration through freeze-thaw cycles and steel corrosion. Mitigation strategies involving low-alkali cement and supplementary cementing materials, as well as non-destructive testing methods, are needed for early damage detection. Despite these advances, the gaps in the understanding of long-term effectiveness and the development of advanced FEMs to simulate complex interactions exist. Future research should center around the development of new materials and long-term field studies to validate findings and refine models in general to enhance the resilience and longevity of RC structures affected by AAR.

## 6. Future Recommendations and Limitations

Future research needs to focus on the development of advanced finite element models with capabilities to simulate the complex interactions between the AAR-induced damage and other deteriorating mechanisms for enhancing predictive capabilities. Another area of interest should be the exploration of new materials and technologies in self-healing concrete and nanoengineered additives, which could offer more effective AAR effect mitigations. Long-term field studies that monitor the performance of AAR-affected structures will provide valuable data for the validation of laboratory findings and refinement of existing models. Nevertheless, the limitations of current research include variability in experimental conditions and methodologies, making it difficult to generalize the results. Furthermore, the long-term effectiveness of the mitigation strategies in diverse environments remains understudied, and as such, comprehensive studies are required to ensure the durability and safety of the reinforced concrete structures.

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