RILEM Technical Letters (2026) 11: 107-116
https://doi.org/10.21809/rilemtechlett.2026.233

Report of RILEM TC 301-ASR: Framework for risk assessment of mixture designs incorporating alkali-silica reactive aggregates

Ana Bergmann[1,*], Leandro F. M. Sanchez[1]

[1]University of Ottawa, Canada

This article has been prepared within the framework of RILEM TC 301-ASR. The article has been reviewed and approved by all members of the TC 301-ASR.

Received: 09 December 2025 / Accepted: 03 August 2026 / Published online: 24 August 2026

Abstract

Alkali-aggregate reaction (AAR), a harmful durability mechanism affects concrete structures worldwide. Over the years, it has become clear that prevention is the best strategy against AAR. In this sense, guidelines have been developed relying on accelerated laboratory tests, including the Accelerated Mortar Bar Test (AMBT), as per ASTM C1260, and Concrete Prism Test (CPT), as per ASTM C1293, to define mitigation strategies and plans. However, current thresholds frequently fail to predict the actual field behavior of concrete over extended periods. In this sense, this study introduces a probabilistic framework integrating laboratory and field data with logistic regression to predict ASR risk, a flexible coupled threshold-time (FCTT) approach. The framework incorporates environmental conditions, alkali content, and structural classification to define the risk of AAR field occurrence. It allows for dynamic risk assessments and informed decisions on mitigation strategies based on a structure's specific information, improving alignment between laboratory outcomes and real-world durability.

Keywords: Alkali-aggregate reaction (AAR), Concrete durability, Probabilistic risk assessment.

1 Introduction

Alkali-aggregate reaction (AAR), a harmful durability mechanism affecting concrete structures worldwide, impacts the integrity and serviceability of structures in over 50 countries [1,2]. This reaction, predominantly alkali-silica reaction (ASR), involves the interaction between siliceous phases in the aggregates and the alkali hydroxides present in the concrete pore solution, producing secondary reaction products, including amorphous gel-like and crystalline phases. Through swelling upon water uptake or solidification pressure caused by confined crystallization and electrostatic repulsion, these products lead to internal stresses and cracking, reducing the mechanical properties of affected concrete [3–5].

Over the years, it became quite evident that the best approach against AAR is its prevention; in this context, a wide number of laboratory test procedures were developed to appraise the potential reactivity of aggregates and the efficiency of preventive measures prior to concrete pouring. The accelerated mortar bar test (AMBT), as per ASTM C1260 [6], and concrete prism test (CPT), as per ASTM C1293 [7], are widely employed and essential for assessing aggregate's reactivity and the effectiveness of preventative measures [3,8,9].

The AMBT, as per ASTM C1260 [6], is performed by immersing mortar bars (i.e., 25x25x285 mm^3) in a high-alkali solution (1M NaOH) at 80°C, with expansions measured over 14 days [6,10]. This accelerated method yields rapid results and is often recommended for preliminary screenings of aggregate reactivity. In contrast, the CPT, as per ASTM C1293 [7], employs concrete prisms (i.e., 75x75x250 mm^3) and monitors expansion over a longer duration, typically 1 to 2 years for mixtures without and with supplementary cementitious materials (SCMs), under conditions of moderate temperature (i.e., 38°C) and high relative humidity (i.e., 95%) [7]. Therefore, these methods classify aggregates based on their reactivity levels, ranging from non-reactive to very highly reactive [8,11,12]. However, a critical challenge remains since the currently established expansion thresholds often fail to accurately predict long-term performance, leading to discrepancies between laboratory test outcomes and the

*Corresponding author: Ana Bergmann, E-mail: aberg065@uottawa.ca

actual performance of concrete in field conditions [3,8,13–19].

In response to this issue, recent research has focused on systematically integrating documented field data (i.e., exposed concrete blocks) with laboratory results and evaluating their relationship through probabilistic analysis, enabling the assessment of ASR risk in real-world conditions [20–22]. Discrepancies remain particularly significant when samples are submitted to varying environments (i.e., cold vs warm), alkali content (i.e., low – less than 2.94 kg/m^3, moderate – from 2.94 kg/m^3 to 4.20 kg/m^3, high – above 4.20 kg/m^3) and the presence of SCMs. Although AMBT (ASTM C1260 [6]) outperforms in identifying non-reactive cases for both mixes with and without SCMs, both AMBT (ASTM C1260 [6]) and CPT (ASTM C1293 [7]) demonstrate similar reliability for detecting reactive cases in the field, with CPT (ASTM C1293 [7]) slightly better at higher alkali levels [22]. However, the ability of laboratory expansion thresholds from both methods, or their predictive reliability, to represent field performance decreases in warm climates with high alkali levels and no SCMs, whereas higher agreement with field performance improves in colder climates with low alkali levels and the presence of SCMs. Therefore, it underscores the need for a more dynamic assessment approach, considering laboratory expansion levels, test duration, environmental factors, and alkali content to better predict AAR occurrence.

In this sense, this study aims to propose a comprehensive framework for assessing the risk of ASR in concrete mixtures by integrating laboratory and field data with probabilistic methods, such as logistic regression. The framework also aims to include the structure class to limit potential risks associated with the reaction, ensuring that critical infrastructure is given greater consideration. This approach will allow for more reliable and assertive AAR risk assessments, helping to align laboratory predictions with field outcomes and improve the long-term durability of concrete structures exposed to ASR.

2 ASR risk assessment in concrete mixture

Guiding documents have been proposed on how to interpret the results of ASR test methods or suggest steps to reduce the risk of ASR [15]. In North America, the current strategies for mitigating ASR in concrete structures are outlined in the ASTM C1778, AASHTO R 80, and CSA A23.2-27A standards [12,23–25]. In general, the standards offer two pathways: performance-based and prescriptive approaches [15].

In the performance-based approach, laboratory tests, such as the CPT (ASTM C1293 [7]), are employed to assess the effectiveness of SCMs in mitigating ASR. Therefore, the SCM replacement level is tested and must successfully reduce expansion below the established threshold to be considered effective. Conversely, in the prescriptive approach, aggregates are first classified through AMBT (ASTM C1260 [6]) or CPT (ASTM C1293 [7]) tests. Then, the exposure conditions of the concrete structure and its structural classification are evaluated to determine the necessary preventive measures, such as the required SCM replacement level or alkali content limits [23].

CSA A23.2-27A provides a detailed flowchart for determining aggregate reactivity and selecting appropriate preventive measures [24]. It evaluates the petrographic composition of the aggregates and includes a brief geological field examination, considering factors such as rock type, age, formation, and quarry location, alongside durability tests. When reviewing past performance history in Portland cement (PC) concrete, CSA recommends assessing structures that are at least 10 years old and have similar mixture proportions and exposure conditions as the intended project. The standard (CSA A23.2-27A [24]) sets a fixed 0.040% expansion limit for the CPT (ASTM C1293 [7]) at 1 year, while the AMBT (ASTM C1260 [6]) expansion limit is 0.150% at 14 days. If preventive measures are required, the size of the structure and its environmental conditions are considered to assess the ASR risk level, determining the necessary prevention strategy.

Similarly, ASTM C1778 provides guidelines for interpreting test results and selecting mitigation strategies to prevent ASR [12]. It incorporates a flowchart and considers field history for aggregate approval, alongside the concept of maximum alkali loading for determining the level of prevention. The expansion thresholds are set at 0.04% for CPT (ASTM C1293 [7]) over 1-2 years and 0.10% for AMBT (ASTM C1260 [6]) over 14 days, depending on whether the mix includes SCMs or not. Lastly, AASHTO R80-17 is closely aligned with ASTM C1778 [23,25], but a key distinction is its guidance on testing the efficacy of lithium nitrate to prevent ASR, specifically within the AMBT (ASTM C1260 [6]), which is not covered in ASTM C1778.

Regarding the level of ASR risk, the standard (ASTM C1778 [12]) take into account three key factors: the size of the structure, its exposure conditions, and the reactivity of the aggregate. These factors help categorize the risk of ASR into six levels, as shown in Table 1. Based on this risk level, the structure's classification, outlined in Table 2, is used to determine the required level of prevention, which is further defined by the maximum alkali loading in Table 3. The consequences of ASR damage are typically evaluated in terms of safety, economic costs, and environmental impact. For instance, if a massive concrete element is exposed to humid air, buried, or immersed and uses R1 (i.e., moderately reactive aggregate), Table 1 categorizes this scenario as Risk Level 3. Next, if the structure is a Class SC4 type, such as a nuclear facility or dam, where even minor ASR damage cannot be tolerated, Table 3 indicates that the appropriate level of prevention is Y, which would require a reduction in alkali loading to 1.8 kg/m³.

Complementing North American standards, the RILEM AAR-7.1 specification [26] provides a performance-based framework for minimizing ASR damage, focusing on structural risk (i.e., some deterioration acceptable-S1, minor damage is acceptable/manageable-S2, no significant damage acceptable-S3), but also including moisture exposure (i.e., dry environment protected from extraneous moisture-E1, exposed to extraneous moisture-E2, and, exposed to extraneous moisture plus aggravating factors-E3), and corresponding precaution levels (i.e., no precautions-P1, normal level-P2, special level-P3, extraordinary level-P4).

Table 1. Level of ASR Risk, as per ASTM C1778 [12].

Size and Exposure conditions	Aggregate-Reactivity Class			
	R0	R1	R2	R3
Non-massive[A] concrete in a dry[B] environment	Level 1	Level 1	Level 2	Level 3
Massive[A] concrete in a dry[B] environment	Level 1	Level 2	Level 3	Level 4
All concrete exposed to humid air, buried or immersed	Level 1	Level 3	Level 4	Level 5
All concrete exposed to alkalis in service[C]	Level 1	Level 4	Level 5	Level 6

[A]A massive element has at least dimensions greater than 0.9m [3ft].

[B]A dry environment corresponds to an average ambient relative humidity lower than 60%, normally only found in the interior of buildings.

[C]Examples of structures exposed to alkalis in service include marine structures exposed to seawater and highway structures exposed to de-icing salts (for example, NaCl) or anti-icing salts (for example, potassium acetate, sodium formate, and so forth).

Table 2. Structures classified based on the severity of consequences should ASRA occur, as per ASTM C1778 [12].

Class	Consequence of ASR	Acceptability of ASR	Examples[B]
Class SC1	Safety, economic, or environmental consequences small or negligible	Some deterioration from ASR may be tolerated	Non-load-bearing elements inside buildings Concrete elements not exposed to moisture Temporary structures (service life < 5 years)
Class SC2	Safety, economic, or environmental consequences if major deterioration	Moderate risk of ASR is acceptable	Sidewalks, curbs, and gutters Elements with service life <40 years
Class SC3	Safety, economic, or environmental consequences if minor deterioration	Minor risk of ASR may be acceptable	Pavements Foundation elements Retaining walls Culverts Highway barriers Rural, low-volume roads Precast elements in which economic costs of replacement are severe Service life normally 40 to 74 years
Class SC4	Serious safety, economic, or environmental consequences if minor damage	ASR cannot be tolerated	Major bridges Power plants Dams Nuclear facilities Water treatment facilities Waste water treatment facilities Tunnels Critical elements that are very difficult to inspect of repair Service life normally ≥ 75 years

[A]This table does not consider the consequences of damage as a result of ACR. This protocol does not permit the use of alkali-carbonate aggregates.

[B]The types of structures listed under each class are meant to serve as examples. Some owners may decide to use their own classification system. For example, sidewalks, curbs and gutters may be placed in the SC3 class in some jurisdiction.

It outlines four mitigation strategies: limiting concrete alkali content, using non-reactive aggregates, reducing moisture ingress, and the use of admixtures (i.e., lithium-based admixtures). While RILEM does not define fixed expansion thresholds, it recommends alkali content limits in the range of 2.5–3.5 kg/m³ Na_2O_{eq} based on aggregate reactivity, and prescribes minimum SCMs replacement levels (i.e., 25–50% slag or fly ash).

Yet, while these approaches offer a detailed framework for developing mitigation strategies, it overlooks the influence of varying environmental conditions (i.e., warm vs cold), which are known to affect the reaction kinetics of ASR. Factors such as temperature and relative humidity, which can significantly accelerate or slow down the reaction, are not fully considered [27]. Therefore, there is an opportunity to refine this approach by incorporating these environmental variables alongside laboratory test results, alkali content, and specific structural classification. This could lead to the development of a risk-based system, where acceptable risk levels vary for different structural classifications, guiding the appropriate mitigation strategies and preventive measures for each class.

Table 3. Level of prevention and respective maximum alkali loading. Adapted from ASTM C1778 [12].

Level of ASR Risk	Classification of Structure			
	Class SC1	Class SC2	Class SC3	Class SC4
Risk Level 1	V (No limit)	V (No limit)	V (No limit)	V (No limit)
Risk Level 2	V (No limit)	V (No limit)	W (3 kg/m³)	X (2.4 kg/m³)
Risk Level 3	V (No limit)	W (3 kg/m³)	X (2.4 kg/m³)	Y (1.8 kg/m³)
Risk Level 4	W (3 kg/m³)	X (2.4 kg/m³)	Y (1.8 kg/m³)	Z[B]
Risk Level 5	X (2.4 kg/m³)	Y (1.8 kg/m³)	Z[B]	ZZ[B]
Risk Level 6	Y (1.8 kg/m³)	Z[B]	ZZ[B]	[A]

[A]It may not be permitted to construct a Class SC4 structure if the risk of ASR is Level 6. Measures should be taken to reduce the level of risk in these circumstances.

[B]SCMs may be used in prevention levels Z and ZZ.

3 Model development

Predicting the occurrence of AAR in the field based on laboratory test outcomes is a complex task due to the numerous interacting variables and the variability in test durations. As previously defined, to address these challenges and better understand the impact of each variable on AAR, a logistic regression model has been employed. This model allows for probabilistic estimation of AAR occurrence in field conditions, taking into account environmental factors, mix design parameters, and the expansion over time of accelerated laboratory tests. The ultimate goal is to establish a flexible threshold-time approach that can be systematically applied to reduce the risk of AAR across diverse concrete structure scenarios. In this context, the expansion threshold refers to a probability-based expansion level derived from the model, rather than a fixed prescriptive limit.

This model has been specifically designed to include variables that are most relevant to AAR development, such as environmental conditions (i.e., temperature (TEMP), relative humidity (RH)), laboratory expansion (EXP), and field alkali content (ALK). The predictors were retained in their original units for direct application of the framework, such as TEMP in ºC, RH in %, EXP in %, and ALK in kg/m^3, resulting in unit-dependent coefficients. The β (beta) parameters in the model are estimated within a Bayesian inference framework. Prior distributions were assigned to the model parameters, and the posterior distributions were estimated using Markov Chain Monte Carlo (MCMC) sampling. This approach allows the model to quantify uncertainty in the estimated parameters while fitting the relationship between predictors and the observed data. In this context, the posterior mean of each coefficient, reported to three decimal places, is used as a point estimate for interpretability and prediction.

Moreover, each coefficient represents the change in the log-odds of the outcome associated with a one-unit change in the predictor variable, while keeping the other variables constant. For instance, if β_{ALK} is 0.2, then an increase on alkali content (ALK) from 2.5 to 3.5kg/m^3 (ΔALK=1 kg/m^3) increases the log odds of field reactivity by 0.2, corresponding to an increase in predicted probability of field reactivity from 62.3% to 66.8%, assuming all other variables remain constant. In that sense, this approach was employed to train the model to predict the occurrence of reactivity in the field. Finally, the model's accuracy is measured indicating the ability to correctly classify field reactivity (i.e., proportion of true positives and true negatives over the total number of observations) based on the selected input variables.

The model is defined as per Equation 3.1 and the probability of reactivity can, therefore, be calculate as per Equation 3.2 trough the logistic function (sigmoid transformation).

$$x=\beta_0+\beta_{TEMP}\cdot\text{TEMP}+\beta_{RH}\cdot\text{RH}+\beta_{EXP}\cdot\text{EXP}+\beta_{ALK}\cdot\text{ALK} \quad (3.1)$$

$$P(x)=\frac{1}{1+e^{-x}} \quad (3.2)$$

Based on a robust database correlating laboratory and field information [21,22], the binary outcome of field reactivity (i.e., YES or NO) was based on the last recorded expansion of field blocks, with exposure durations ranging from 1.3 years to 29 years for AMBT (ASTM C1260 [6]) and 1 to 29 years for CPT (ASTM C1293 [7]), with average exposure times of 8.3 and 6.2 years respectively. The outcomes of the logistic regression model are provided for both the AMBT (ASTM C1260 [6]) and the CPT (ASTM C1293 [7]) without the use of SCMs, as observed in Tables 4 and 5.

Table 4. Overall coefficients for the AMBT (ASTM C1260 [6]) regression model.

Test duration (days)	β_0	β_{TEMP}	β_{RH}	β_{EXP}	β_{ALK}	Accuracy
5	0.276	0.008	-0.085	13.156	0.983	0.77 (44)
7	0.012	0.014	-0.087	10.151	1.029	0.77 (44)
9	0.047	0.011	-0.087	8.013	1.024	0.75 (44)
10	0.127	0.008	-0.087	7.204	1.018	0.75 (44)
11	0.024	0.009	-0.085	6.520	1.009	0.75 (44)
12	-0.200	0.010	-0.082	5.992	1.008	0.75 (44)
13	-0.029	0.007	-0.083	5.478	0.997	0.75 (44)
14	0.065	0.006	-0.083	5.068	0.987	0.75 (44)

Note: The number in parentheses next to the accuracy corresponds to the total number of observations used in the regression model to calculate the reported accuracy.

As observed, EXP exhibited a consistently positive association with the probability of field reactivity at all AMBT (ASTM C1260 [6]) test durations, indicating that higher laboratory expansion was associated with a higher predicted probability of field reactivity, while the other variables were held constant. The EXP coefficients ranged from 13.156 at 5 days to 5.068 at 14 days. ALK also exhibited a positive association with AAR field probability in the AMBT (ASTM C1260 [6]) model, with coefficients ranging from 0.983 to 1.029. This relatively narrow range indicates that the conditional association between alkali content and field reactivity remained consistent across the evaluated test ages, reinforcing the importance of controlling alkali levels to mitigate AAR.

In the AMBT (ASTM C1260 [6]) model, temperature exhibits a generally positive association with the likelihood of AAR occurrence. This aligns with the understanding that higher temperatures accelerate the chemical reactions associated with AAR, leading to increased expansion and cracking in concrete [28]. Finally, RH exhibited small negative coefficients close to zero with AAR probability. However, its combined variation with temperature resulted in meaningful changes in the predicted probability of AAR occurrence under different environmental conditions (Figure 2).

In the CPT (ASTM C1293 [7]) model, laboratory expansion (EXP) exhibited a consistently positive association with the probability of field reactivity, with coefficients ranging from 30.014 at 28 days to 6.191 at 365 days. The positive EXP coefficients indicated that higher laboratory expansion was associated with a higher predicted probability of field reactivity while other variables were held constant.

Moreover, in the CPT (ASTM C1293 [7]) model, the ALK coefficients remained positive, ranging from 0.736 to 1.033. Although the ALK coefficient decreased slightly at longer durations, it remained a positive association with AAR probability. This slight reduction in ALK influence could be attributed to the longer exposure period in CPT (ASTM C1293 [7]), which allows for more significant alkali leaching. As alkalis are gradually leached out of the concrete, their availability for driving AAR decreases, thereby potentially reducing the association between alkali content and AAR probability over time.

Table 5. Overall Coefficients for the CPT (ASTM C1293 [7]) regression model.

Test duration (days)	β_0	β_{TEMP}	β_{RH}	β_{EXP}	β_{ALK}	Accuracy
28	0.413	0.000	-0.053	30.014	0.736	0.78 (67)
90	0.420	-0.017	-0.071	15.654	0.975	0.78 (67)
121	-0.717	0.000	-0.064	13.921	1.033	0.79 (67)
154	1.857	-0.018	-0.089	10.408	0.904	0.79 (67)
182	1.860	-0.016	-0.089	9.308	0.887	0.79 (67)
210	1.480	-0.012	-0.084	8.887	0.883	0.79 (67)
243	1.259	-0.009	-0.081	8.466	0.870	0.78 (67)
270	1.064	-0.007	-0.078	7.713	0.859	0.78 (67)

Note: The number in parentheses next to the accuracy corresponds to the number of observations used in the regression model to calculate the reported accuracy.

The TEMP coefficients in the CPT (ASTM C1293 [7]) model were slightly negative, ranging from −0.018 to 0.000, while the RH coefficients ranged from −0.089 to −0.053. Although their individual coefficients were relatively small, the combined variation in temperature and RH produced meaningful differences in the predicted probability of field reactivity (Figure 2) while the other factors were held constant.

Finally, the analysis of the logistic regression model for both AMBT (ASTM C1260 [6]) and CPT (ASTM C1293 [7]) data reveals that laboratory expansion and alkali content were consistently positively associated with the predicted probability of field reactivity. However, although temperature and relative humidity coefficients showed smaller and more complex associations, their combined effects were captured when comparing different climatic conditions. Also, it is worth mentioning that the temperature and RH coefficients are associated with the data available mostly from two environments (i.e., Ottawa and Austin).

Therefore, a parametric analysis is further conducted to define a flexible coupled threshold-time approach that accounts for variations in alkali content and environmental conditions (i.e., temperature and RH). Two distinct environments are considered based on data availability: a colder environment (i.e., TEMP = 7°C and RH = 75%) representing Ottawa, ON, Canada, and a warmer environment (i.e., TEMP = 21°C and RH = 63%) representing Austin, Texas, US.

As observed in Figure 1, each subplot represents the probability of AAR occurrence as a function of test duration (x-axis) and expansion threshold (y-axis), for a specific alkali content level. The red colors indicate higher probability of field reactivity, while green indicate lower probability. For example, in the bottom-right plot (i.e., mix alkali content = 5.25kg/m^3), if a mixture shows a laboratory result of 0.2% expansion at 10 days, the corresponding probability of field reactivity is approximately 75%. Conversely, in the top-left plot (i.e., mix alkali content = 1.8kg/m^3), the same expansion and test duration correspond to a much lower probability, closer to 20%. These plots demonstrate how expansion results cannot be evaluated independently of test duration, alkali content, and environmental conditions, reinforcing the flexible threshold-time approach.

As shown in Figure 2a, under cold conditions, the expansion threshold required to reach a high probability of AAR is generally higher over the test duration. This suggests that in colder environments, the AAR process may be slower to initiate, requiring more significant expansion in the accelerated laboratory test before AAR becomes a critical concern. However, when moving to a warmer environment as observed in Figure 2b, the expansion threshold decreases, and the probability of AAR increases more rapidly over the same test duration. This indicates that warmer conditions accelerate the AAR process, making concrete more vulnerable to AAR at lower laboratory expansion levels.

4 Proposed framework and risk limits

Figure 3 presents the proposed framework, which consists of six essential steps. The process begins by establishing risk acceptance thresholds, where risk limits are defined according to the structural classification. Next, gather critical input data, considered in the flexible threshold-time approach, including environmental factors such as temperature and relative humidity, as well as mix properties such as alkali content. In the following step, the probability of ASR occurrence is calculated using logistic

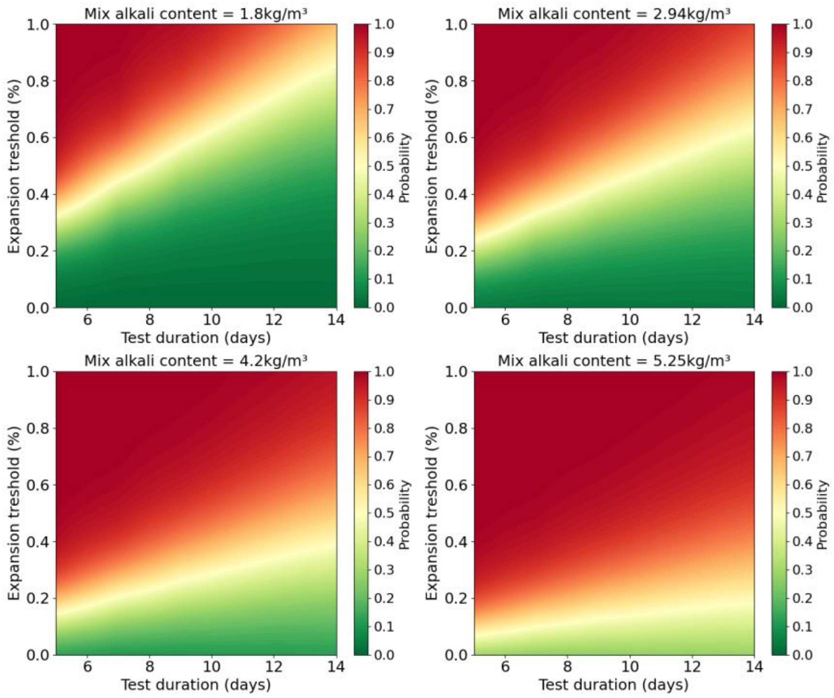

Figure 1. Probability of AAR occurrence based on AMBT (ASTM C1260 [6]) results, under cold environment (i.e., TEMP=7°C and RH=75%), for different alkali content: (a) 1.8 kg/m³, (b) 2.94 kg/m³, (c) 4.2 kg/m³, and (d) 5.25 kg/m³.

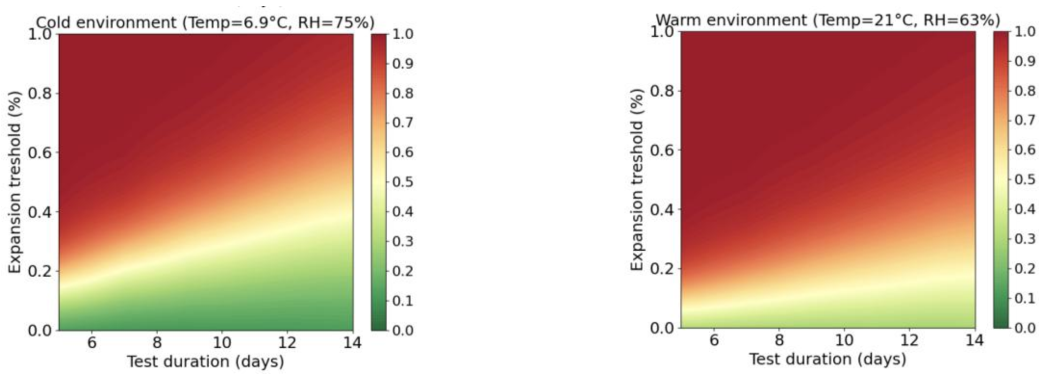

Figure 2. Probability of AAR occurrence based on AMBT (ASTM C1260 [6]) results, 4.2 kg/m³ alkali content for (a) cold environment (i.e., TEMP=7°C and RH=75%), and (b) warm environment (i.e., TEMP=21°C and RH=63%).

regression to predict the likelihood of reactivity. Once the risk is computed, it is compared against the established acceptance limits to determine whether it falls within the acceptable risk range. If necessary, parameters are adjusted, and risk recalculated, with a focus on reducing alkali content or selecting aggregates with lower expansion potential (EXP). The final step is to make an informed decision on the appropriate mitigation strategies, which could involve modifying the mix design, incorporating SCMs, or implementing other preventive measures to effectively manage ASR risk.

The classification of ASR risk should be determined based on the structural classification and the probability of correctly identifying reactive outcomes, as outlined in Table 6. In this framework, less tolerance is allowed for structures with higher consequences of ASR damage, and stricter thresholds are applied to those classified as critical. For lower-risk structures, more tolerance for ASR may be acceptable, allowing for a higher probability of risk classification.

In the following steps of calculating and comparing the probability of ASR occurrence, data gathering becomes a crucial aspect. For instance, Figures 4 and 5 illustrate the assessment of ASR risk based on laboratory test results exposed to cold environmental conditions (i.e., 7°C and 75% relative humidity) with a fixed alkali content of 4.2 kg/m³. This highlights how the proposed framework integrates critical input data from environmental conditions and mix properties to predict the likelihood of ASR across different structural classifications. Such data is essential for accurately

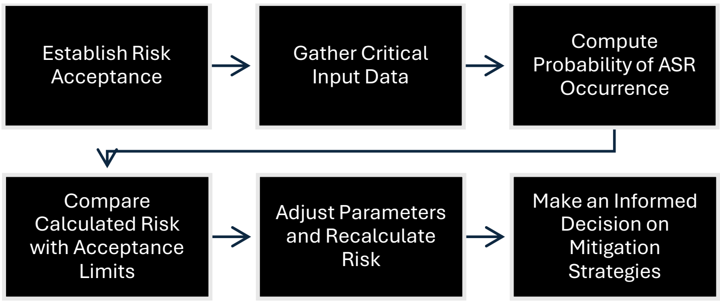

Figure 3. Proposed framework for ASR risk assessment.

Table 6. Structural classification and risk levels based on the probability outcomes.

Structural Class	Consequence of ASR	Risk Level Acceptability	Very Low risk	Low risk	Moderate risk	High risk
Class SC1	Safety, economic, or environmental consequences small or negligible	Some deterioration from ASR may be tolerated	Probability < 40%	Probability 40-60%	Probability 60-80%	Probability >80%
Class SC2	Safety, economic, or environmental consequences if major deterioration	Moderate risk of ASR is acceptable	Probability < 30%	Probability 30-50%	Probability 50-70%	Probability >70%
Class SC3	Safety, economic, or environmental consequences if minor deterioration	Minor risk of ASR may be acceptable	Probability < 20%	Probability 20-40%	Probability 40-60%	Probability >60%
Class SC4	Serious safety, economic, or environmental consequences if minor damage	ASR cannot be tolerated	Probability < 10%	Probability 10-20%	Probability 20-40%	Probability >40%

calculating the probability of occurrence and enables a detailed comparison against the suggested risk acceptance thresholds, ensuring that mitigation strategies are tailored to the specific structural and environmental context.

Figure 4, which is based on AMBT (ASTM C1260 [6]) results, shows how different structural classes respond to potential ASR development over a 14-day period. For Class SC1 structures (i.e., non-load-bearing elements), the risk remains very low until the probability of occurrence exceeds 40%. In contrast, for Class SC4 (i.e., critical structures such as dams and nuclear facilities), even minor expansion presents a significant risk, emphasizing the need for stricter preventive measures. This pattern illustrates how the framework dynamically adjusts the level of risk based on both the structural classification and the conditional evaluated parameters.

Similarly, Figure 5, which is based on CPT (ASTM C1293 [7]) results, illustrates how different structural classes respond to potential ASR development over a longer period. For Class SC1 structures (i.e., non-load-bearing elements), the risk of ASR remains very low until the probability of occurrence exceeds 40%. In contrast, for Class SC4 structures (i.e., critical infrastructure like dams and nuclear facilities), even small expansion levels pose a significant risk much earlier in the test. This demonstrates how critical structures have much stricter tolerances, underscoring the framework's ability to adjust risk levels dynamically based on both the test duration and the structural importance of the element being evaluated.

This process of calculating and comparing risk levels against acceptable thresholds is key to the decision-making phase. For instance, if the calculated risk exceeds the acceptable level for a given structural class, parameters like alkali content or the choice of aggregates with lower expansion potential can be adjusted to mitigate the risk. Ultimately, the framework allows for informed decisions on mix design adjustments, the incorporation of SCMs, or other preventive measures to effectively manage ASR risk across various structural applications.

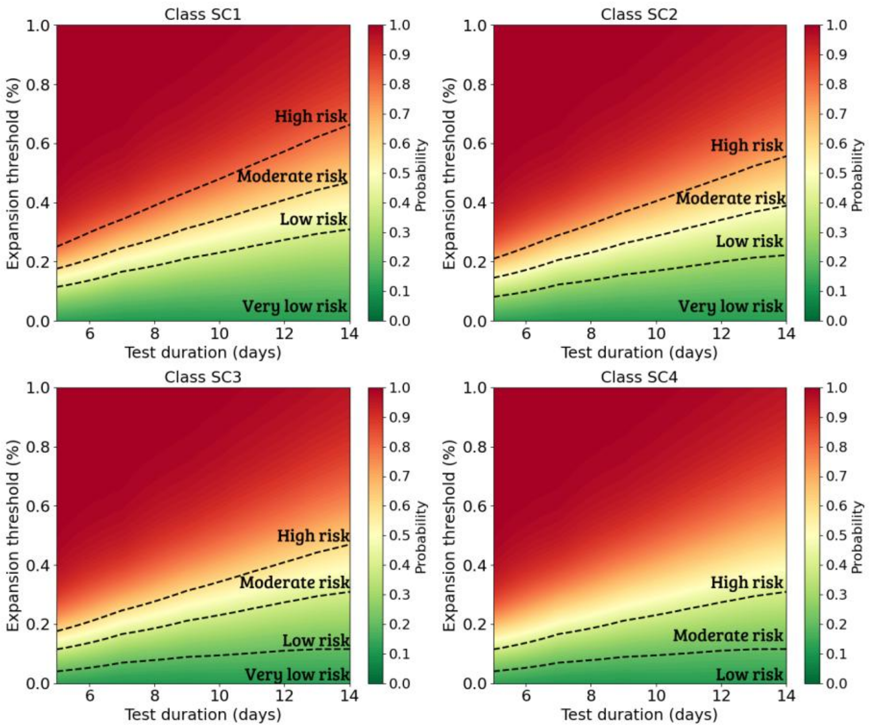

Figure 4. Risk of AAR occurrence based on AMBT (ASTM C1260 [6]) results, under cold environment (i.e., TEMP=7°C and RH=75%), 4.2 kg/m^3 alkali content for different structural classes: (a) SC1, (b) SC2, (c) SC3, and (d) SC4.

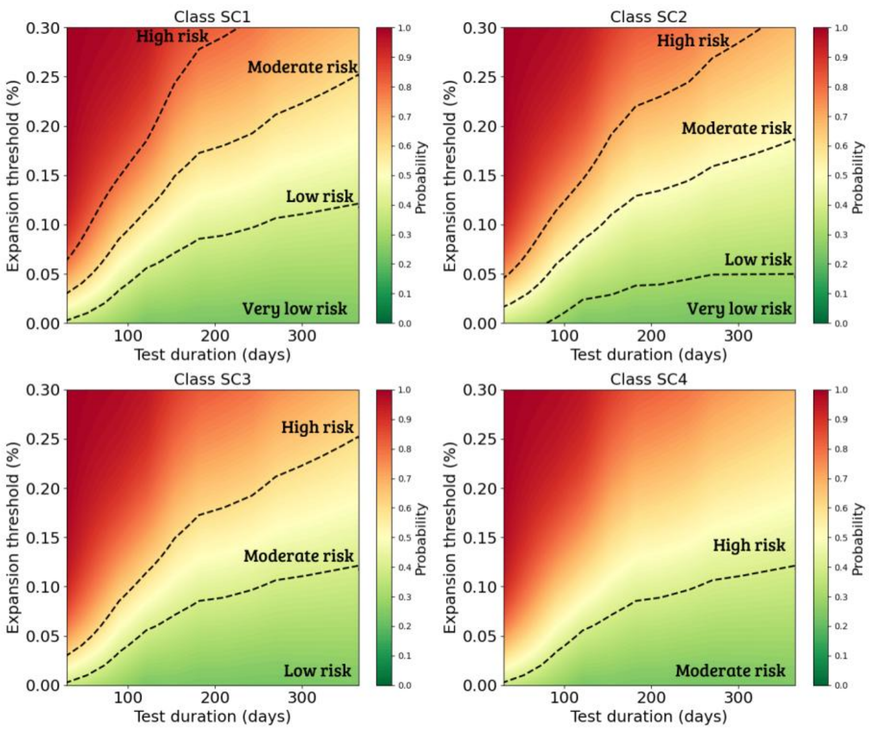

Figure 5. Risk of AAR occurrence based on CPT (ASTM C1293 [7]) results, under cold environment (i.e., TEMP=7°C and RH=75%), 4.2 kg/m^3 alkali content for different structural classes: (a) SC1, (b) SC2, (c) SC3, and (d) SC4.

5 Conclusion

In summary, this study presents a comprehensive approach to assessing ASR risk in concrete structures by integrating laboratory and field data with probabilistic methods. The main findings are:

- A probabilistic framework is proposed, combining logistic regression with laboratory and field data to assess ASR risk in concrete mixtures.
- Environmental factors such as temperature, relative humidity, and alkali content are integrated with structural classification to provide dynamic risk assessments.
- Mitigation strategies are dependent on structural classification, with stricter requirements applied to critical infrastructure to ensure long-term durability.

Acknowledgement

The authors would like to thank the members of RILEM TC 301-ASR, in particular Jan Lindgård, Josée Duchesne, Mario de Rooij, and Pierre Seguin, for their valuable comments and contributions toward the development of this work.

Conflict of interest statement

The authors declare no conflict of interest.

Authorship statement (CRediT)

Ana Bergmann: Conceptualisation; Methodology; Formal Analysis; Visualisation; Writing – Original Draft. **Leandro F. M. Sanchez:** Supervision; Writing – Review & Editing.

References

[1] M.D.A. Thomas, K.J. Folliard, J.H. Ideker, North America (USA and Canada), in: Alkali-Aggregate Reaction in Concrete: A World Review, CRC Press, 2017. https://doi.org/10.1201/9781315708959

[2] I. Sims, A. Poole, eds., Alkali-Aggregate Reaction in Concrete: A World Review, 1st ed., CRC Press, 2017. https://doi.org/10.1201/9781315708959

[3] B. Fournier, M.-A. Bérubé, Alkali-aggregate reaction in concrete: a review of basic concepts and engineering implications, Can. J. Civ. Eng. 27 (2000) 167–191. https://doi.org/10.1139/l99-072

[4] P.J. Nixon, I. Sims, eds., RILEM Recommendations for the Prevention of Damage by Alkali-Aggregate Reactions in New Concrete Structures, Springer Netherlands, Dordrecht, 2016. https://doi.org/10.1007/978-94-017-7252-5

[5] A. Leemann, M. Góra, B. Lothenbach, M. Heuberger, Alkali silica reaction in concrete - Revealing the expansion mechanism by surface force measurements, Cem. Concr. Res. 176 (2024) 107392. https://doi.org/10.1016/j.cemconres.2023.107392

[6] ASTM C1260, Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method), ASTM International, 2022. https://doi.org/10.1520/C1260-22

[7] ASTM C1293, Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction, 2024. https://doi.org/10.1520/C1293_C1293M-23A

[8] I. Sims, P. Nixon, RILEM Recommended Test Method AAR-0: Detection of Alkali-Reactivity Potential in Concrete—Outline guide to the use of RILEM methods in assessments of aggregates for potential alkali-reactivity, Mater. Struct. 36 (2003) 472–479. https://doi.org/10.1007/BF02481527

[9] T.F. Ronning, B.J. Wigum, J. Lindgard, Recommendation of RILEM TC 258-AAA: RILEM AAR-10: determination of binder combinations for non-reactive mix design using concrete prisms-38 degrees C test method, Mater. Struct. 54 (2021). https://doi.org/10.1617/s11527-021-01679-w

[10] R.E. Oberholster, G. Davies, An accelerated method for testing the potential alkali reactivity of siliceous aggregates, Cem. Concr. Res. 16 (1986) 181–189. https://doi.org/10.1016/0008-8846(86)90134-1

[11] B. Fournier, M. Berube, Alkali-aggregate reaction in concrete: a review of basic concepts and engineering implications, Can. J. Civ. Eng. 27 (2000) 167–191. https://doi.org/10.1139/l99-072

[12] ASTM C1778, Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete, ASTM International, 2022. https://doi.org/10.1520/C1778-22

[13] T. Drimalas, K.J. Folliard, J.H. Ideker, Findings from the University of Texas at Austin ASR Exposure Site after 20 Years, in: L.F.M. Sanchez, C. Trottier (Eds.), Proceedings of the 17th International Conference on Alkali-Aggregate Reaction in Concrete, Springer Nature Switzerland, Cham, 2024, pp. 516–523. https://doi.org/10.1007/978-3-031-59349-9_59

[14] C.A. MacDonald, The Kingston Exposure Site for ASR at 32 Years, in: L.F.M. Sanchez, C. Trottier (Eds.), Proceedings of the 17th International Conference on Alkali-Aggregate Reaction in Concrete, Springer Nature Switzerland, Cham, 2024, pp. 540–549. https://doi.org/10.1007/978-3-031-59349-9_62

[15] J.H. Ideker, T. Drimalas, K.J. Folliard, A. Ghanizadeh, A. Parashar, K.S.T. Chopperla, A. Snyder, M.D.A. Thomas, Preventing Alkali - Silica Reaction in Concrete, Ce Papers 6 (2023) 1101 - 1109. https://doi.org/10.1002/cepa.2935

[16] M. Thomas, A. Dunster, P. Nixon, B. Blackwell, Effect of fly ash on the expansion of concrete due to alkali-silica reaction – Exposure site studies, Cem. Concr. Compos. 33 (2011) 359–367. https://doi.org/10.1016/j.cemconcomp.2010.11.006

[17] B. Fournier, A. Bilodeau, N. Bouzoubaa, P.-C. Nkinamubanzi, Field and Laboratory Investigations on the Use of Fly Ash and Li-Based Admixtures to Prevent ASR in Concrete, in: United Kingdom, 2018.

[18] I. Borchers, J. Lindgård, C. Müller, Evaluation of laboratory test methods for assessing the alkali-reactivity potential of aggregates by field site tests, Mater. Constr. 72 (2022) e286. https://doi.org/10.3989/mc.2022.17221

[19] S. Hayman, M. Thomas, N. Beaman, P. Gilks, Selection of an effective ASR-prevention strategy for use with a highly reactive aggregate for the reconstruction of concrete structures at Mactaquac generating station, Cem. Concr. Res. 40 (2010) 605–610. https://doi.org/10.1016/j.cemconres.2009.08.015

[20] A. Bergmann, L. Sanchez, Assessing the Variability of Laboratory Test Procedures for Predicting Concrete Field Performance Against Alkali-Aggregate Reaction (AAR), in: L.F.M. Sanchez, C. Trottier (Eds.), Proceedings of the 17th International Conference on Alkali-Aggregate Reaction in Concrete, Springer Nature Switzerland, Cham, 2024, pp. 507–515. https://doi.org/10.1007/978-3-031-59349-9_58

[21] A. Bergmann, L.F.M. Sanchez, Assessing the reliability of laboratory test procedures for predicting concrete field performance against alkali-aggregate reaction (AAR), Cement 19 (2025) 100133. https://doi.org/10.1016/j.cement.2025.100133

[22] A. Bergmann, L.F.M. Sanchez, Multifactorial analysis of AAR development: Integrating laboratory and field data with statistical and probabilistic modelling, Cem. Concr. Compos. 166 (2026) 106387. https://doi.org/10.1016/j.cemconcomp.2025.106387

[23] J.H. Ideker, A. Parashar, L. Fenstemacher, A. Ghanizadeh, T. Drimalas, K.J. Folliard, A. Hossack, M.D.A. Thomas, A. Snyder, A New Approach to Preventing ASR, in: L.F.M. Sanchez, C. Trottier (Eds.), Proceedings of the 17th International Conference on Alkali-Aggregate Reaction in Concrete, Springer Nature Switzerland, Cham, 2024, pp. 476–484. https://doi.org/10.1007/978-3-031-59419-9_56

[24] CSA A23.2-27A, Standard Practices to identify degree of alkali-reactivity of aggregates and to identify measures to avoid deleterious expansion in concrete, in: CSA Standards A23.1–09/A23.2–09 Concrete Materials and Methods of Concrete Construction/Test Methods and Standard Practices for Concrete, 13th ed., CSA Group, Ontario, Canada, 2019, pp. 594–610.

[25] AASHTO R80-17, Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction, 2021.

[26] P.J. Nixon, I. Sims, RILEM Recommended Specification: AAR-7.1—International Specification to Minimise Damage from Alkali Reactions in Concrete—Part 1: Alkali-Silica Reaction, in: P.J. Nixon, I. Sims (Eds.), RILEM Recommendations for the Prevention of Damage by Alkali-Aggregate Reactions in New Concrete Structures, Springer Netherlands, Dordrecht, 2016, pp. 131–145. https://doi.org/10.1007/978-94-017-7252-5_8

[27] O.D. Olajide, M.R. Nokken, L.F.M. Sanchez, Evaluation of the induced mechanical deterioration of ASR-affected concrete under varied moisture and temperature conditions, Cem. Concr. Compos. 157 (2025) 105942. https://doi.org/10.1016/j.cemconcomp.2025.105942

[28] J. Lindgård, P.J. Nixon, I. Borchers, B. Schouenborg, B.J. Wigum, M. Haugen, U. Åkesson, The EU “PARTNER” Project — European standard tests to prevent alkali reactions in aggregates: Final results and recommendations, Cem. Concr. Res. 40 (2010) 611–635. https://doi.org/10.1016/j.cemconres.2009.09.004