designs

MDPI

Review

Advances and Perspectives in Alkali–Silica Reaction (ASR) Testing: A Critical Review of Reactivity and Mitigation Assessments

Osama Omar [1,*], Hussain Al Hatailah [2] and Antonio Nanni [1]

[1] Civil and Architectural Engineering Department, University of Miami, Coral Gables, FL 33124-6914, USA
[2] College of Engineering, Najran University, Najran 11001, Saudi Arabia
* Correspondence: obo14@miami.edu

Abstract: The alkali–silica reaction (ASR) is a critical concern for concrete durability, yet its assessment remains challenging and directly impacts mixture design decisions. This review shows that the inconsistencies are more prevalent in mitigation evaluations compared to aggregate reactivity assessments, mainly due to the chemical variations in supplementary cementitious materials (SCMs). A validated framework is suggested to determine the optimal SCM replacement levels for ASR mitigation based on extensive field data, offering direct guidance for mix design decisions involving potentially reactive aggregates. The combination of the accelerated mortar bar test (AMBT) and the miniature concrete prism test (MCPT) is shown to be a reliable alternative for the concrete prism test (CPT) in aggregate reactivity. Also, their extended versions, AMBT (28-day) and MCPT (84-day), can be applied for SCMs mitigation evaluation. Given the slower reactivity of SCMs compared to ordinary Portland cement (OPC), the importance of incorporating indirect test methods, such as the modified R3 test and bulk resistivity is underscored. In addition, emerging sustainability shifts further complicate ASR assessment, including the adoption of Portland limestone cement (PLC), the use of seawater in concrete, and the declining availability of fly ash (FA) and slag. These changes call for updated ASR testing specifications and increased research into natural pozzolans (NPs) as promising SCMs for future ASR mitigation.

Keywords: alkali–silica reaction (ASR); alkali–silica reaction mechanism; supplementary cementitious materials (SCMs); mitigation mechanism of SCMs in alkali–silica reaction; concrete durability; concrete sustainability; natural pozzolans (NPs)

check for updates

Academic Editor: Aziz Ahmed

Received: 23 April 2025
Revised: 18 May 2025
Accepted: 20 May 2025
Published: 11 June 2025

Citation: Omar, O.; Al Hatailah, H.; Nanni, A. Advances and Perspectives in Alkali–Silica Reaction (ASR) Testing: A Critical Review of Reactivity and Mitigation Assessments. *Designs* **2025**, *9*, 71. https://doi.org/10.3390/designs9030071

Correction Statement: This article has been republished with a minor change. The change does not affect the scientific content of the article and further details are available within the backmatter of the website version of this article.

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

With an annual production rate of 25 billion tons, concrete is the second most consumed material in the world after water [1]. It is a composite material consisting of coarse and fine aggregates mixed with cementitious binders, such as Portland cement and supplementary cementitious materials (SCMs). The hydration of these cementitious materials provides the required compressive strength for concrete structures [2]. Concrete structures are exposed to a wide range of environmental conditions. Therefore, they are subjected to various forms of distress that can compromise their durability and performance over the service life. These types of distress include cracking, scaling, spalling, corrosion, and chemical deterioration. Since each distress has a distinct mechanism and contributing factors, it is essential to understand and address each form of distress according to these causes, which include environmental exposure, freeze–thaw cycles, sulfate attacks, and an alkali–silica reaction (ASR), among others [3].

ASR is a chemical reaction between hydroxyl ions (OH^-) and the reactive siliceous aggregate in concrete. With sufficient moisture and available alkalis, the reaction product can expand and generate internal stresses that lead to cracking, which adversely influence the performance of concrete structures [4]. ASR is a prominent distress due to its expansive reaction, causing a premature failure, especially in environments with high moisture and alkali levels [5,6]. The first identification of ASR in concrete was made by Stanton [7], who discovered map cracking in concrete containing a specific type of aggregate. This map cracking was continuous in its propagation, ending with a significant concrete deterioration [8]. Later, several studies defined ASR as a chemical reaction between reactive siliceous constituents of concrete aggregates and alkaline pores solution of concrete [9]. The product of this reaction is hygroscopic gel that creates tensile stress in concrete after absorbing moisture. Numerous studies demonstrated that the required conditions to initiate ASR are sufficient availability of alkalis in cement, reactive siliceous constituents in aggregates, and sufficient moisture in concrete [10,11]. The reaction between siliceous compounds and alkalis creates the reaction, while the presence of moisture causes the expansion of the gel. For that reason, controlling the structures by preventing the penetration of moisture can halt its progression [12].

Since ASR can cause serious damage to concrete structures, several approaches have been proposed for its mitigation, including the addition of lithium compounds and the incorporation of SCMs. Currently, SCMs have gained significant attention toward ASR mitigation due to their additional benefits in concrete mixtures. Along with the ASR mitigation, SCMs are utilized to improve the fresh and hardening properties of concrete, such as durability, longevity, workability, and strength, while also reducing cost and supporting sustainability aspects through the use of industrial by-products [13,14]. In addition, SCMs generally have less carbon footprint compared to Portland cement. Typical SCMs include fly ash (FA) (Class F and Class C), silica fume, ground granulated blast-furnace slag, natural pozzolans (NPs), and metakaolin among others [15].

The chemical complexity of ASR has led to the development of several performance tests aimed at evaluating aggregate reactivity and assessing the effectiveness of preventive measures. These tests are designed to simulate the expansion of ASR by accelerating the field conditions during the laboratory testing. For example, the accelerated mortar bar test (AMBT) measures the expansion of mortar bars immersed in an alkaline solution for 14 days at 80 °C [16]. The concrete prism test (CPT) measures the expansion in concrete prisms stored in a full humid environment for 1 year at 38 °C [17]. ASR performance tests have another version that is used to assess the efficacy of mitigation measures in mitigating ASR with specified limits. While ASTM C1260 [16] was mainly developed to assess the aggregate reactivity, ASTM C1567 [18] specified the testing procedures to assess the ASR mitigation via SCMs with similar testing conditions for the aggregate reactivity version. Also, the CPT performance test has two versions under the ASTM C1293 [17] standard including the testing conditions for mitigation measures using SCMs.

As different tests specify various testing conditions, several concerns have been raised regarding their practicality and reliability. For instance, CPT, although reliable, is time intensive. AMBT offers a shorter screening option but is prone to inaccuracies such as false positives and negatives. Others proposed the miniature concrete prism test (MCPT) as a more balanced version with quicker results and better sensitivity to SCMs. Much of the literature examines the correlation between different performance tests and assesses their outcomes with field exposure blocks, which have recently shown extensive research. However, despite these advancements, there is still no widely accepted approach for evaluating ASR performance, especially in assessing the efficacy of mitigation measures.

Therefore, this study aims to bridge the existing gaps in ASR performance testing by critically evaluating the reliability of widely used ASR performance tests and current

methods for assessing the effectiveness of SCMs. By emphasizing recent advancements and offering an extensive comparison with the long-term field exposure data, this critical review provides a thorough assessment of current ASR testing frameworks. The findings of this study are intended to support engineering design decisions by providing testing-based recommendations for SCM selection and replacement level determination when using potentially reactive aggregates in durable concrete mixtures. Additionally, emerging techniques, such as the modified R3 test and bulk resistivity, are explored as complementary indirect methods capable of accurately evaluating the efficacy of SCMs in mitigating ASR expansion. Finally, this review addresses the recent industry shifts driven by sustainability considerations, including the growing adoption of Portland limestone cement (PLC), the use of seawater in concrete structures, and the declining availability of traditional SCMs such as FA and slag. This decline underscores the potential of NPs as a promising alternative due to their abundant natural deposits and comparable performance in concrete applications.

This review critically collected a total of 119 articles, of which 102 were included in the following sections of ASR performance tests and SCM mitigation assessment. The articles were selected based on their relevance to experimental investigations, test validation, and long-term performance assessments. The majority of the cited sources were published from 2010 to 2025, with a few studies considered for historical significance and contribution to research development.

2. Aggregate Screening Tests

The reactivity of aggregates is primarily attributed to the presence of reactive silica [19]. Therefore, quantifying reactive constituents in aggregates can be used to determine and detect the potential for ASR. For this reason, ASTM C1778 [20] recommends petrographic analysis (ASTM C295 [21]) as an initial step in evaluating the reactivity of aggregates for the unknown sources. The systematic procedure for evaluating aggregate reactivity is shown in Figure 1.

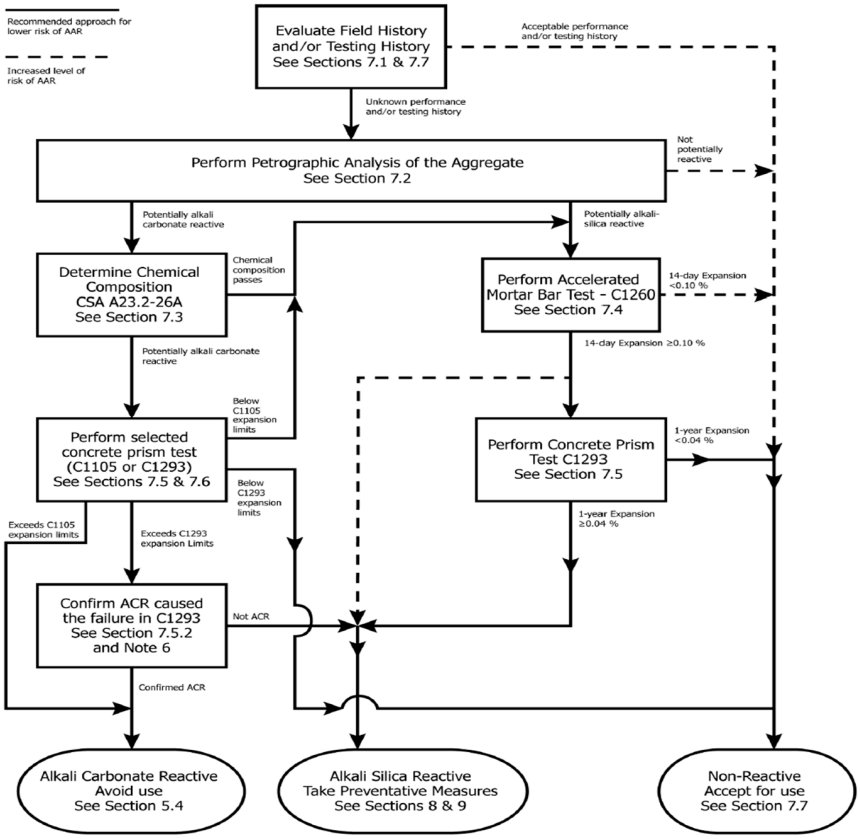
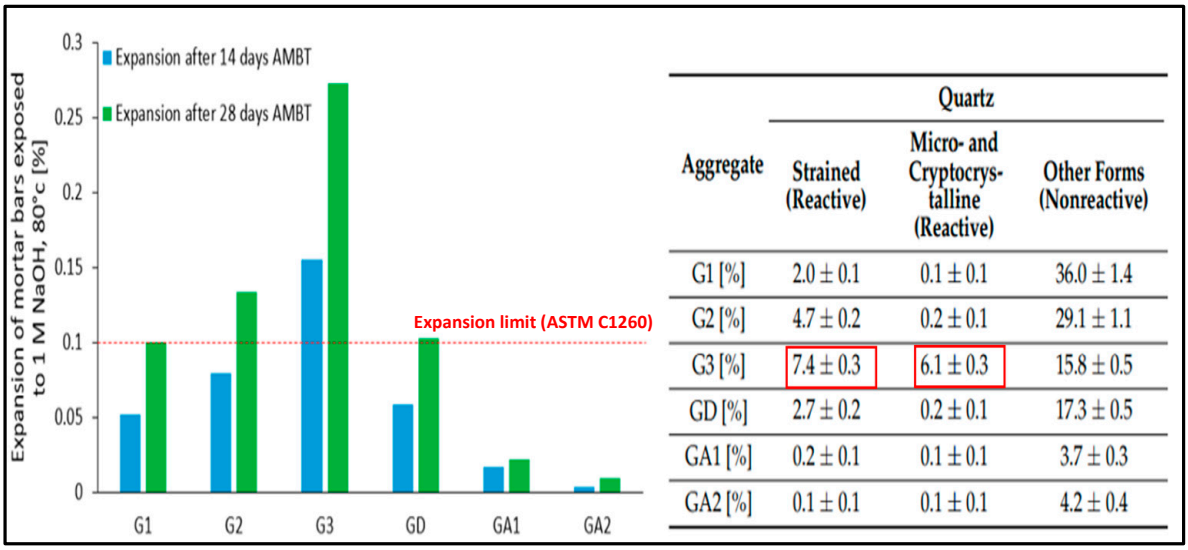


Figure 1. Sequence of laboratory tests for evaluating aggregate reactivity in accordance with ASTM C1778.

2.1. Petrographic Analysis

Petrographic examination can be used as a first detection tool for ASR potential in new aggregate sources and as a periodic quality check for existing deposits. It evaluates the ASR potential in the constituents of aggregates by identifying reactive minerals and evaluating their texture and distribution. It utilizes both visual and advanced microscopic techniques to identify reactive constituents, including opal, chalcedony, cristobalite, tridymite, highly strained quartz, microcrystalline quartz, cryptocrystalline quartz, volcanic glass, and synthetic siliceous glass [21,22].

Antolik et al. [23] explored the correlation between ASR expansion and the reactive mineral content in granite aggregates (G1, G2, G3), granodiorite aggregate (GD), and gabbro aggregates (GA1, GA2). G3 showed a high percentage of strained, microcrystalline, and cryptocrystalline quartz, which was related to a significant expansion in AMBT after 14 and 28 days, as shown in Figure 2. The petrographic analysis aligned well with the expansion results, demonstrating that the greater the quantity of reactive quartz forms, the more extensive the ASR expansion. This relationship emphasizes the importance of screening and quantifying reactive silica in aggregates for ASR assessment [23].



Aggregate	Quartz		
	Strained (Reactive)	Micro- and Cryptocrystalline (Reactive)	Other Forms (Nonreactive)
G1 [%]	2.0 ± 0.1	0.1 ± 0.1	36.0 ± 1.4
G2 [%]	4.7 ± 0.2	0.2 ± 0.1	29.1 ± 1.1
G3 [%]	7.4 ± 0.3	6.1 ± 0.3	15.8 ± 0.5
GD [%]	2.7 ± 0.2	0.2 ± 0.1	17.3 ± 0.5
GA1 [%]	0.2 ± 0.1	0.1 ± 0.1	3.7 ± 0.3
GA2 [%]	0.1 ± 0.1	0.1 ± 0.1	4.2 ± 0.4

Figure 2. Agreement between petrographic examination and AMBT results [23]. Red boxes indicate G3 aggregate, which showed the highest reactive quartz content, aligning with its high AMBT expansion.

However, this method can fail to sufficiently detect reactive minerals [24]. Furthermore, the petrographer experience plays a critical role in the examination process and in the interpretation of results. Antolik et al. [23] suggested using an image analysis approach to minimize personal error in detecting the potential reactive minerals. Jozwiak-Niedzwiedzka et al. [25] successfully quantified reactive minerals using the image analysis technique. However, the authors demonstrated the image analysis limitations when applied to certain rock types with minerals rich in ferrous phases. Additionally, both image and petrographic analyses cannot determine whether the identified reactive constituents will lead to harmful expansion. Therefore, accurate ASR performance tests are required for assessment and validation [26].

2.2. Chemical Tests

A quick chemical test can be conducted to assess the ASR reactivity in aggregates in accordance with ASTM C289 [27] (withdrawn in 2016 with no replacement). In this

test, aggregates are crushed to 150–300 µm and sealed in a 1N sodium hydroxide (NaOH) solution at 80 °C for 24 h. These conditions account for the dissolved reactive silica in the aggregate and the reduction in the solution alkalinity [28]. The results indicate whether the aggregate source is reactive or non-reactive. However, this method is commonly limited by false positives and negatives. Many reactive aggregates pass this test, while many nonreactive aggregates can be identified as deleterious. The poor performance of this method has been attributed to the interaction of NaOH with other minerals found in the aggregate, like calcium or magnesium [26].

This test has raised concerns regarding its reliability of predicting aggregate reactivity compared to their performance in outdoor exposure sites. This is because of the required crushing step that changes the reaction phases of aggregates, which can lead to results that contradict those observed in outdoor sites [24]. For this reason, Muñoz et al. [29] proposed a new chemical method that measures the concentration of silicon, calcium, and aluminum after 21 days of simulating the concrete pore solution at 55 °C. The authors concluded that this novel method showed good agreement with field exposure blocks. However, this method was limited to coarse aggregates and the authors recommended further validation to verify its validity for fine aggregates.

3. ASR Performance Tests

The mechanism of ASR is complex due to the interrelation of multiple factors and conditions that can change the reaction kinetics. For example, higher temperatures accelerate the ASR rate [30], while reactive silica, with its amorphous form, dissolves more readily under high pH conditions [31]. Additionally, the formation of cracks can increase the infiltration of moisture and other detrimental compounds into concrete, such as chloride ions and sulfate ions, further exacerbating ASR-induced damage [32]. Although ASR involves multiple interacting factors, the widely accepted mechanism suggests that the dissolved silica, under attack from hydroxyl ions, reacts with alkalis, sodium ions (Na^+), and potassium ions (K^+), to form ASR gel. Following gel formation, calcium ions (Ca^{2+}) react with silica, producing calcium-alkali–silicate compounds [12]. The role of calcium in ASR gel; however, has remained controversial among researchers [33]. Pan et al. [34] demonstrated that the calcium content in ASR gel determines its potential expansion; high-calcium gels are generally non-expansive, whereas low-calcium gels swell and induce damage. The presence of calcium ions significantly reduces the dissolution rate of soda-lime glass, a form of amorphous silica, by forming a dense, low-porosity barrier. This barrier curbs the diffusion of alkali ions, preventing further dissolution of soda-lime glass [35]. By contrast, Doğruyol [36] reported a high calcium content in an expansive ASR gel, suggesting that the calcium role is complex and context-dependent. However, Vayghan et al. [37] demonstrated that the presence of calcium ions fuels the reaction by exchanging alkalis in the gel, thereby releasing alkalis back into the pore solution. This alkali regeneration maintains silica dissolution process, leading to continuous ASR gel formation and perpetuating ASR-induced damage. Additionally, calcium hydroxide ($Ca(OH)_2$) in the pore solution produces hydroxyl ions, maintaining the high alkalinity necessary for the progression of ASR [38].

These multiple contributing chemical interactions present ASR as a highly sensitive reaction to environmental conditions. Figure 3 illustrates the widely acceptable mechanism of ASR in concrete. Step 1 represents the attack of hydroxyl ions found in the pore solution that dissolves silica from the aggregate surface. In Step 2, the dissolved silica reacts with alkali ions in the presence of water, forming the ASR gel. Step 3 shows the calcium-alkali ions exchange, sustaining the reaction, maintaining high pH levels, and dissolving more silica. These continuous cycles induce accumulated internal stresses in concrete due to the expansion of ASR gel, forming an outward map cracking throughout the entire concrete

structure. Compared to calcium, alkalis have higher affinity for silica and react more readily with dissolved silica due to their greater electronegativity and ability to disrupt the silica lattice structure [39].

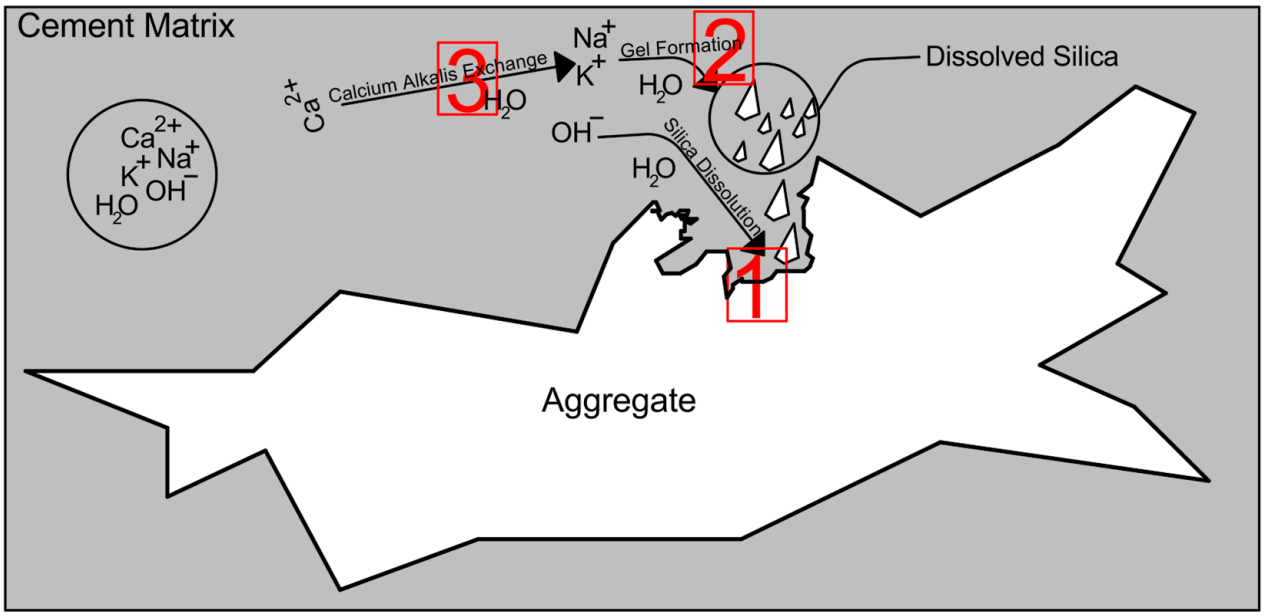


Figure 3. Schematic representation for the ASR mechanism in concrete. Step 1: Silica dissolution by hydroxyl ions (OH^-). Step 2: ASR gel forms from dissolved silica and alkalis. Step 3: Calcium-alkali exchange sustains the reaction.

ASR is a long-term reaction, and its damage can take 10–15 years to propagate in concrete structures [40]. Therefore, ASR performance tests were mainly developed to accelerate the reaction by elevating the testing conditions, including alkali loading, temperature, and humidity. This approach can provide reasonable testing duration with acceptable reliability. Since ASR is expansive, an expansion limit was used to set safe expansion thresholds [41]. Generally, there are two categories of ASR performance tests. The first category was developed to examine the reactivity of aggregates by accelerating the testing conditions to either mortar or concrete, while monitoring the expansion of samples (i.e., length change). Figure 4 shows the length measurement setup during ASR performance test according to ASTM C157 [42]. The expansion is tracked along the monitored length and reported as a percentage of the original gage length. Another category of performance tests was set to determine the efficiency of incorporating compounds and SCMs to mitigate ASR expansion [43]. In the following subsections, the common ASR performance tests will be discussed. Following that, newly advanced techniques, with the assessment of SCMs efficiency in ASR mitigation, will be discussed.

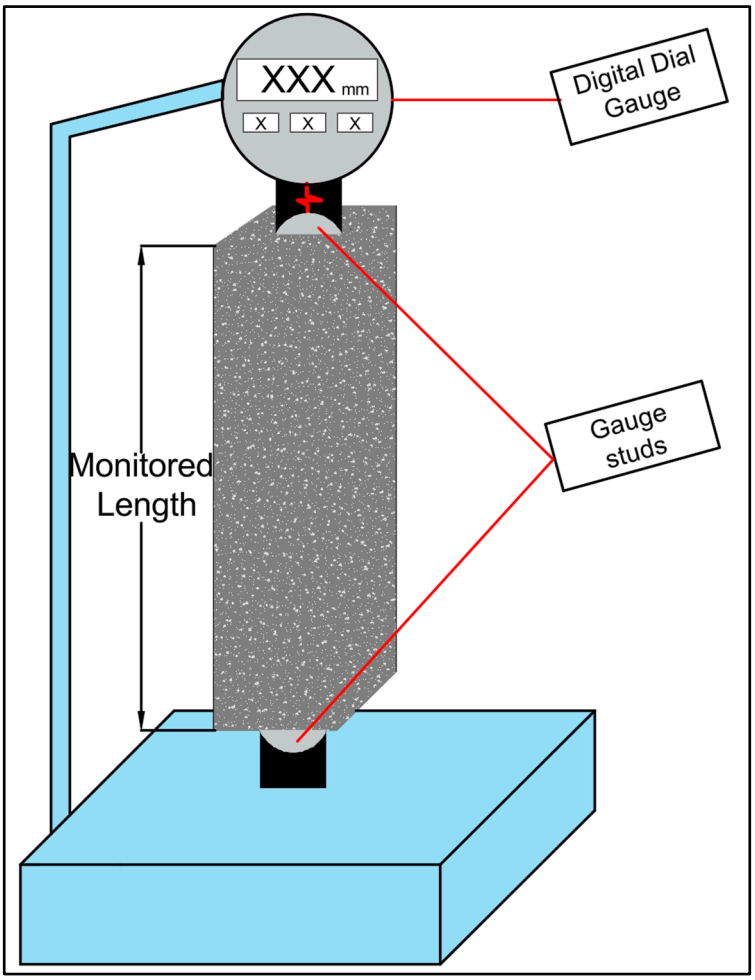


Figure 4. Schematic representation of an ASR expansion measurement setup according to ASTM C157.

3.1. Concrete Prism Test (CPT)

The concrete prism test (CPT) is an ASR performance test with a long duration of one year to determine aggregate reactivity and two years to determine the efficiency of SCMs in mitigating ASR expansion ASTM C1293 [17]. In the CPT, nonreactive fine aggregates are combined to evaluate unknown coarse aggregate reactivity, and a nonreactive coarse aggregate is used to determine the reactivity of unknown fine aggregate reactivity. The nonreactive aggregate should previously pass ASTM C1260 [16] for either coarse or fine aggregate specifications. Specimens are prepared with 420 kg/m^3 type I Portland cement content with a total alkali content of 1.25% of Na_2O_{eq} by mass of cement. Otherwise, NaOH should be added to concrete mixture to boost alkali levels to reach the specified cement alkali level. The concrete is cast into prisms and stored in a fully humid environment at 38 °C to simulate and speed up ASR conditions. Measurements of length change are taken at intervals over a year, or up to two years if preventive measures are considered. If the expansion remains below 0.04% at one year for aggregates, or at two years when SCMs are used, the materials might reasonably be considered safe from deleterious ASR potential ASTM C1293 [17].

Several studies confirmed that CPT is the most reliable performance test in identifying aggregate reactivity [44–46]. It is a highly reliable test for evaluating ASR in concrete, offering results that align closely with field performance [40,47,48]. CPT reliability stems from (1) the moderate temperature conditions (2) the storage in humid environment without an excessive amount of crushing [12]. However, its major drawback is the long duration. Therefore, a modified version (the accelerated concrete prism test [ACPT]) was proposed to reduce the

testing duration to 6 months. In the ACPT, the elevated temperature (60 °C) speeds up the chemical interactions between reactive aggregates and alkalis. However, increasing the temperature conditions also increases the risk of alkali leaching, which can alter the accuracy of ACPT [49]. According to Ideker et al. [45], ACPT showed a significant reduction in ASR expansion compared to CPT. The authors reported that the 13-week expansion at 60 °C in ACPT was approximately 62% lower for fine aggregates and 53% lower for coarse aggregates compared to the 1-year CPT expansion at 38 °C. Therefore, this study excluded ACPT as it has received less research compared to other performance tests, and due to the significant reduction in expansion attributed to alkali leaching effects [45,48].

3.2. Accelerated Mortar Bar Test (AMBT)

Accelerated mortar bar test (AMBT) is an ASR performance test with a short testing duration (16 days) conducted to determine the reactivity of aggregate in accordance with ASTM C1260 [16] or the efficiency of SCMs in mitigating ASR in accordance with ASTM C1567 [18]. AASHTO standards adopted AMBT under AASHTO T303 [50], including both versions of reactivity and mitigation tests. In the AMBT, aggregates are finely crushed to meet specific grading requirements. Mortar bars are soaked in high alkaline environment (1N NaOH) for 14 days at 80 °C, preceded by one day for specimens hardening in molds, and one day for soaking in water before the alkali soaking. The purpose of using these severe conditions is to accelerate the reaction in mortar bars, thereby reliable expansion levels can be obtained within 16 days after casting. The samples are classified as innocuous (<0.10%), innocuous and deleterious in field (i.e., uncertain) for 0.10–0.20%, and potentially deleterious (>0.20%) ASTM C1260 [16].

Several studies indicated that the AMBT should be used with caution when rejecting aggregates. The testing conditions (1N NaOH and 80 °C) are severe and the results are poorly correlated with field performance [29,47,48]. Aggregates with an unreactive history can be classified as reactive under AMBT conditions [51]. This is supported by the observation when some aggregates failed by the AMBT and passed by the CPT (i.e., false negatives) [52]. These false results are critical with slow reactive aggregates that can show damage in concrete in the long-term. Therefore, if the change in length falls in innocuous and deleterious in field category (0.10–0.20%), further investigation using petrographic specifications (ASTM C295 [21]) should be conducted and it is recommended to extend the AMBT readings for 28 days.

3.3. Miniature Concrete Prism Test (MCPT)

The miniature concrete prism test (MCPT) is an ASR performance test that balances between the reliability of CPT and the short testing duration of AMBT. It was developed by Latifee and Rangaraju [53], which was later adopted under AASHTO T380 [54]. Due to the moderate testing conditions (1 N NaOH solution at 60 °C) and the larger concrete sample sizes, it efficiently predicts the aggregate reactivity within 56 days and up to 84 days for slowly reactive aggregates [53]. Measurements are taken at specific intervals (3, 7, 10, 14, 21, 28, 42, and 56 days) to monitor expansion. Aggregates are classified based on their 56-day expansion and the rate of expansion between 8 and 12 weeks. An aggregate is considered nonreactive if its expansion is $\leq$0.030%. For expansions between 0.031% and 0.040%, the aggregate remains nonreactive only if the 2-week average rate from 8 to 12 weeks is $\leq$0.010%. If the rate exceeds 0.010%, the aggregate is classified as slow reactive. Expansions between 0.041% and 0.120% are considered moderate reactive, between 0.121% and 0.240% are highly reactive, and values above 0.240% are classified as very highly reactive AASHTO T380 [54].

Previous work indicated that MCPT correlates well with the field performance and provides reasonable results with minimal false positives or negatives, suggesting it as a potential alternative to the CPT and AMBT. Its testing protocol involves mixing nonreactive aggregates with the tested ones, offering additional advantages than AMBT. Also, it has been employed to assess the effectiveness of SCMs in mitigating ASR with good results [55,56].

3.4. The Correlation of ASR Performance Tests

The accelerated conditions of performance tests are used to obtain quicker results compared to the multi-year duration of ASR development. However, they can alter ASR behavior, which may lead to inappropriate assessments. Therefore, outdoor exposure blocks were implemented to validate the tests reliability [44,57–59]. Ideker et al. [58] examined the accuracy of AMBT and CPT in determining the aggregate reactivity compared to outdoor exposure blocks (monitored for up to five years in Texas, USA). The reported results are summarized in Table 1.

Table 1. Comparison of disagreement results between CPT and AMBT with field performance for fine and coarse aggregates.

Aggregate Type	Total Samples	CPT vs. Field (Disagreement)	AMBT vs. Field (Disagreement)
Fine Aggregates	7	None	1 (F1)
Coarse Aggregates	17	5 (C1, C5, C6, C7, C10)	10 (C1, C2, C3, C4, C5, C6, C7, C8, C9, C10)

F1 (quartz), C1 (gravel), C2 (quartzite), C3 (dolomite), C4 (sandstone), C5 (basalt), C6 (limestone), C7 (granite), C8 (chert), C9 (andesite), and C10 (gneiss).

The CPT results showed 100% agreement for fine aggregates and approximately 71% agreement for coarse aggregates with field blocks. In contrast, the AMBT results showed approximately 86% and 41% agreement for fine and coarse aggregates, respectively. The authors concluded that CPT is more reliable than AMBT due to its less severe conditions.

Crushing coarse aggregates in AMBT can alter their reactive phases, increasing the discrepancy with field blocks. In addition, Thomas et al. [44] demonstrated that the ASR performance tests suffer from significant alkali leaching during the soaking process, where smaller sample sizes lead to higher leaching. Figure 5 shows that the estimated amount of leached alkalis during one year of the CPT is approximately 35%, compromising the accuracy of CPT results [44]. Lindgård et al. [60] highlighted significant alkali leaching from concrete prisms in humid environments during ASR tests, which in turn reduces prism expansion during ASR tests. This was also shown by studying the 50-year-old Votna I dam in Norway, where it was shown that the areas with alkali leaching induced fewer cracks compared to non-leached zones within the same concrete structure [61,62]. Another limitation of ASR performance tests is the effect of temperature cycles in the field. This variation in temperature results in higher expansion for the field blocks compared to testing results, further increasing the inconsistency between field results and testing results [59].

Given the inconsistencies in expansion measurements, researchers further analyzed the accuracy of CPT and AMBT in predicting aggregate reactivity. Bergmann and Sanchez [48] analyzed the performance of CPT and AMBT in determining aggregate reactivity using 208 outdoor exposure concrete blocks under varying conditions. The CPT had an accuracy of 68% in detecting reactive aggregates and 25% in detecting nonreactive aggregates. This indicates its tendency to misrepresent aggregate reactivity and potentially underestimate expansion compared to field blocks. Nevertheless, CPT expansions are generally well correlated with field exposure blocks due to the boosted alkali content of cement during the mixing phase [44]. Figure 6 shows that 19 out of 20 concrete mixes showed agreement

between CPT results and field results, suggesting a good correlation in determining the aggregate reactivity.

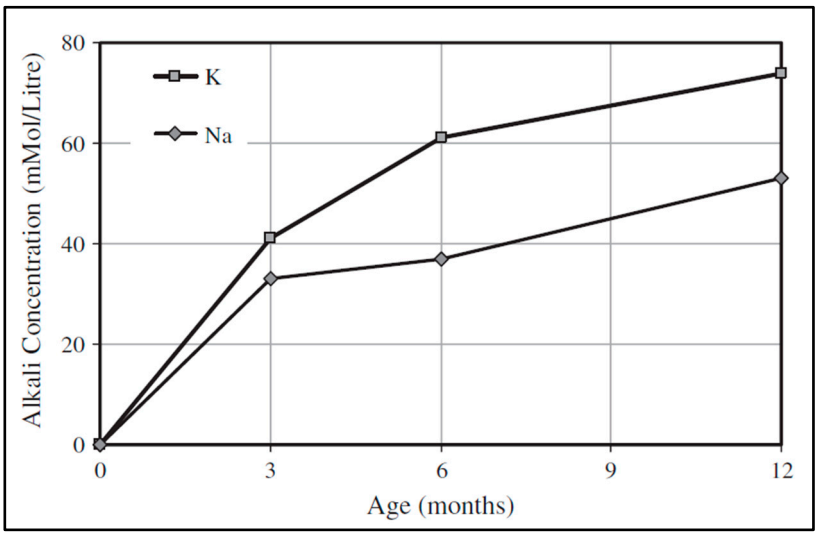


Figure 5. Concentration of alkalis in water reservoir during the concrete prism test (CPT) [44].

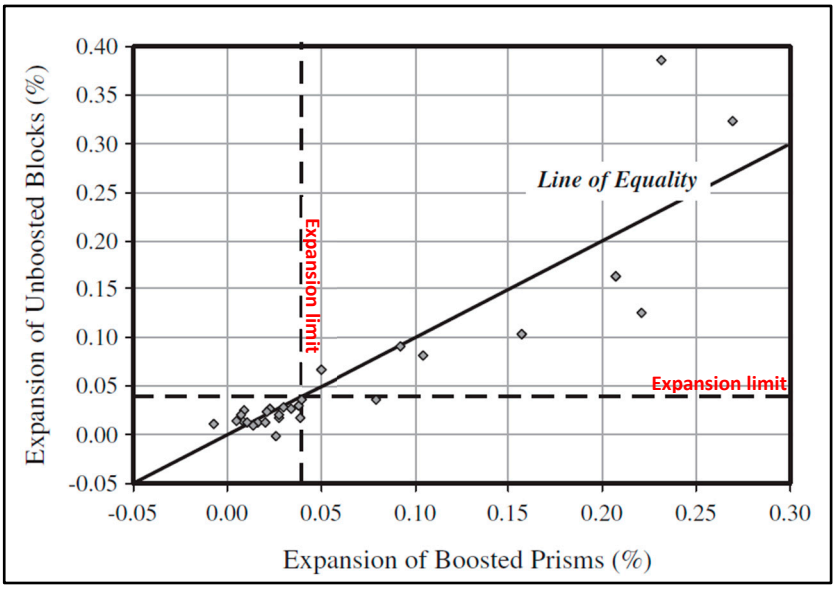


Figure 6. Comparison of expansion data for blocks stored on exposure site and concrete prisms stored over water at 38 °C [44].

Although CPT demonstrated its reliability in predicting the aggregate reactivity, the AMBT, with its severe conditions, can be more conservative, avoiding false negative results. The AMBT achieved an accuracy of 72% in detecting reactive aggregates, minimizing the false negative results. However, it achieved only 32% accuracy in detecting nonreactive aggregates, leading to a higher number of false positive results [48].

Following the development of AMBT and CPT, MCPT was developed to provide a balanced version in terms of testing conditions and duration. Figure 7 shows the summary of testing conditions and sample sizes of AMBT, MCPT, and CPT. The MCPT sample size (50 × 50 × 285 mm) is between AMBT (25 × 25 × 285 mm) and CPT (75 × 75 × 285 mm) sample sizes with moderate alkali conditions at a moderate elevated temperature. Rangaraju et al. [63] examined the performance of MCPT by investigating its correlation with AMBT and CPT results. By testing the reactivity of 16 fine aggregates and 26 coarse ag-

gregates, the authors concluded that the MCPT showed good correlation in identifying nonreactive and highly reactive aggregates. However, most inconsistencies between MCPT and AMBT, as well as between MCPT and CPT were observed in moderately reactive cases. Also, they demonstrated that the MCPT expansion results were greater than the CPT results due to the more aggressive alkaline environment of MCPT. This suggests that MCPT has less alkali leaching along with fewer false negatives compared to CPT.

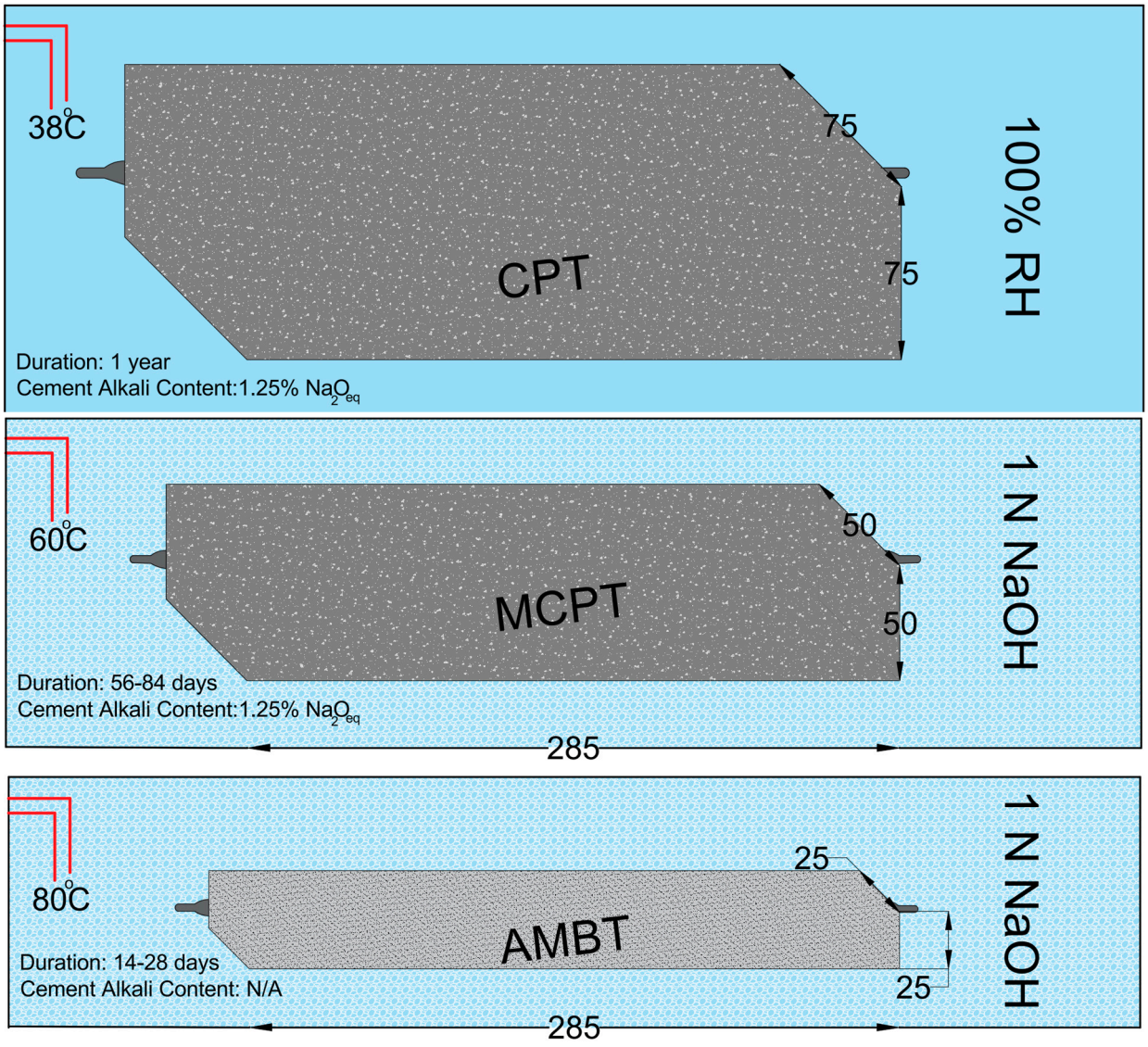


Figure 7. Testing schemes of CPT, MCPT, and AMBT for aggregate reactivity. All dimensions are in mm.

Due to the inconsistencies of MCPT against AMBT and CPT in moderate reactivity groups, Konduru et al. [55] correlated their performance with 16 fine and 26 coarse aggregates with more moderate reactive aggregates. The authors reported a reasonable to strong correlation between the CPT and MCPT with a coefficient of determination (R^2) of 0.9435 and 0.7522 for the fine and coarse aggregates, respectively. For AMBT, the analysis showed a reasonable correlation with MCPT with R^2 of 0.54 and 0.75 for the coarse and fine aggregates, respectively. The MCPT fully agreed with the classification of CPT for moderate reactivity aggregates, unlike the AMBT, which showed two disagreement results as shown in Table 2. The authors concluded that MCPT performs well in all reactivity cases, as it shows strong correlation with CPT. Since CPT is widely considered the most reliable method for evaluating aggregate reactivity and has been well validated through

outdoor exposure sites, this suggests that MCPT is also a dependable test. Furthermore, due to the less severe conditions of MCPT compared to AMBT, the former has greater reliability due to the minimal false positive outcomes [55]. As a result, MCPT can reduce the false negatives observed in CPT due to its harsher conditions and lower alkali leaching, while also minimizing the false positive results in AMBT by avoiding overly aggressive test conditions.

Table 2. Comparison of CPT, MCPT, and AMBT classifications for moderately reactive aggregates. The moderate reactivity classification follows the thresholds defined by Konduru et al. [55].

Aggregate Mineralogy	CPT Classification	MCPT Classification	AMBT Classification
Dolomite	M (0.033%)	M (0.042%)	M (0.105%)
Chert (fine)	M (0.050%)	M (0.046%)	M (0.235%)
Argillite	M (0.083%)	M (0.083%)	M (0.120%)
Limestone	M (0.046%)	M (0.055%)	N (0.070%)
Limestone	M (0.065%)	M (0.054%)	N (0.054%)

Although the correlation between different ASR performance tests can provide an indication of their reliability, they should be interpreted with caution, especially with small dataset sizes. Also, a more robust approach would be one-to-one comparisons, including the outdoor exposure results, rather than relying on statistical parameters with relatively small datasets. For example, Fanijo et al. [64] reported a high R^2 value (0.88) between the AMBT and MCPT and a moderate correlation (R^2 = 0.69) between the CPT and MCPT (Figure 8). However, despite the stronger correlation between MCPT and AMBT, two disagreement points were observed (Figure 8a), whereas CPT and MCPT showed full agreement. Moreover, these results do not align with the correlation results reported by Konduru et al. [55], where a larger dataset size was utilized, and aggregate size variations (fine and coarse aggregates) were considered. Therefore, the dataset size may influence the reliability of statistical correlations in ASR test comparisons.

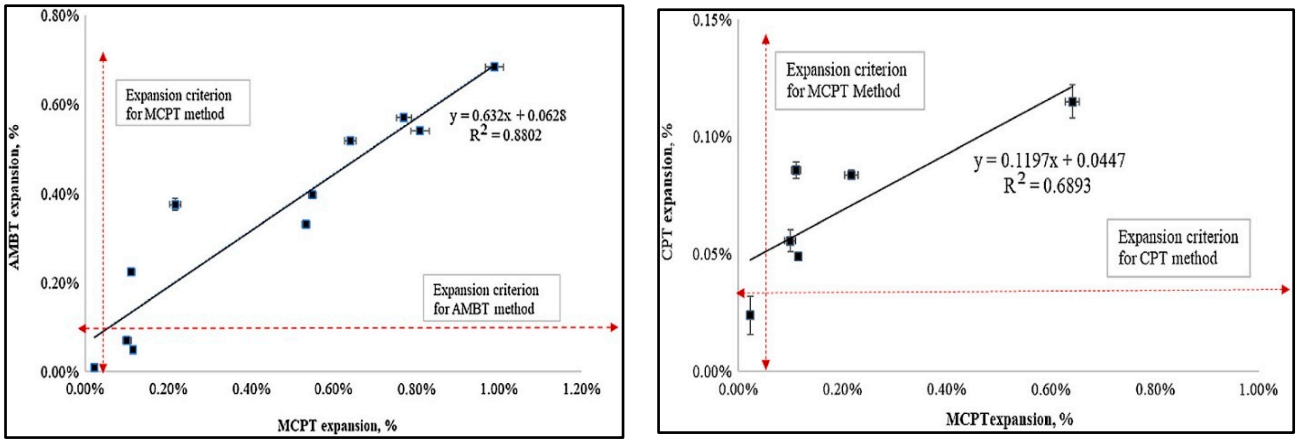


Figure 8. Correlations between (**a**) AMBT and MCPT; (**b**) CPT and MCPT [64].

Another concern relates to the correlation between CPT and ACPT reported by Fanijo et al. [64]. With only six expansion data points, the authors reported a strong correlation (R^2 = 0.94) between ACPT and CPT. They suggested that the ACPT, with further validation, can be adopted instead of CPT due to its shorter duration (six months vs. one year). However, previous research showed several limitations of the ACPT, including exces-

sive expansion, altered ASR gel viscosity, and significant alkali leaching compared to CPT [45,48,62]. These findings suggest a high level of discrepancy between ACPT and CPT, which requires further assessment prior to considering ACPT as a potential alternative. Hence, dataset size plays a critical role in statistical parameters and their interpretation. Also, while statistical correlations can be informative, they should be complemented by one-to-one comparison based on each test reactivity limits to enhance the significance of the correlations between ASR performance tests.

3.5. The Correlation of ASR Mitigation Performance Tests

This section presents the mechanism of SCMs in mitigating ASR expansion and assesses the reliability of AMBT, CPT, and MCPT in evaluating their effectiveness. While CPT is the most reliable ASR performance test for assessing aggregate reactivity, CPT, with the 2-year limit for mitigation measures, is the least reliable test. The comparison of ASR performance tests highlights the challenges in assessing SCMs efficacy using current methods. At the end of this section, a combination approach between MCPT and AMBT for determining the optimal dosage level is considered, which was developed extensively based on field exposure blocks.

The primary mechanism by which SCMs mitigate ASR is through the reduction in alkali content in concrete mixtures. Portland cement is one of the major sources of alkalis in concrete and those alkalis play a critical role in activating ASR. Therefore, the partial replacement of Portland cement by SCMs significantly reduces alkalis, thereby mitigating ASR expansion. Beyond mix design, SCMs continue to mitigate ASR during the hydration phase [44,65–67]. SCMs retain more alkalis than conventional mixtures due to their lower Ca/Si ratio. This low atomic ratio enhances the ability of portlandite products to react with alkalis [65]. Kian [68] concluded that the calcium–silicate–hydrate (C-S-H) compounds produced by conventional concrete mixtures bind fewer alkalis compared to the same compounds produced by SCMs concrete mixtures. Similarly, Shehata and Thomas [69] concluded that portlandite in SCM-modified concrete has more affinity to react with available alkalis for the ASR, further influencing ASR mitigation.

Although SCMs have a significant influence on mitigating ASR, their effectiveness depends on their reactivity, chemical compositions, and the replacement levels in concrete [70]. As a result, different optimum dosage levels have been proposed for different types of SCMs. Tapas et al. [71] demonstrated that the recommended dosage of FA and slag for ASR is about 25%, and 50–65%, respectively. However, due to the variations in the FA composition, Saha et al. [72] concluded that the FA with low calcium levels is more efficient in mitigating ASR compared to high calcium ones. Figure 9 shows the association of low expansion results according to the calcium content of FA.

Along with the several properties of SCMs, their effectiveness in mitigating ASR is also influenced by the testing conditions. Thomas et al. [44] highlighted that SCM mitigation in AMBT differs from outdoor exposure blocks, where alkalis diffuse internally. In contrast, alkalis, in AMBT, are continuously supplied from an external NaOH solution, which overestimates the required SCM dosage. Nevertheless, AMBT can be useful for assessing SCMs mitigation efficiency due to: (1) short-term evaluation results [44,48], (2) sensitivity to the dosage level of SCMs [44,69], (3) conservative evaluation results (i.e., false positives) [44,58], (4) supplementary to other ASR performance tests like CPT [44,60].

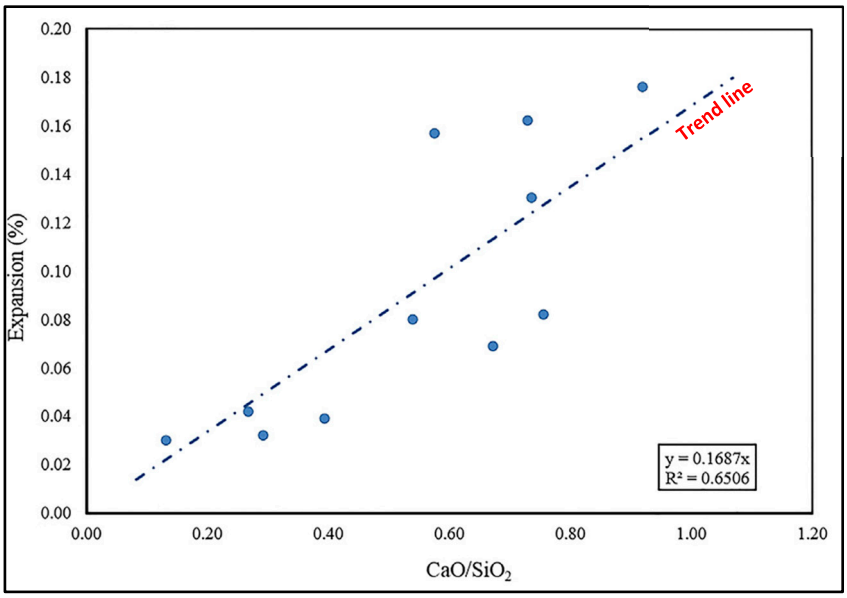


Figure 9. Correlation between ASR expansion and CaO/SiO2 of fly ash (FA) [72].

Several concerns of AMBT, with the false positives for both aggregate reactivity and mitigation assessments, have led researchers to propose extending the testing duration from 14 to 28 days [49]. Table 3 summarizes previous findings of the extension of AMBT to 28 days. This extension may be useful for lowering false positive results along with a better detection of slow reacting SCMs performance in preventative measures. The extended test duration can be beneficial for slow reacting aggregates, as well as for SCMs, which often contain slower reacting phases compared to the main clinker phases in Portland cement [73]. Math et al. [74] compared the AMBT expansion of 31 different aggregates and concluded that there was no significant difference in the expansion trend between 14 days or 28 days. Similarly, Thomas et al. [75] demonstrated that the trend of expansion is nearly the same for both durations, as shown in Figure 10. Alaejos et al. [76] reported a good linear correlation between both durations, suggesting that the 28-day extension may not offer an additional value for high reactive aggregates. Nonetheless, some agencies adopted the 28-day extension with an adjusted threshold limit for slow reactive aggregates. Spanish standards require a 28-day extension with a reactivity threshold equal to 0.20% if the 14-day expansion falls between 0.10% and 0.20% (slowly reactive category) [76]. Also, the Army Corps of Engineer uses 28-day expansion instead of 14-day expansion rate [77].

However, extending the test duration may not resolve AMBT limitations. The crushing process of AMBT can result in a lack of reaction phases during crushing and sieving aggregates. This explains why some aggregates classified as reactive in CPT were identified as nonreactive in AMBT, leading to false negative results [78]. Similarly, Mukhopadhyay and Liu [52] demonstrated that the extension of the testing duration can be insufficient to overcome the false negatives and positives of this test. While the 28-day AMBT offers additional information on slow-reacting aggregates and slow-reacting SCMs, it may not be adequate as a standalone method for predicting long-term ASR performance. Additionally, Thomas et al. [79] concluded that for SCMs mixes, 28-day expansion limit overestimates the dosage of SCMs by 1.5 based on outdoor exposure blocks. Despite that, a recent comprehensive report that used a total of 450 outdoor exposure blocks concluded that the 14-day reactivity limit should be used for aggregate reactivity, and the 28-day limit is more appropriate for the determination of SCMs dosages [47].

Table 3. Summary of the reported results of the 14-day vs. 28-day limits of AMBT.

14-Day Limit of AMBT	28-Day Limit of AMBT	Ref.
AMBT at 14 days can successfully detect reactive aggregates in mixes without SCMs, minimizing false negatives. However, it suffers from false positives.	The 28-day limit can be used for mixes containing SCMs to consider their slow reactivity and provide a more balanced prediction of long-term field performance.	[48]
The 14-day limit underestimates the reactivity of moderately reactive aggregates compared to CPT. Therefore, the 28-day limit can be used for aggregates with delayed reactivity.	The 28-day limit correlates better with field exposure block for SCMs mixes and can reduce the underestimation of reactivity.	[47]
The 14-day limit of 0.10% correlates well with field performance for SCMs mixes.	The extension to 28 days overestimates the required SCM dosage to mitigate ASR, with 1.5 times higher dosage on average.	[79]
Reliable for screening highly reactive aggregates but limited accuracy for slow-reacting aggregates.	The extension to 28 days shows improved classification of slow-reacting aggregates and aligns well with CPT results.	[80]
Poor correlation between the 14-day limit and field performance for certain aggregates (e.g., quartzite).	The 28-day limit shows better consistency in capturing slow-reacting aggregate behavior.	[81]
The 14-day AMBT limit of 0.06% instead of 0.10% is recommended for minimal false results.	The 28-day limit of 0.13% instead of 0.10% is equivalent to the 14-day 0.06% limit but provides more conservative results.	[82]
Several inaccuracies in AMBT at 14 days due to severe test conditions and rapid alkali exposure.	The 28-day limit improves accuracy in capturing delayed expansions, especially with low-reactivity aggregates.	[83]
The 14-day limit is typically used for rapid screening of ASR.	The 28-day limit at 0.28% instead of 0.10% provides better accuracy for identifying aggregates with delayed reactivity.	[84]

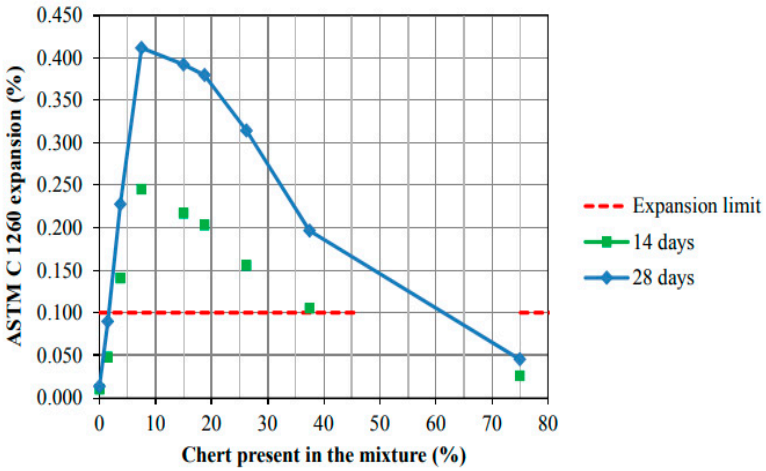
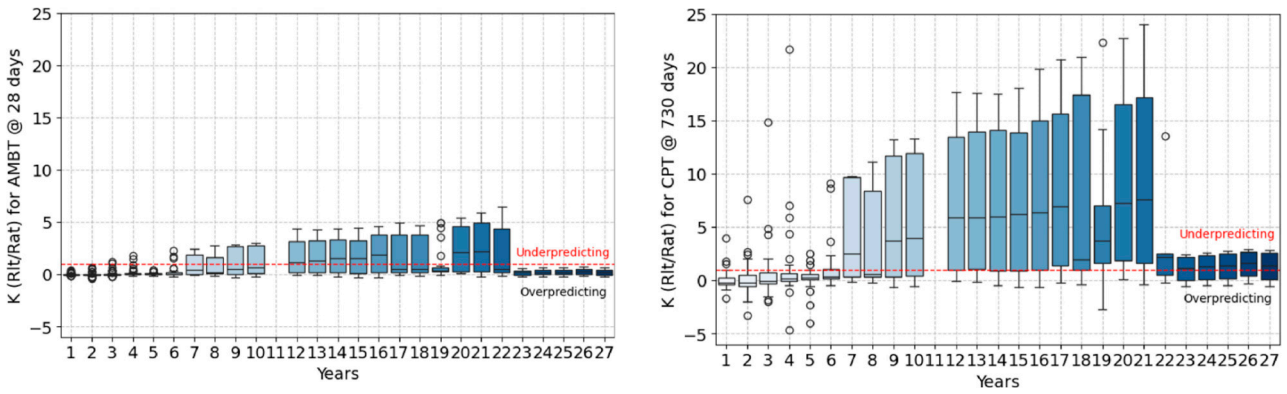


Figure 10. Pessimum phenomenon for coarse aggregate, expressed as chert percent [85].

Given the harsh conditions of AMBT, previous articles assessed its performance in examining the efficacy of SCMs compared to outdoor exposure blocks and other performance tests like CPT and MCPT. For mixes containing SCMs, Bergmann and Sanchez [48] reported that the AMBT 28-day limit showed an accuracy of 76%, with a sensitivity (true positives) of 75%, and a specificity (true negatives) of 64%. These findings highlighted its effectiveness in detecting reactive cases while being prone to false positives. The CPT 2-year limit demonstrated an accuracy of 76% but showed a much lower sensitivity of 19%, suggesting significant inaccuracies in identifying true reactive cases. However, its high specificity of 91% made it reliable in detecting nonreactive cases. These findings suggest that AMBT is more reliable for detecting the reactivity in SCMs mixes compared to CPT that can underestimate SCMs dosages [48]. Fournier et al. [86] concluded that AMBT for preventive measures using SCMs has better precision than 2-year CPT due

to the significant alkali leaching during the latter longer testing duration. This significant leaching underestimates the expansion values and the required dosage of SCMs to prevent ASR.

To analysis the stability of expansion values derived from AMBT (28-day) and CPT (2-years) compared to long-term field results, Bergmann and Sanchez [48] collected ASR data from 208 outdoor exposure sites including different SCMs like FAs, slags, and silica fumes. The outdoor exposure samples were monitored between 1.1 and 29 years, with an average field exposure of 13.3 years, providing extensive ASR field datasets. The authors used the K coefficient to examine the variation between ASR expansion values predicted by performance tests and actual field results (Figure 11). The K coefficient was defined as the ratio of the long-term field expansion to the performance test expansion at a given time, with a typical compatibility of one. For the AMBT, the k-value was relatively stable at around one, suggesting the good reliability of AMBT in predicting the SCMs efficacy based on long-term field measurements. By contrast, CPT, with the 2-year expansion limit, had a higher variation with initial k-values (up to 6 years) below one (overpredicting), and then changed to significantly underpredicting. While CPT results initially correlated well with the field results conservatively (overpredicting), the results underpredicted the required SCMs dosage in the long-run [48].



(**a**) (**b**)

Figure 11. K coefficient over 27 years of exposed concrete blocks with SCMs compared to (**a**) AMBT (28-day expansion); (**b**) CPT (2-year expansion) [48].

Due to the reliability issues of the CPT 2-year limit, several authors adopted different modifications to improve its predictive performance. Sirivivatnanon et al. [80] demonstrated that the 2-year CPT expansion limit of 0.04% should be changed to 0.03% based on field exposure results (20 years age). Table 4 shows that the adoption of 0.03% 2-year expansion limit (AS 1141.60.1 [87]) correlated better than the adopted ASTM C1293 [17] 0.04% limit [80]. It should be noted that the AMBT (14-day) results were also correlated well with the field blocks, highlighting the good reliability of AMBT for SCMs mixes. Similarly, Bavasso et al. [88] increased the testing temperature from 38 °C to 60 °C to accelerate the ASR chemistry [89]. Nevertheless, several articles reported that these modifications compromised the accuracy results of CPT. These modifications decreased the expansion values because of the reduction of OH^- ions concentration in the prism pore solution, the increase in alkali leaching, and the increase in the exudative properties of ASR gels [88,90,91]. Folliard et al. [92] recommended further investigation to improve the validity of the CPT 2-year limit with the effect of the proposed modifications on its accuracy. However, a key concern with the CPT 2-year limit is its prolonged duration, which may exacerbate certain limitations of ASR tests, including the significant alkali leaching.

Table 4. Comparison of AMBT (ASTM C1260) and CPT (ASTM C1293 and AS 1141.60.1) with field expansions after 20 years of exposure.

Mixes with SCMs	Expansion Results			
	AMBT (0.01% at 14 Days)	**CPT (ASTM C1293) (0.04% at 2 Years)**	**CPT (AS 1141.60.1) (0.03% at 2 Years)**	**Field Expansion (0.05% at 20 Years)**
50% S [1]	N (0.059)	N (0.029) *	N (0.029) *	N
18% FA [2]	R (0.111)	N (0.037)	R (0.037)	R
25% S	R (0.187)	R (0.045)	R (0.045)	R
25% S and 3.8% SF	N (0.041)	N (0.029) *	N (0.029) *	N

[1] Slag (S), [2] Fly ash (FA), Silica Fume (SF). * The expansion values were indicated by <0.03%.

Because of the long testing duration and low reliability of CPT (2 years) in SCMs mixes, MCPT can be alternatively applied for preventive measures. Also, MCPT has less harsh conditions compared to AMBT that can interfere with the expansion results, provided that AMBT showed good correlation with field performance for preventive measures [80]. Liu et al. [93] compared MCPT and CPT results for SCMs mixes in ASR mitigation (Figure 12). The study found a linear correlation, with an R^2 value of 0.6697. Out of 33 mixes made with FAs and Ss, MCPT and CPT agreed on 26 mixes. The results attributed the seven disagreement results to the accelerated conditions in the MCPT that can alter the mitigation mechanism of SCMs [93]. However, this justification can be limited since it was previously shown that there are several issues in the CPT 2-year limit. Additionally, Tanesi et al. [56] concluded that MCPT correlated well with the field blocks for preventive measures unlike with the CPT 2-year limit. The authors used field exposure blocks aged between 13 and 15 years. Table 5 shows the good agreement results between field blocks and MCPT for SCMs mixes (3 disagreements out of 13), unlike higher miscorrelation between field blocks and CPT (9 disagreements out of 13). These findings highlight the capability of MCPT in efficiently determining the required SCMs dosage in mitigating ASR expansion.

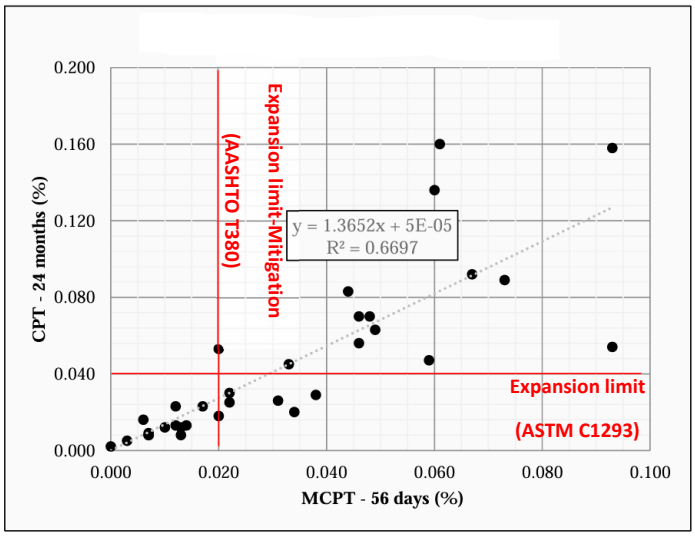


Figure 12. The correlation of MCPT and CPT for SCMs mixes [93].

Table 5. Expansion of blocks and specimens tested by CPT (2-years), MCPT (56 and 84 days) for SCMs mixes.

Aggregate Type	Mixes with SCMs	Expansion Results			
		CPT (ASTM C1293) (0.04% at 2-Years)	MCPT (AASHTO T380) (0.03% at 56 Days)	MCPT (AASHTO T380) (0.03% at 84 Days)	Field Expansion (0.05% at 20-Years)
Spratt	40% FA-Class C	N 0.14	R 0.029	R 0.038	R 0.05
	20% FA-Class C	N 0.26	R 0.052	R 0.063	R 0.16
Placitas	40% FA-Class C	N 0.013	R 0.029	R 0.038	R 0.32
	20% FA-Class C	R 0.043	R 0.061	R 0.08	R 0.45
	100% lithium nitrate	R 0.046	R 0.091	R 0.137	R 0.33
Wright	40% FA-Class F	N 0.005	R 0.021	R 0.044	R 0.14
	20% FA-Class C	N 0.033	R 0.077	R 0.113	R 0.42
	40% S	N 0.025	R 0.052	R 0.052	R 0.34
	35% S and 5% SF	N 0.023	N 0.015	N 0.017	R 0.20
	35% C and 5% SF	N 0.017	R 0.025	R 0.033	R 0.13
Jobe	20% Class F	N 0.02	R 0.033	R 0.071	N 0.02
	50% S	N 0.033	R 0.063	R 0.115	N 0.02
	100% lithium nitrate	N 0.038	R 0.261	R 0.447	R 0.12

Slag (S), Fly ash (FA), Silica Fume (SF).

Recently, AASHTO R80 [94] and ASTM C1778 [20] specifications were developed to improve the assessment of aggregate reactivity and the selection of appropriate preventive measures to allow the use of potentially reactive aggregates in concrete. However, the ASR performance tests, such as CPT, AMBT, and MCPT were generally developed based on high alkali cement contents. This has raised several concerns related to mixtures with moderate or low alkali cement contents. According to Ideker et al. [95], the amount of SCMs recommended by ASR performance tests may not be sufficient to control the ASR expansion in outdoor exposure blocks that contain large amounts of high-alkali cements and a validation of current ASR tests may be needed. As a result, a recent NCHRP study (Project 10-103) was conducted to address the shortcoming of current ASR assessment methods including the use of limestone cement with moderate to low alkali content [47]. It should be noted that under the last delivery of the project, Dr. M. D. Thomas passed away, who significantly contributed to the ASR research topic and was a co-author of the NCHRP study (Project 10-103). The main findings of the project are summarized in Table 6. The authors proposed a systematic approach in determining the optimal replacement level for preventive measures based on extensive historical data and extensive outdoor exposure blocks (450 blocks with different alkaline loadings under different climates). First, MCPT

(56 days at 0.03%) and AMBT (14 days at 0.10%) were recommended as a replacement for CPT (1 year at 0.04%) in aggregate reactivity assessment. This is due to their strong correlation with both CPT and field exposure blocks. Second, a combination of MCPT and AMBT was suggested for evaluating the aggregate reactivity. If they yield the same results (fail/fail), AMBT (28-day at 0.10% limit) should be conducted to determine the required dosage. However, if AMBT fails but MCPT passes, or vice versa, the authors did not explicitly outline the next step. To address this gap, this study suggests conducting MCPT (84-day at 0.025%) when AMBT passes but MCPT fails. This approach provides a more conservative assessment to ensure adequate ASR mitigation. Alternatively, if MCPT passes but AMBT fails, additional verification steps may be needed, such as historical CPT data, field exposure records, or supplementary testing. If no additional data are available, AMBT (28-day) could serve as a secondary check, though its suitability for aggregate reactivity classification requires further study due to its false results. Those steps are shown in Figure 13. The authors excluded the CPT (2-year) for preventive measures as it underestimates the required replacement level with its sensitivity lack for different alkali loadings. This systematic approach in ASR testing with its well-established large datasets can be adopted to determine the required replacement level for the usage of potentially reactive aggregates in concrete.

Table 6. The main findings of Drimalas et al. [47].

Test Method	Aggregate Reactivity Testing	Preventative Measures Testing
AMBT (ASTM C1260 /1567 or AASHTO T303)	The 14-day at 0.10% limit is appropriate for aggregate reactivity and it correlated well with MCPT and CPT.	The 28-day at 0.10% limit is more appropriate for preventive measures since it correlated well with field results and MCPT (84-day).
CPT (ASTM C1293)	It is the best indicator for aggregate reactivity since it showed the best correlation with field results. It benchmarks well with AMBT (14 days) and MCPT (56 days).	The 2-year at 0.04% limit should not be used for preventive measures as it underestimates the required dosage for mitigating ASR, and it lacks the sensitivity for different alkali loadings.
MCPT (AASHTO T380)	Excellent test for aggregate reactivity at 56 days of 0.03% limit since it strongly correlated with CPT and AMBT. The slow reactivity category between 8 and 12 weeks should be removed. The adoption of 0.03% as a reactivity limit should be adequate.	It was recommended to adopt the expansion limit of 0.025% at 84 days since it correlated well with the field results.

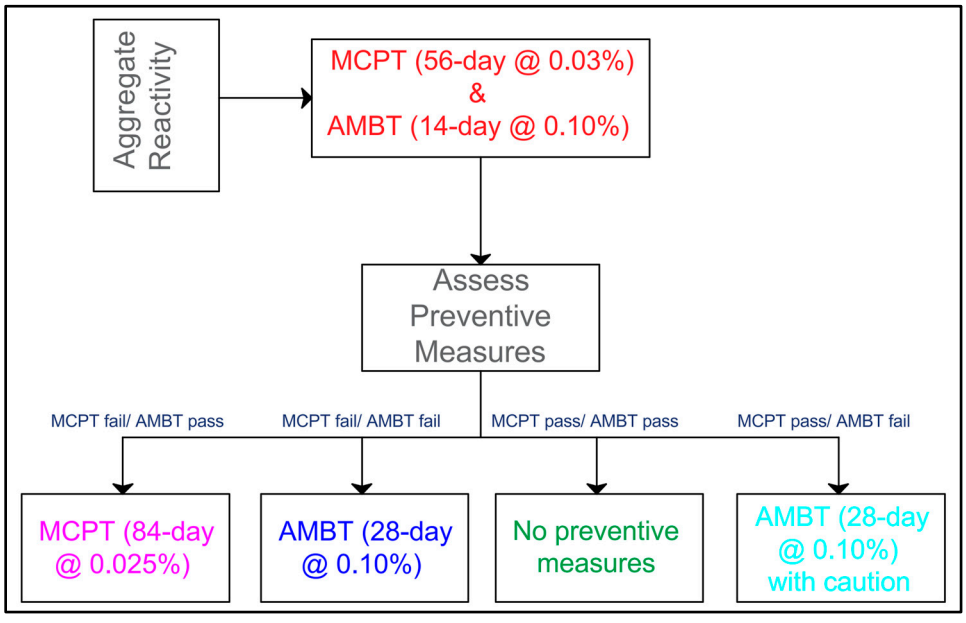


Figure 13. Decision flowchart for determining the required dosage to mitigate ASR using a combination of MCPT and AMBT.

3.6. Indirect Assessments of ASR Mitigation Efficiency

ASR performance tests focus mainly on the expansion measurements under accelerated conditions and often fail in detecting the pore solution chemistry and SCMs reactivity levels [96]. Therefore, additional screening tests that can indirectly measure the efficacy of SCMs in suppressing ASR expansion can support and verify performance test results. This is important because the efficacy of SCMs in mitigating ASR is highly influenced by their chemical compositions, interaction with the cementitious phases, and reactivity levels [71,72]. This section assesses the modified R3 test and bulk resistivity, which have been recently developed for the potential of SCMs to mitigate ASR in concrete. Those tests focused on measuring the reactivity levels, pore solution alkalinity, and transport properties of SCMs, allowing for more accurate results in the selection of preventive measures for ASR mitigation.

3.6.1. R3 and Modified R3 Tests

The rapid, relevant, reliable (R3) test evaluates the reactivity levels of SCMs based on their pozzolanic reactivity. It measures the heat release or bond water content due to the SCMs reaction with calcium hydroxide and alkali-sulfate solution under controlled conditions [97]. The test should be conducted at 40 °C for one week in accordance with ASTM C1897 [98]. Unlike traditional SCMs reactivity tests, R3 test isolates SCM reactions by removing hydration effect of cement, offering a simplified test as it lacks a fully cementitious system [99]. The R3 test measures the reactivity through two primary parameters: the heat release and the bond water content. In the heat release measurement, an isothermal calorimetry is used to measure the cumulative heat released during SCM hydration. The amount of heat release measures the SCM pozzolanic reactivity, where the higher the heat release the greater the reactivity. This parameter is associated with the consumption of calcium hydroxide that reduces the pore solution alkalinity, which can indicate the mitigation of ASR expansion [100]. In a case of calorimetric equipment lack, the bond water content can be used to provide an alternative measure for the SCMs reactivity. After the hydration of the SCM paste, bound water content is quantified via drying and thermal process [101].

The R3 test with its current version lacks the prediction of the SCMs in ASR mitigation because of its lack of measurements of alkalis and CaO contents [100]. For example, FA class-C (FA-C) are not recommended to mitigate ASR due to its high calcium content [102]. However, based on the R3 test results, FA-C is considered a high reactive SCM [103]. This underscores the need for the inclusion of additional specifications in R3 test, by which it can be used to determine the efficiency of SCMs in mitigating ASR.

Recently, a modified R3 test has been developed to further assess SCMs reactivity, especially for slow reacting materials [104]. The modified R3 test was proposed to be conducted at 50 °C for 10 days. These elevated conditions, compared to the R3 test, enhance the reaction rate of SCMs, specifically for slow reacting materials. Also, it eliminates the addition of sulfates and carbonates to establish a clearer distinction of SCMs reactivity when a chemical composition is uncertain. Both tests examine the pozzolanic or latent hydraulic nature of SCMs. However, the modified R3 test focuses on calcium hydroxide consumption rate for a more detailed evaluation of the reactivity classification of SCMs with an indication of the ASR mitigation potential [99,100].

The consumption rate of calcium hydroxide was correlated with the ASR expansion level to assess the efficacy of SCMs in ASR mitigation. Suraneni [100,105] observed a good correlation between AMBT expansion rates and calcium hydroxide consumption measured by the modified R3 test. Figure 14 shows the correlation between AMBT expansion levels at 14 days and a novel parameter, which is the multiplication of the calcium hydroxide

consumption rate by the SCM replacement level in mortars. This relationship suggested that the quantification of calcium hydroxide consumption rate can indicate the SCMs efficacy in mitigating ASR. Also, this approach showed an interesting non-linear trend, encompassing all reactivity classifications including highly, moderate, and nonreactive cases. There are a limited number of studies that considered the modified R3 test in ASR mitigation, despite its promising evaluation for slow reactive SCMs. Nevertheless, the R3 test has shown an increasing attention due to its reliability and short testing duration. Recently, Min et al. [106] developed the R3 test, producing an ultra-rapid reactivity test for real time (UR2). By using 4N NaOH solutions at 90 °C for 5 min, the authors developed a reliable SCMs evaluation test with a strong correlation with R3 test (R^2 = 0.92).

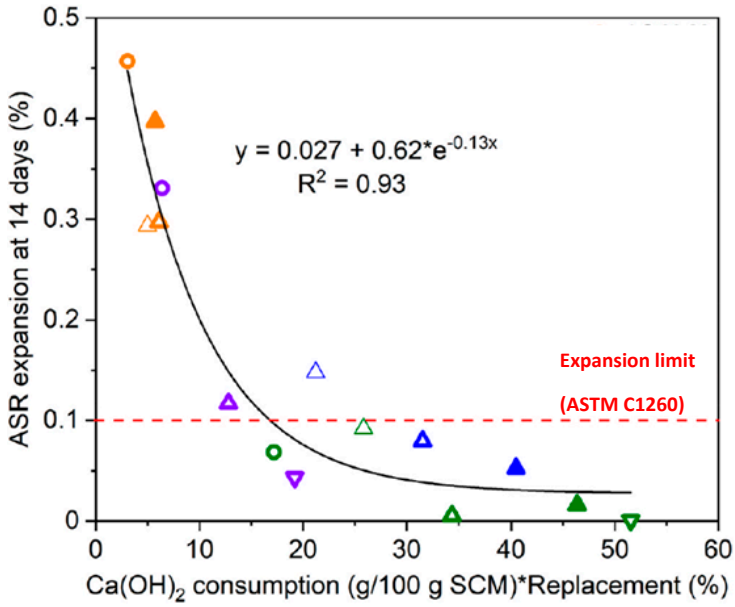


Figure 14. AMBT expansion at 14 days as a function of calcium hydroxide ($Ca(OH)_2$) consumption by SCM multiplied by SCM replacement in mortars. The asterisk (*) indicates multiplication throughout the figure. Adapted from [105].

3.6.2. Bulk Resistivity

Bulk resistivity has been extensively applied for the examination of the concrete quality and durability [107,108]. It measures the electrical current flow resistance by concrete [109]. Concrete resistivity is influenced by the pore structure refinement and the free ions concentration in the pore solution of concrete. Bulk resistivity has also been indirectly used to assess the effectiveness of SCMs in mitigating ASR. SCMs reactions refine the pore concrete structure by forming C-S-H (in latent hydraulic reactions) and C-A-S-H (in pozzolanic reactions), which reduce pore size and connectivity, thereby increasing resistivity. Also, trapping alkalis by SCMs in the reaction products increases the concrete resistance by lowering free ions in the pore solution [105,110–113].

High correlations were reported between bulk resistivity and ASR expansion, with highly resistive concrete exhibiting lower ASR expansions [105,110–113]. Wang et al. [105] reported a good correlation (R^2 = 0.89) between AMBT expansion values and bulk resistivity and recommended further validation based on MCPT expansion results. Chopperla and Ideker [111] found a strong correlation (R^2 = 0.94) between MCPT expansion values and bulk resistivity. Figure 15 shows the correlations between bulk resistivity and the ASR expansion measured by MCPT and AMBT [110,111]. Chopperla and Ideker [111] showed that high resistive concrete mixtures with SCMs exhibit lower ASR expansions due to reduced pore solution alkalinity and limited moisture infiltration. Also, Wang et al. [105]

demonstrated that the bulk resistivity indicator can capture the differences in the chemical reactions of various SCMs in concrete mixes. For example, after 180 days with 60% replacement, pumice pozzolan concrete mixture showed the highest increase in resistivity (around 825 Ω·m), slag pozzolan mix had a moderate increase (around 150 Ω·m), and a decrease in the resistivity for limestone mix (around 36.3 Ω·m) compared to the control mixes (around 37.5 Ω·m). These differences contributed to (1) pumice pozzolans have a strong pozzolanic reactivity that bind alkalis found in the pore solution and reduce ions concentrations, which significantly increase the resistivity (2) slags undergo a latent hydraulic reaction that lacks the alkalis binding but with a pore structure refinement, showing a moderate increase in the resistivity (3) limestone reacts as a filler in the concrete mixtures lacking any effect on the pore structures and alkalis concentrations. These findings highlight the capability of bulk resistivity measurements in classifying the SCMs based on their chemical reaction along with the capability of assessing SCMs effectiveness in ASR mitigation.

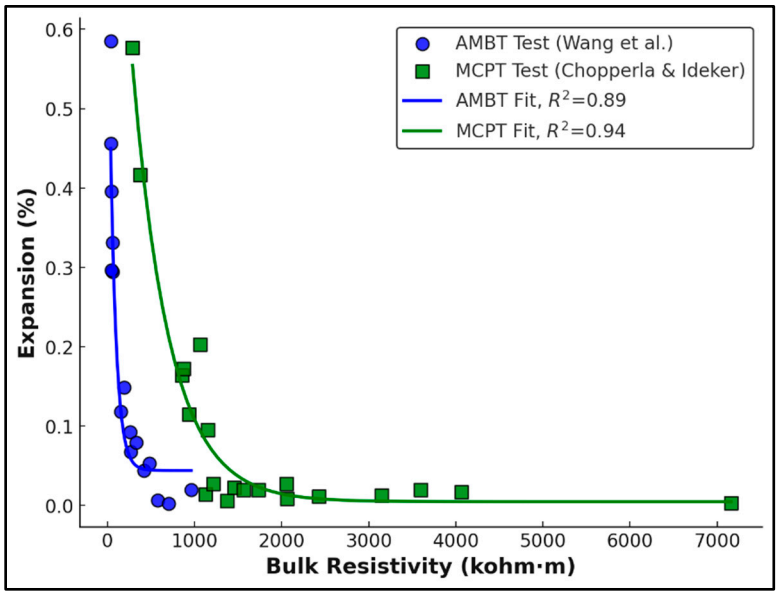


Figure 15. Correlation between bulk resistivity and ASR expansion values of AMBT and MCPT.

Additionally, the modified R3 test results showed a good correlation with resistivity measurements (Figure 16), underscoring the reliability of bulk resistivity as an indirect method for ASR mitigation assessment. Chopperla and Ideker [111] concluded that the application of those parameters could reduce the testing duration and improve the prediction performance of ASR performance tests. Wang et al. [105,111] concluded that the application of resistivity parameters can be used as an additional screening method along with ASR performance tests to assess the efficacy of SCMs in mitigating ASR expansion. Nevertheless, the bulk resistivity in concrete needs further research for further validations and to propose standard frameworks to extract the bulk resistivity results. Chopperla and Ideker [111] used concrete cylinders at 10kHz frequency resistivity with moisture correction applied. Chopperla et al. [114] sliced MCPT concrete samples with 50 mm cubes with dimensional correction applied, and Wang et al. [105] sliced AMBT mortar cubes at 1 kHz frequency under different curing conditions. These varied conditions should be further investigated with their effect on the resistivity results. This is critical because resistivity can vary significantly based on the testing conditions. The accuracy of resistivity measurements is highly influenced by curing temperatures and saturation degrees. Additionally, variations in the particle size, chemical composition, and alkali content complicate direct comparisons. Although resistivity measurements often correlate well with ASR

expansion for the short-term, the long-term reactivity of SCMs may continue to increase resistivity, potentially resulting in an underestimation of SCMs long-term performance in ASR mitigation [105,111].

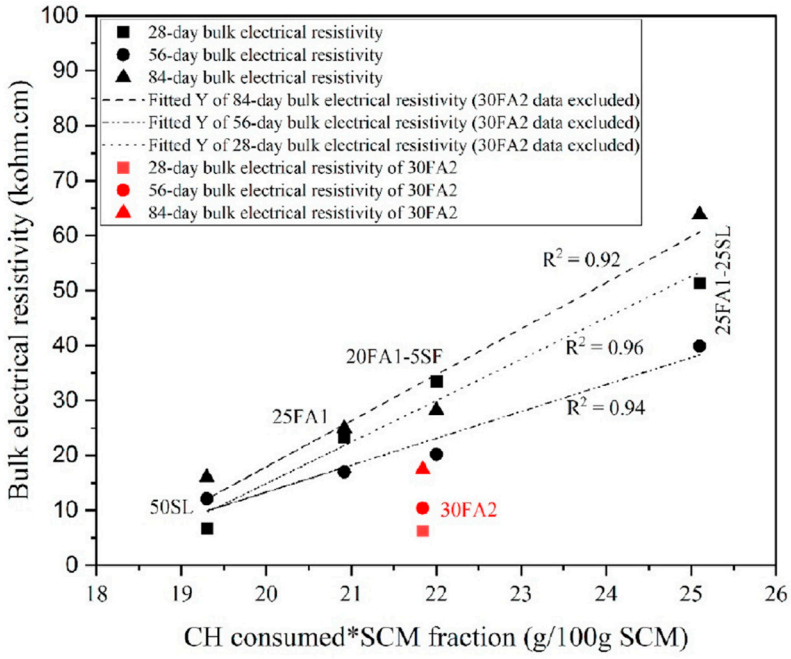


Figure 16. Correlation between SCM pozzolanicity (calcium hydroxide (CH) consumed in the pozzolanic reactivity test) and amount of SCM and 28-day bulk electrical resistivity of the controlled concrete specimens. The asterisk (*) indicates multiplication throughout the figure [111].

4. Future Perspectives

The long-term progression of ASR remains a challenge to accurately predict using ASR performance tests, given the different reactivity classifications of aggregates, the limitations of existing testing methods, and the variability in SCMs with diverse chemical compositions. Despite the advancements in ASR testing, the lack of a widely accepted framework in predicting long-term ASR behavior and determining the optimal preventive measures underscores the need for further development and alternative testing frameworks.

A critical gap remains in reliably assessing preventive measures, as even well-established results yield contradictory findings. The inconsistent results between studies can be primarily shown when preventive measures are assessed. For the assessment of aggregate reactivity, it is well-known that CPT (1-year) is the best indicator, with acceptable results obtained by MCPT (56-day) and AMBT (14-day), with a recommended extension for slow reactive aggregates to MCPT (84-day) and AMBT (28-day). However, for preventive measures assessment, the results can be inconsistent, despite the usage of field exposure blocks. For example, Thomas et al. [79] concluded that the extension of AMBT from 14 days to 28 days overestimates the SCM replacement level required to mitigate ASR expansion by an average 1.5; however, Drimalas et al. [47] concluded that the usage of AMBT 28-day limit is the best limit for preventive measures. Both studies used extensive field exposure blocks to validate their findings. Therefore, combining additional screening methods for preventive measures that evaluate the chemistry of the pore solution and transport properties, is of interest. In contrast to the expansion measurement of specimens, indirect methods, such as the modified R3 test and bulk resistivity, provide supplementary information that can complement current ASR performance tests. The integration of these methods can reduce the inconsistent results with a better framework for performance predictions.

Compounding these testing and classification challenges, recent sustainability trends have further complicated ASR mitigation efforts. Due to sustainability measures, the recent shift from ordinary Portland cement (OPC) to Portland limestone cement (PLC) introduced another challenge in ASR performance tests. Most tests were developed based on OPC. The chemical difference between OPC and PLC may alter the pore solution chemistry and the expansion behavior, potentially leading to the misclassifications of aggregate reactivity. Previous studies highlighted the importance of analyzing the effect of using PLC instead of high alkali OPC [47,114]. The usage of PLC can significantly influence the ASR expansion, underestimating the required dosage to mitigate ASR expansion. The particle size of PLC can have a significant impact on the ASR expansion that compromises the classification of reactivity. It can reduce the pore solution alkalinity and refine the concrete pore structure, which in turn mitigates ASR expansion [114]. Nguyen et al. [115] reported that replacing OPC with a 30% blend of limestone and calcined clay (2:1 ratio) reduced AMBT expansion from 0.30% to around 0.10%, shifting the classification from reactive to potentially reactive. In contrast, Wang et al. [105] demonstrated that neither the high dosage nor the higher fineness of limestone was able to mitigate ASR expansion and it only reacts as a filler in concrete mixtures. These results indicate that limestone effectiveness is likely enhanced when combined with reactive SCMs such as calcined clay. Therefore, more research is recommended to establish the effect of PLC in ASR expansion, especially with blended systems. Moreover, while CPT was developed based on Type I OPC with high alkali content, the alkali content of cement does not affect AMBT results [16,17]. However, the usage of PLC with the same alkali content may affect the testing results, given its different chemical compositions. Diluting alkalis with the effect on pore structure may lead to false negatives. Therefore, further studies are recommended to analyze and evaluate the specified limits of ASR tests with the new binder chemistry, ensuring accurate classification and mitigation dosage predictions.

Broader sustainability measures have also influenced the availability of SCMs, such as FA and slag, with the recent shift away from using coal-fired power plants for cleaner energy production. While FA and slag have been widely studied for ASR mitigation, there is a need for an investigation of other pozzolanic materials, like NPs. Given their cost-effectiveness and widespread natural availability, NPs present a promising class of SCMs for ASR mitigation [116]. Although several studies have explored their use in concrete, a significant research gap remains. For example, the incorporation of diatomaceous earth NP significantly reduced ASR expansion [117]. However, limited literature focused on this NP, despite its large deposits in western U.S. states, where over 620,000 tons of diatomaceous earth were mined in 2004, accounting for approximately 30% of global production [118].

Another recent sustainability aspect is the usage of seawater in concrete infrastructure. With the increase in adoption of fiber-reinforced-polymers (FRPs) bars instead of steel reinforcement, the durability of concrete made with seawater is of interest. In this regard, the quantification of external alkalis added to concrete becomes a need for investigation, specifically for the ASR distress. Controlling the alkali contribution from cement can be an effective solution to prevent ASR in concrete. However, other external sources of alkalis like deicing salts should be considered [44]. Ranger et al. [57] demonstrated that the ASR damage was, in some cases, connected to the presence of deicing salts, mainly NaCl. Several explanations were proposed for the effect of NaCl in ASR, such as the acceleration of dissolution rate of amorphous silica. Zhang et al. [119] concluded that the ASR mechanism in seawater sea-sand concrete (SWSCC), which is generally used with FRP bars, was significantly changed due to the high sodium concentrations. Higher sodium ion concentrations, such as those from seawater, exacerbates ASR by increasing gel formation, reducing C–S–H polymerization, and deteriorating the internal matrix structure. Altogether,

resolving these interrelated challenges, from test variability to material transitions, is critical to develop an adaptable ASR mitigation strategy for future concrete construction.

5. Conclusions and Future Directions

ASR severely deteriorates concrete structures through deleterious expansive cracks. Its slow progression over the years and the influence of multiple internal and external factors create uncertainties in reliably assessing its expansion. This critical review evaluates recent literature concerning the accuracy of AMBT, MCPT, and CPT in correlation with field exposure results. The widely accepted mechanism of ASR and the role of SCMs in mitigating ASR were included to identify limitations and propose a testing framework for determining the optimal SCM dosage to mitigate ASR. For aggregate reactivity, CPT (1-year) is considered the most reliable test. Alternatively, a combination of AMBT (14-day) and MCPT (56-day) was validated with respect to long-term field data for fail/fail outcomes. For preventive measures, AMBT (28-day) and MCPT (84-day) demonstrated good sensitivity and conservative evaluations, while CPT (2-year) is unreliable due to the significant alkali leaching. This suggested framework can mitigate inconsistencies in evaluating the effectiveness of SCMs in ASR mitigation and provides a well-established decision basis for designing concrete mixtures under evolving exposure and material constraints. Moreover, the incorporation of the modified R3 test and bulk resistivity offers additional screening tools to guide mixture design by evaluating pore solution chemistry and internal structure characteristics that complement ASR performance tests.

To address current gaps in ASR assessment, future research should integrate indirect methods, long-term field exposure data, and current data-driven modeling techniques, such as artificial intelligence. Furthermore, emerging sustainability shifts, such as the use of PLC, seawater, and natural pozzolans, warrant further investigation that may affect ASR mechanism and tests performance. These evolving practices call for updated specifications and a more adaptive testing framework that ensures durable and long-lasting concrete infrastructure.

Author Contributions: Conceptualization, O.O.; methodology, O.O.; validation, O.O., H.A.H. and A.N.; formal analysis, O.O.; investigation, O.O.; resources, A.N.; data curation, O.O.; writing—original draft preparation, O.O.; writing—review and editing, O.O., H.A.H. and A.N.; visualization, O.O.; supervision, A.N.; project administration, A.N.; funding acquisition, A.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors acknowledge the support of the University of Miami.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ASR	Alkali–silica reaction
AMBT	Accelerated Mortar Bar Test
CPT	Concrete Prism Test
MCPT	Miniature Concrete Prism Test
ACPT	Accelerated Concrete Prism Test
OPC	Ordinary Portland cement
PLC	Portland limestone cement

NP	Natural pozzolan
SCM	Supplementary cementitious material
FA	Fly ash
SF	Silica fume
S	Slag
R3 test	The rapid, relevant, reliable test
UR2	Ultra-rapid reactivity test for real time
FRP	Fiber-reinforced-polymers
SWSCC	Seawater sea-sand concrete

References

1. Watson, R.; Abbassi, B.; Abu-Hamatteh, Z.S. Life cycle analysis of concrete and asphalt used in road pavements. *Environ. Eng. Res.* **2020**, *25*, 52–61.
2. Li, Z.; Zhou, X.; Ma, H.; Hou, D. *Advanced Concrete Technology*; John Wiley & Sons: Hoboken, NJ, USA, 2022.
3. Chiew, S.M.; Ibrahim, I.S.; Ariffin, M.A.M.; Lee, H.-S.; Singh, J.K. Development and properties of light-transmitting concrete (LTC)–A review. *J. Clean. Prod.* **2021**, *284*, 124780. [CrossRef]
4. Snyder, K.A.; Lew, H.S. *Alkali-Silica Reaction Degradation of Nuclear Power Plant Concrete Structures: A Scoping Study*; Document ID-NISTIR 2013; National Institute of Standards and Technology (NIST), US Department of Commerce: Gaithersburg, MD, USA, 2013; p. 7937.
5. Martínez, A.; Miller, S.A. A review of drivers for implementing geopolymers in construction: Codes and constructability. *Resour. Conserv. Recycl.* **2023**, *199*, 107238. [CrossRef]
6. Chen, L.; Wei, L.; Zheng, J.; Zhou, J. Study on the Inhibition Effect of Fly Ash on Alkali–Silica Reaction and Its Influence on Building Energy Performance. *Buildings* **2025**, *15*, 392. [CrossRef]
7. Stanton, T.E. Expansion of concrete through reaction between cement and aggregate. *Trans. Am. Soc. Civ. Eng.* **1942**, *107*, 54–84. [CrossRef]
8. Abd-Elssamd, A.; Ma, Z.J. *Alkali Silica Reactivity (ASR) Risk Assessment and Mitigation in Tennessee*; Tennessee Department of Transportation: Nashville, TN, USA, 2021.
9. Alsaif, A. Utilization of ceramic waste as partially cement substitute—A review. *Constr. Build. Mater.* **2021**, *300*, 124009. [CrossRef]
10. Rajabipour, F.; Giannini, E.; Dunant, C.; Ideker, J.H.; Thomas, M.D. Alkali–silica reaction: Current understanding of the reaction mechanisms and the knowledge gaps. *Cem. Concr. Res.* **2015**, *76*, 130–146. [CrossRef]
11. Olajide, O.D.; Nokken, M.R.; Sanchez, L.F. Alkali–Silica Reactions: Literature Review on the Influence of Moisture and Temperature and the Knowledge Gap. *Materials* **2023**, *17*, 10. [CrossRef]
12. Fanijo, E.O.; Kolawole, J.T.; Almakrab, A. Alkali-silica reaction (ASR) in concrete structures: Mechanisms, effects and evaluation test methods adopted in the United States. *Case Stud. Constr. Mater.* **2021**, *15*, e00563. [CrossRef]
13. Mosaberpanah, M.A.; Umar, S. Utilizing rice husk ash as supplement to cementitious materials on performance of ultra high performance concrete:—A review. *Mater. Today Sustain.* **2020**, *7*, 100030. [CrossRef]
14. Mahmoud, A.A.; El-Sayed, A.A.; Aboraya, A.M.; Fathy, I.N.; Abouelnour, M.A.; Tayeh, B.A.; Nabil, I.M. Investigating the effects of granite, marble, granodiorite, and ceramic waste powders on the physical, mechanical, and radiation shielding performance of sustainable concrete. *Ann. Nucl. Energy* **2025**, *216*, 111274. [CrossRef]
15. Althoey, F.; Ansari, W.S.; Sufian, M.; Deifalla, A.F. Advancements in low-carbon concrete as a construction material for the sustainable built environment. *Dev. Built Environ.* **2023**, *16*, 100284. [CrossRef]
16. *ASTM C1260*; Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method). Annual Book of ASTM Standards. ASTM International: West Conshohocken, PA, USA, 2023. [CrossRef]
17. *ASTM C1293*; Standard Test Method for Determination of Length Change of Concrete Due to Alkali–Silica Reaction. Annual Book of ASTM Standards. ASTM International: West Conshohocken, PA, USA, 2020. [CrossRef]
18. *ASTM C1567*; Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method). Annual Book of ASTM Standards, Volume 04.02, Concrete and Aggregates. ASTM International: West Conshohocken, PA, USA, 2022. [CrossRef]
19. Mindess, S. *Developments in the Formulation and Reinforcement of Concrete*; Woodhead Publishing: Sawston, UK, 2019.
20. *ASTM C1778*; Standard Guide for Reducing the Risk of Deleterious Alkali–Aggregate Reaction in Concrete. Annual Book of ASTM Standards, Volume 04.02. ASTM International: West Conshohocken, PA, USA, 2022. [CrossRef]
21. *ASTM C295*; Standard Guide for Petrographic Examination of Aggregates for Concrete. Annual Book of ASTM Standards. ASTM International: West Conshohocken, PA, USA, 2019. [CrossRef]

22. Thomas, M.D.; Fournier, B.; Folliard, K.J. *Report on Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction*; Federal Highway Administration: Washington, DC, USA, 2008.
23. Antolik, A.; Dąbrowski, M.; Jóźwiak-Niedźwiedzka, D. Petrographic Evaluation of Aggregate from Igneous Rocks: Alkali–Silica Reaction Potential. *Minerals* **2023**, *13*, 1004. [CrossRef]
24. Federal Highway Administration. *Alkali-Aggregate Reactivity (AAR) Workshops for Engineers and Practitioners Reference Manual*; Federal Highway Administration: Washington, DC, USA, 2013.
25. Jozwiak-Niedzwiedzka, D.; Jaskulski, R.; Glinicki, M.A. Application of Image Analysis to Identify Quartz Grains in Heavy Aggregates Susceptible to ASR in Radiation Shielding Concrete. *Materials* **2016**, *9*, 224. [CrossRef]
26. Mishra, D.; Emad, K.; Shahjalal, C.; Ebenezer, F. *Implementing AASHTO TP 110 for Alkali-Silica Reaction Potential Evaluation of Idaho Aggregates*; Idaho Transportation Department: Boise, ID, USA, 2020.
27. *ASTM C289*; Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates (Chemical Method). ASTM International: West Conshohocken, PA, USA, 2007. [CrossRef]
28. Munir, M.J.; Abbas, S.; Qazi, A.U.; Nehdi, M.L.; Kazmi, S.M.S. Role of test method in detection of alkali–silica reactivity of concrete aggregates. *Proc. Inst. Civ. Eng. Constr. Mater.* **2018**, *171*, 203–221. [CrossRef]
29. Muñoz, J.F.; Balachandran, C.; Arnold, T.S. New chemical reactivity index to assess alkali–silica reactivity. *J. Mater. Civ. Eng.* **2021**, *33*, 04021037. [CrossRef]
30. Kawabata, Y.; Dunant, C.; Yamada, K.; Scrivener, K. Impact of temperature on expansive behavior of concrete with a highly reactive andesite due to the alkali–silica reaction. *Cem. Concr. Res.* **2019**, *125*, 105888. [CrossRef]
31. Rao, B.; Dai, H.; Gao, L.; Xie, H.; Gao, G.; Peng, K.; Zhang, M.; He, F.; Pan, Y. Surprisingly highly reactive silica that dissolves rapidly in dilute alkali (NaOH) solution even at ambient temperatures (25 °C). *J. Clean. Prod.* **2022**, *341*, 130779. [CrossRef]
32. Thomas, M.D.; Fournier, B.; Folliard, K.J.; Ideker, J.H.; Resendez, Y. *The Use of Lithium to Prevent or Mitigate Alkali-Silica Reaction in Concrete Pavements and Structures*; Turner-Fairbank Highway Research Center: McLean, VA, USA, 2007.
33. Mohammadi, A.; Ghiasvand, E.; Nili, M. Relation between mechanical properties of concrete and alkali-silica reaction (ASR); a review. *Constr. Build. Mater.* **2020**, *258*, 119567. [CrossRef]
34. Pan, J.; Feng, Y.T.; Wang, J.T.; Sun, Q.C.; Zhang, C.H.; Owen, D.R.J. Modeling of alkali-silica reaction in concrete: A review. *Front. Struct. Civ. Eng.* **2012**, *6*, 1–18. [CrossRef]
35. Maraghechi, H.; Rajabipour, F.; Pantano, C.G.; Burgos, W.D. Effect of calcium on dissolution and precipitation reactions of amorphous silica at high alkalinity. *Cem. Concr. Res.* **2016**, *87*, 1–13. [CrossRef]
36. Doğruyol, M. Determination of ASR in concrete using characterization methods. *Buildings* **2024**, *14*, 657. [CrossRef]
37. Vayghan, A.G.; Rajabipour, F.F.; Arndt, C. The influence of ASR gels composition on their swelling properties. In Proceedings of the 15th International Conference on Alkali-Aggregate Reaction, Sao Paulo, Brazil, 3–7 July 2016.
38. Lei, J.; Law, W.W.; Yang, E.-H. Effect of calcium hydroxide on the alkali-silica reaction of alkali-activated slag mortars activated by sodium hydroxide. *Constr. Build. Mater.* **2021**, *272*, 121868. [CrossRef]
39. Lindgård, J.; Andiç-Çakır, Ö.; Fernandes, I.; Rønning, T.F.; Thomas, M.D.A. Alkali–silica reactions (ASR): Literature review on parameters influencing laboratory performance testing. *Cem. Concr. Res.* **2012**, *42*, 223–243. [CrossRef]
40. Cao, J.; Gowripalan, N.; Sirivivatnanon, V.; South, W. Accelerated test for assessing the potential risk of alkali-silica reaction in concrete using an autoclave. *Constr. Build. Mater.* **2021**, *271*, 121871. [CrossRef]
41. Wu, W.; Kang, S.; Gong, Q.; Yao, H.; Zhang, K.; Yang, H.; Li, H.; Wang, D. Influences of aggregate gradation on alkali-silica reaction of seawater and sea sand concrete. *Constr. Build. Mater.* **2024**, *427*, 136268. [CrossRef]
42. *ASTM C157*; Standard Test Method for Length Change of Hardened Hydraulic Cement Mortar and Concrete. Annual Book of ASTM Standards. ASTM International: West Conshohocken, PA, USA, 2017. [CrossRef]
43. De Souza, D.J.; Sanchez, L.F. Evaluating the efficiency of SCMs to avoid or mitigate ASR-induced expansion and deterioration through a multi-level assessment. *Cem. Concr. Res.* **2023**, *173*, 107262. [CrossRef]
44. Thomas, M.; Fournier, B.; Folliard, K.; Ideker, J.; Shehata, M. Test methods for evaluating preventive measures for controlling expansion due to alkali–silica reaction in concrete. *Cem. Concr. Res.* **2006**, *36*, 1842–1856. [CrossRef]
45. Ideker, J.H.; East, B.L.; Folliard, K.J.; Thomas, M.D.; Fournier, B. The current state of the accelerated concrete prism test. *Cem. Concr. Res.* **2010**, *40*, 550–555. [CrossRef]
46. Wang, W.; Noguchi, T. Alkali-silica reaction (ASR) in the alkali-activated cement (AAC) system: A state-of-the-art review. *Constr. Build. Mater.* **2020**, *252*, 119105. [CrossRef]
47. Drimalas, T.; Folliard, K.J.; Parashar, A.; Thomas, M.D.A.; Ghanizadeh, A.; Hossack, A.M.; Fournier, B. *Alkali-Silica Reactivity Potential and Mitigation: Test Methods and State of Practice*; The National Academies Press: Washington, DC, USA, 2023.
48. Bergmann, A.; Sanchez, L.F. Assessing the reliability of laboratory test procedures for predicting concrete field performance against alkali-aggregate reaction (AAR). *CEMENT* **2025**, *19*, 100133. [CrossRef]

49. Golmakani, F.; Hooton, R.D. Impact of pore solution concentration on the accelerated mortar bar alkali-silica reactivity test. *Cem. Concr. Res.* **2019**, *121*, 72–80. [CrossRef]
50. *AASHTO T303*; Standard Method of Test for Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to Alkali-Silica Reaction. American Association of State Highway and Transportation Officials (AASHTO): Washington, DC, USA, 2022.
51. Drimalas, T.; Ideker, J.; Arrietta, G.; Folliard, K.J.; Fournier, B.; Thomas, M. Evaluating combination of aggregates in the accelerated mortar bar test. In Proceedings of the 14th International Conference on Alkali-Aggregate Reactivity in Concrete, Austin, TX, USA, 20–25 May 2012.
52. Mukhopadhyay, A.K.; Liu, K.-W. *ASR Testing: A New Approach to Aggregate Classification and Mix Design Verification: Technical Report*; Department of Transportation Research and Technology Implementation Office: Austin, TX, USA, 2014.
53. Latifee, E.R.; Rangaraju, P.R. Miniature concrete prism test: Rapid test method for evaluating alkali-silica reactivity of aggregates. *J. Mater. Civ. Eng.* **2015**, *27*, 04014215. [CrossRef]
54. *AASHTO T380*; Standard Method of Test for Potential Alkali Reactivity of Aggregates and Effectiveness of ASR Mitigation Measures (Miniature Concrete Prism Test, MCPT). American Association of State Highway and Transportation Officials (AASHTO): Washington, DC, USA, 2012.
55. Konduru, H.; Rangaraju, P.; Amer, O. Reliability of miniature concrete prism test in assessing alkali-silica reactivity of moderately reactive aggregates. *Transp. Res. Rec.* **2020**, *2674*, 23–29. [CrossRef]
56. Tanesi, J.; Drimalas, T.; Chopperla, K.S.T.; Beyene, M.; Ideker, J.H.; Kim, H.; Montanari, L.; Ardani, A. Divergence between performance in the field and laboratory test results for alkali-silica reaction. *Transp. Res. Rec.* **2020**, *2674*, 120–134. [CrossRef]
57. Ranger, M.; Hasholt, M.T.; Lindgård, J.; Barbosa, R.A. Laboratory and field investigations of alkali-silica reaction prevention by supplementary cementitious materials: Influence of the free alkali loading. *Constr. Build. Mater.* **2024**, *442*, 137599. [CrossRef]
58. Ideker, J.H.; Bentivegna, A.F.; Folliard, K.J.; Juenger, M.C.G. Do current laboratory test methods accurately predict alkali-silica reactivity? *ACI Mater. J.* **2012**, *109*, 395–402.
59. Nguyen, T.N.; Sanchez, L.F.; Li, J.; Fournier, B.; Sirivivatnanon, V. Correlating alkali-silica reaction (ASR) induced expansion from short-term laboratory testings to long-term field performance: A semi-empirical model. *Cem. Concr. Compos.* **2022**, *134*, 104817. [CrossRef]
60. Lindgård, J.; Thomas, M.D.A.; Sellevold, E.J.; Pedersen, B.; Andiç-Çakır, Ö.; Justnes, H.; Rønning, T.F. Alkali–silica reaction (ASR)—Performance testing: Influence of specimen pre-treatment, exposure conditions and prism size on alkali leaching and prism expansion. *Cem. Concr. Res.* **2013**, *53*, 68–90. [CrossRef]
61. Plusquellec, G.; Geiker, M.; Lindgård, J.; De Weerdt, K. Determining the free alkali metal content in concrete–Case study of an ASR-affected dam. *Cem. Concr. Res.* **2018**, *105*, 111–125. [CrossRef]
62. Lindgård, J.; Østnor, T.; Fournier, B.; Lindgård, Ø.; Danner, T.; Plusquellec, G.; De Weerdt, K. Determining alkali leaching during accelerated ASR performance testing and in field exposed cubes using cold water extraction (CWE) and μXRF. *MATEC Web Conf.* **2018**, *199*, 03004. [CrossRef]
63. Rangaraju, P.; Afshinnia, K.; Enugula, S.S.R.; Latifee, E.R. Evaluation of alkali-silica reaction potential of marginal aggregates using miniature concrete prism test (MCPT). In Proceedings of the 15th International Conference on Alkali-Reaction in Concrete, Sao Paulo, Brazil, 3–7 July 2016.
64. Fanijo, E.O.; Chowdhury, S.; Kassem, E.; Mishra, D. Evaluating Alkali-Silica Reactivity of Aggregates Using the New Miniature Concrete Prism Test and Other Standard Test Methods. *J. Mater. Civ. Eng.* **2022**, *34*, 04022163. [CrossRef]
65. Kasaniya, M.; Thomas, M.D. Role of the alkalis of supplementary cementing materials in controlling pore solution chemistry and alkali-silica reaction. *Cem. Concr. Res.* **2022**, *162*, 107007. [CrossRef]
66. Shehata, M.H.; Thomas, M.D. The role of alkali content of Portland cement on the expansion of concrete prisms containing reactive aggregates and supplementary cementing materials. *Cem. Concr. Res.* **2010**, *40*, 569–574. [CrossRef]
67. Wei, S.; Zheng, K.; Zhou, J.; Prateek, G.; Yuan, Q. The combined effect of alkalis and aluminum in pore solution on alkali-silica reaction. *Cem. Concr. Res.* **2022**, *154*, 106723. [CrossRef]
68. Kian, A. *Alkali-Silica Reactivity of Mortars Containing Natural Pozzolan*; University of Nevada: Las Vegas, NV, USA, 2019.
69. Shehata, M.H.; Thomas, M.D. Alkali release characteristics of blended cements. *Cem. Concr. Res.* **2006**, *36*, 1166–1175. [CrossRef]
70. Al-Jabari, M.; Al-Rashed, R.; Ayers, M.E. Mitigation of alkali silica reactions in concrete using multi-crystalline intermixed waterproofing materials. *Cement* **2023**, *12*, 100065. [CrossRef]
71. Tapas, M.J.; Sofia, L.; Vessalas, K.; Thomas, P.; Sirivivatnanon, V.; Scrivener, K. Efficacy of SCMs to mitigate ASR in systems with higher alkali contents assessed by pore solution method. *Cem. Concr. Res.* **2021**, *142*, 106353. [CrossRef]
72. Saha, A.K.; Khan, M.; Sarker, P.K.; Shaikh, F.A.; Pramanik, A. The ASR mechanism of reactive aggregates in concrete and its mitigation by fly ash: A critical review. *Constr. Build. Mater.* **2018**, *171*, 743–758. [CrossRef]
73. Skibsted, J.; Snellings, R. Reactivity of supplementary cementitious materials (SCMs) in cement blends. *Cem. Concr. Res.* **2019**, *124*, 105799. [CrossRef]

74. Math, S.; Wingard, D.; Rangaraju, P.R. Assessing potential reactivity of aggregates in presence of potassium acetate deicer: Revised mortar bar test method. *Transp. Res. Rec.* **2011**, *2232*, 10–24. [CrossRef]
75. Thomas, M.D.; Fournier, B.; Folliard, K.J. *Alkali-Aggregate Reactivity (AAR) Facts Book*; Federal Highway Administration Office of Pavement Technology: Washington, DC, USA, 2013.
76. Alaejos, P.; Lanza, V.; Bermúdez, M.; Velasco, A. Effectiveness of the accelerated mortar bar test to detect rapid reactive aggregates (including their pessimum content) and slowly reactive aggregates. *Cem. Concr. Res.* **2014**, *58*, 13–19. [CrossRef]
77. *CRD C662*; Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials, Lithium Nitrate Admixture and Aggregate (Accelerated Mortar-Bar Method). U.S. Army Corps of Engineers: Washington, DC, USA, 2010.
78. Coutinho, Y.; Montefalco, L.; Carneiro, A. Influence of aggregate crushing on the results of accelerated alkali-silica reactivity tests. *Constr. Build. Mater.* **2022**, *325*, 126737. [CrossRef]
79. Thomas, M.D.; Fournier, B.; Folliard, K.J.; Shehata, M.H.; Ideker, J.H.; Rogers, C. Performance limits for evaluating supplementary cementing materials using accelerated mortar bar test. *ACI Mater. J.* **2007**, *104*, 115.
80. Sirivivatnanon, V.; Thomas, P.; Tapas, M.J.; Nguyen, T.N. Reliability of AMBT and CPT in testing the effectiveness of SCM to mitigate alkali–silica reaction of field concrete. *Constr. Build. Mater.* **2023**, *369*, 130510. [CrossRef]
81. Lu, D.; Fournier, B.; Grattan-Bellew, P. Evaluation of accelerated test methods for determining alkali-silica reactivity of concrete aggregates. *Cem. Concr. Compos.* **2006**, *28*, 546–554. [CrossRef]
82. Lenke, L.R.; Malvar, L.J. Alkali silica reaction criteria for accelerated mortar bar tests based on field performance data. In Proceedings of the 2009 World of Coal Ash (WOCA) Conference, Lexington, KY, USA, 4–7 May 2009.
83. Joshua Tapas, M.; Thomas, P.; Vessalas, K.; Sirivivatnanon, V. Mechanisms of alkali-silica reaction mitigation in AMBT conditions: Comparative study of traditional supplementary cementitious materials. *J. Mater. Civ. Eng.* **2022**, *34*, 04021460. [CrossRef]
84. Islam, M.S. Comparison of ASR mitigation methodologies. *Int. J. Concr. Struct. Mater.* **2014**, *8*, 315–326. [CrossRef]
85. Arrieta Martinez, G. Experimental Studies of the Behavior of Pessimum Aggregates in Different Test Procedures Used to Evaluate the Alkali Reactivity of Aggregates in Concrete. Master's Thesis, The University of Texas at Austin, Austin, TX, USA, 2012. Available online: http://hdl.handle.net/2152/ETD-UT-2012-05-5463 (accessed on 19 May 2025).
86. Fournier, B.; Rogers, C.; MacDonald, C.-A. Multilaboratory study of the concrete prism and accelerated mortar bar expansion tests with Spratt aggregate. In Proceedings of the 14th International Conference on Alkali Aggregate Reaction, Austin, TX, USA, 20–25 May 2012.
87. *AS 1141.60.1*; Methods for Sampling and Testing Aggregates Method 60.1: Potential Alkali-Silica Reactivity-Accelerated Mortar Bar Method. Standards Australia Limited: Sydney, Australia, 2014.
88. Bavasso, I.; Costa, U.; Mangialardi, T.; Paolini, A.E. Assessment of alkali–silica reactivity of aggregates by concrete expansion tests in alkaline solutions at 38 °C. *Materials* **2020**, *13*, 288. [CrossRef]
89. des Laboratoires d'Essais, R.I. *RILEM Recommendations for the Prevention of Damage by Alkali-Aggregate Reactions in New Concrete Structures: State-of-the-Art Report of the RILEM Technical Committee 219-ACS*; Springer: Berlin/Heidelberg, Germany, 2016.
90. Golmakani, F.; Hooton, R. Comparison of laboratory performance tests used to assess alkali-silica reactivity. In *Resilient Infrastructure*; Curran Associates Inc.: Red Hook, NY, USA, 2016; pp. 1167–1173.
91. Gautam, B.P.; Panesar, D.K. The effect of elevated conditioning temperature on the ASR expansion, cracking and properties of reactive Spratt aggregate concrete. *Constr. Build. Mater.* **2017**, *140*, 310–320. [CrossRef]
92. Folliard, K.J.; Ideker, J.H.; Thomas, M.D.A.; Fournier, B. Assessing aggregate reactivity using the accelerated concrete prism tests. In *Aggregates: Asphalt Concrete, Portland Cement Concrete, Bases, and Fines*; Twelfth Annual Symposium International Center for Aggregates Research (ICAR); University of Texas at Austin; Texas A&M University System; Aggregates Foundation for Technology, Research & Education (AFTRE); National Stone, Sand & Gravel Association (NSSGA); Florida Rock Industries: Austin, TX, USA, 2004.
93. Liu, Z.; Milla, J.; Saunders, W. *Evaluation of the Miniature Concrete Prism Test (MCPT) for Use in LADOTD*; Final Report No. FHWA/LA.24/700; Louisiana Transportation Research Center (LTRC): Baton Rouge, LA, USA, 2024.
94. *AASHTO R80*; Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction. American Association of State Highway and Transportation Officials (AASHTO): Washington, DC, USA, 2017.
95. Ideker, J.H.; Drimalas, T.; Folliard, K.J.; Ghanizadeh, A.; Parashar, A.; Chopperla, K.S.T.; Snyder, A.; Thomas, M.D.A. Preventing Alkali-Silica Reaction in Concrete. *CE/Papers* **2023**, *6*, 1101–1109. [CrossRef]
96. Kim, T.; Olek, J. Influence of alkali silica reaction on the chemistry of pore solutions in mortars with and without lithium ions. In *Brittle Matrix Composites 10*; Elsevier: Amsterdam, The Netherlands, 2012; pp. 11–20.
97. Li, X.; Snellings, R.; Antoni, M.; Alderete, N.M.; Ben Haha, M.; Bishnoi, S.; Cizer, Ö.; Cyr, M.; De Weerdt, K.; Dhandapani, Y.; et al. Reactivity tests for supplementary cementitious materials: RILEM TC 267-TRM phase 1. *Mater. Struct.* **2018**, *51*, 151. [CrossRef]
98. *ASTM C1897*; Standard Test Methods for Measuring the Reactivity of Supplementary Cementitious Materials by Isothermal Calorimetry and Bound Water Measurements. ASTM International: West Conshohocken, PA, USA, 2020. [CrossRef]

99. Ramanathan, S.; Croly, M.; Suraneni, P. Comparison of the effects that supplementary cementitious materials replacement levels have on cementitious paste properties. *Cem. Concr. Compos.* **2020**, *112*, 103678. [CrossRef]
100. Suraneni, P. Recent developments in reactivity testing of supplementary cementitious materials. *RILEM Tech. Lett.* **2021**, *6*, 131–139. [CrossRef]
101. Sivakumar, P.P.; Matthys, S.; De Belie, N.; Gruyaert, E. Reactivity assessment of modified ferro silicate slag by R3 method. *Appl. Sci.* **2021**, *11*, 366. [CrossRef]
102. *ASTM C618*; Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. ASTM International: West Conshohocken, PA, USA, 2022. [CrossRef]
103. Al-Shmaisani, S. Assessing Supplementary Cementitious Materials for Use in Concrete: Long-Term and Rapid Testing. Ph.D. Dissertation, The University of Texas at Austin, Austin, TX, USA, 2020. [CrossRef]
104. Suraneni, P.; Hajibabaee, A.; Ramanathan, S.; Wang, Y.; Weiss, J. New insights from reactivity testing of supplementary cementitious materials. *Cem. Concr. Compos.* **2019**, *103*, 331–338. [CrossRef]
105. Wang, Y.; Ramanathan, S.; Chopperla, K.S.T.; Ideker, J.H.; Suraneni, P. Estimation of non-traditional supplementary cementitious materials potential to prevent alkali-silica reaction using pozzolanic reactivity and bulk resistivity. *Cem. Concr. Compos.* **2022**, *133*, 104723. [CrossRef]
106. Min, Y.; Kabir, H.; Kothari, C.; Iqbal, M.F.; Garg, N. UR2: Ultra-rapid reactivity test for real-time, low-cost quality control of calcined clays. *Cem. Concr. Res.* **2025**, *191*, 107806. [CrossRef]
107. Araújo, L.B.; Targino, D.L.L.; Babadopulos, L.F.A.L.; Fabbri, A.; Cabral, A.E.B.; Chehade, R.; Costa, H.N. Impact of Curing Temperature and Steel Slag Aggregates on High-Strength Self-Compacting Alkali-Activated Concrete. *Buildings* **2025**, *15*, 457. [CrossRef]
108. Ramezani, A.M.; Khajehdezfuly, A.; Poorveis, D. Structural Lightweight Concrete Containing Basalt Stone Powder. *Buildings* **2024**, *14*, 1904. [CrossRef]
109. Azarsa, P.; Gupta, R. Electrical resistivity of concrete for durability evaluation: A review. *Adv. Mater. Sci. Eng.* **2017**, *2017*, 8453095. [CrossRef]
110. Chopperla, K.S.T.; Drimalas, T.; Beyene, M.; Tanesi, J.; Folliard, K.; Ardani, A.; Ideker, J.H. Combining reliable performance testing and binder properties to determine preventive measures for alkali-silica reaction. *Cem. Concr. Res.* **2022**, *151*, 106641. [CrossRef]
111. Chopperla, K.S.T.; Ideker, J.H. Using electrical resistivity to determine the efficiency of supplementary cementitious materials to prevent alkali-silica reaction in concrete. *Cem. Concr. Compos.* **2022**, *125*, 104282. [CrossRef]
112. Ghiasvand, E.; Mohammadi, H.; Rezaei, Z.; Ayyoubi, M.; Dehghani, S. Evaluation of the durability of concretes containing alkali-activated slag exposed to the alkali-silica reaction by measuring electrical resistivity. *Constr. Build. Mater.* **2023**, *367*, 130094. [CrossRef]
113. Khajehnouri, Y.; Rivard, P.; Chouteau, M.; Bérubé, C.L. Validation of complex electrical properties of concrete affected by accelerated alkali-silica reaction. *Cem. Concr. Compos.* **2020**, *113*, 103660. [CrossRef]
114. Chopperla, K.S.T.; Smith, J.A.; Ideker, J.H. The efficacy of portland-limestone cements with supplementary cementitious materials to prevent alkali-silica reaction. *Cement* **2022**, *8*, 100031. [CrossRef]
115. Nguyen, Q.D.; Kim, T.; Castel, A. Mitigation of alkali-silica reaction by limestone calcined clay cement (LC3). *Cem. Concr. Res.* **2020**, *137*, 106176. [CrossRef]
116. Ramezanianpour, A.A. *Cement Replacement Materials*; Springer Geochemistry/Mineralogy; Springer: Berlin/Heidelberg, Germany, 2014; Volume 10, pp. 978–983.
117. Tagnit-Hamou, A.; Petrov, N.; Luke, K. Properties of concrete containing diatomaceous earth. *ACI Mater. J.* **2003**, *100*, 73–78.
118. Wallace, A.R.; Frank, D.G.; Founie, A. *Freshwater Diatomite Deposits in the Western United States*; U.S. Geological Survey Fact Sheet 2006–3044, Version 1.0; U.S. Geological Survey: Reston, VA, USA, 2006. [CrossRef]
119. Zhang, Y.; Xu, X.; Zhao, Q.; Chang, J.; Ding, S.; Liu, X.; Poon, C.S. Long-term investigation of alkali-silica reaction behaviors in seawater sea-sand concrete. *Cem. Concr. Compos.* **2024**, *151*, 105611. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.