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Alkali-Silica Reaction (ASR) Mitigation in High-Alkali Content Cements

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This study presents a comprehensive evaluation of alkali-silica reaction (ASR) in concrete mixtures, focusing on the performance-based specifications and the critical role of supplementary cementitious materials (SCMs) in mitigation. A modified version of American Association of State Highway and Transportation Officials (AASHTO) T380 was developed to assess ASR susceptibility in job-specific mixtures. A moderately reactive aggregate, i.e., R1 aggregate reactivity class per ASTM C1778, was used, as this is representative of reactive aggregates in Virginia. Concrete prisms were prepared using actual project mix designs, immersed in alkaline host solutions matched to expected pore solution chemistry, and monitored for expansion over 84 days. The results demonstrated that increased cement content—and thus higher alkali loading—consistently led to greater expansion, whereas plain concretes without SCMs remained vulnerable to ASR regardless of cement alkali content or total alkali loading. These findings highlight that prescriptive specification restricting alkali content of cement or total alkali loading, as several state departments of transportation have historically practiced, is not a reliable standalone strategy. Indeed, infrastructure performance revealed that low-alkali cements and alkali loading limits alone do not prevent ASR when reactive aggregates are present. However, for simplicity, prescriptive specifications with appropriate safety factors can be considered. The proposed modified AASHTO T380 method also provides a more realistic framework for determining SCM dosages. By calibrating SCM levels against specific alkali loadings and aggregate reactivity in job mixtures, this approach supports a performance-based framework for ASR mitigation. SCMs such as fly ash, slag, and silica fume were confirmed to be highly effective in mitigating ASR when applied in sufficient dosages. However, their effectiveness is mix-specific, depending on alkali loading, aggregate reactivity, and SCM type. The results also indicate that cements with higher alkali contents can be used safely when appropriate SCM dosages are incorporated, providing greater flexibility and sustainability in mix design.

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FINAL REPORT

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Virginia Transportation Research Council
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ABSTRACT

This study presents a comprehensive evaluation of alkali-silica reaction (ASR) in concrete mixtures, focusing on the performance-based specifications and the critical role of supplementary cementitious materials (SCMs) in mitigation. A modified version of American Association of State Highway and Transportation Officials (AASHTO) T380 was developed to assess ASR susceptibility in job-specific mixtures. A moderately reactive aggregate—R1 aggregate reactivity class per ASTM C1778—was used because it is representative of reactive aggregates in Virginia. Concrete prisms were prepared using actual project mix designs, immersed in alkaline host solutions matched to expected pore solution chemistry, and monitored for expansion for 84 days. The results demonstrated that increased cement content—and thus higher alkali loading—consistently led to greater expansion, whereas plain concretes without SCMs remained vulnerable to ASR regardless of cement alkali content or total alkali loading. These findings highlight that prescriptive specifications restricting alkali content of cement or total alkali loading, as several state departments of transportation have historically practiced, is not a reliable standalone strategy. Indeed, infrastructure performance revealed that low-alkali cements and alkali loading limits alone do not prevent ASR when reactive aggregates are present. However, for simplicity, prescriptive specifications with appropriate safety factors can be considered. The proposed modified AASHTO T380 method also provides a more realistic framework for determining SCM dosages. By calibrating SCM levels against specific alkali loadings and aggregate reactivity in job mixtures, this approach supports a performance-based framework for ASR mitigation. SCMs, such as fly ash, slag, and silica fume, were confirmed to be highly effective in mitigating ASR when applied in sufficient dosages. However, their effectiveness is mix specific, depending on alkali loading, aggregate reactivity, and SCM type. The results also indicate that cements with higher alkali contents can be used safely when appropriate SCM dosages are incorporated, providing greater flexibility and sustainability in mix design.

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INTRODUCTION

The alkali-silica reaction (ASR) has emerged as a significant durability concern on a global scale because of the widespread deterioration seen in concrete infrastructure, including bridges, pavements, barriers, walls, dams, and power plant facilities (Rajabipour et al., 2015; Shi and Lothenbach, 2022). The ASR deterioration begins with the dissolution of reactive silica existing in the aggregate at high pH due to the presence of alkalis in the concrete pore solution, resulting in the creation of alkali-silica gels (Rajabipour et al., 2015; Shi and Lothenbach, 2022). Some ASR gels have a high water absorption and consequently a high swelling capability, which can cause concrete cracking, spalling, pop-outs, and overall durability reduction and result in significant maintenance and reconstruction costs to concrete infrastructure (Brouard, 2012; Muñoz et al., 2021a; Shi and Lothenbach, 2022). Shortly after ASR was discovered in the 1940s, the use of supplementary cementitious materials (SCMs) and chemical admixtures like lithium salts to limit ASR expansion was proposed (Shi and Lothenbach, 2022).

Although using non-reactive aggregates is the safer alternative for avoiding the formation of ASR, it is not always feasible or practical (Hossain et al., 2016; Muñoz et al., 2021a). For instance, the use of siliceous aggregates is required in concretes exposed to traffic to provide skid resistance. On the other hand, slowing down ASR damage in existing structures is difficult and expensive and may require measures such as waterproofing with coatings, slot cutting to release stresses, or applying a compressive force to counter the ASR gel expansion (Shi and Lothenbach, 2022). Any remediation method used in existing structures only buys time until the damaged element is fully replaced, suggesting that implementing mitigation measures in new construction is more practical and cost efficient. Accordingly, it is essential to implement effective ASR mitigation strategies and incorporate them into specifications to enable using aggregates containing reactive silica in concrete without concern for ASR (Muñoz et al., 2021a; Shi and Lothenbach, 2022).

The stages and mechanisms through which ASR expansion occurs are not yet fully understood (Shi et al., 2020). Notwithstanding, different ways to potentially mitigate and stop ASR have been recommended. The most practical approach to prevent ASR in new construction is to implement SCMs in concrete mixtures (Thomas, 2011). The quantity of SCMs required to mitigate ASR is primarily determined by: (1) the SCM's composition, particularly its calcium oxide, silicon dioxide, aluminum oxide, and equivalent sodium oxide (Na_2O_{eq}) content; (2) the aggregate reactivity, dictated by its composition and structure; and (3) the alkali loading in the concrete—provided primarily by the cement, yet other sources such as aggregates, SCMs, chemical admixtures, and external sources do also contribute (Thomas et al., 2006).

Many state departments of transportation (DOTs) have made significant efforts to develop specifications that limit the alkali content of the cement because the main alkalis participating in ASR are sodium and potassium, which are primarily supplied by the cement. The alkali content of the cement has been limited based on the percentage of sodium oxide equivalent ($\%Na_2O_{eq} = \%Na_2O + 0.658 \times \%K_2O$) by weight. Unfortunately, restricting the alkali content in the cement specifications has unwanted consequences, such as increasing the final product cost. Reducing alkali content during production is costly. In practice, because of environmental and sustainability concerns, cements with higher amounts of alkali content are produced, and it can be expensive to ship cement from another region to replace a local cement with an alkali content that is higher than the threshold value specified. Moreover, it has been shown that the alkali loading in the concrete—that is, the total amount of equivalent alkalis in the concrete mixture in lb/yd^3 (obtained by multiplying the $\%Na_2O_{eq}$ of the cement by the cement content of the mixture)—has a considerable effect on the threshold of alkali content of the cement required to initiate ASR expansion (Thomas et al., 2006). This reaction means that concrete made with a large quantity of low-alkali cement could still have enough alkalis to initiate ASR. In both ASTM and Canadian A23.1-14/A23.2-14 standards, when the potential for ASR exists, the accepted allowable alkali loading of concrete has been limited to the range between 3.0 and 5.0 lb/yd^3 (1.8–3.0 kg/m^3), based on the aggregate reactivity, size of the concrete element, and environmental conditions (ASTM International, 2024; CSA Group, 2004). Moreover, some SCMs (e.g., ground glass and Class F coal ash) can have higher alkali content compared with the cement, which may increase the total alkali loading of the concrete and raise concerns about their effectiveness to mitigate ASR (Schlorholtz, 2015). The previous statements demonstrate that it is more appropriate to consider the alkali loading in the concrete mixture instead of the alkali content of the cement when ASR is a concern.

As Section 217.02 of the 2020 Virginia Road and Bridge Specifications outlines, current Virginia Department of Transportation (VDOT) requirements limit the alkali content of cement to a maximum of 1% Na_2O_{eq} and recommend different minimum dosages of SCMs for ASR mitigation, depending on the cement's alkali content. However, as noted previously, for a given aggregate reactivity, it is the alkali loading of concrete that controls ASR, instead of the alkali content of cement. Accordingly, the 1% Na_2O_{eq} limit may not be sufficient to mitigate ASR in cases in which exceedingly high cementitious contents are utilized. In addition, VDOT has received a request for approval of a local cement with alkali content exceeding 1%. Accordingly, a new specification approach is needed that recognizes the role of alkali loading of concrete, instead of the alkali content of cement, on ASR, thus allowing for the use of cements with alkali contents above 1% Na_2O_{eq} while effectively mitigating ASR. As an alternative to the prescriptive cement alkali content limit of 1% Na_2O_{eq}, VDOT specifications also provide a performance-based approach for mitigating ASR based on results from ASTM C227. However, the American Society for Testing and Materials (ASTM) has withdrawn ASTM C227 (ASTM International, 2010), and previous work completed by the Virginia Transportation Research Council (VTRC) has shown that it is not an effective test method for evaluating the reactivity of aggregates containing microcrystalline or strained quartz, which are susceptible to ASR (Lane, 1994). Consequently, new standards have been advised to be used for evaluating ASR.

Several active standard test methods exist for assessing alkali-silica reactivity of aggregates or aggregates-cementitious systems combinations (i.e., ASTM C1260 [ASTM International, 2021], ASTM C1567 [ASTM International, 2025], ASTM C1293 [ASTM International, 2023], and American Association of State Highway and Transportation Officials [AASHTO, 2019] T380), all which rely on expansion measurements as an indicator of ASR through length change evaluation. For example, ASTM C1260 and AASHTO T303 require making mortar bars with dimensions of 1 inch × 1 inch × 11.22 inches (25 mm × 25 mm × 285 mm) and then exposing them to a 176°F (80°C) bath of one normal (1N) sodium hydroxide (NaOH) solution (AASHTO, 2022). Periodic length change measurements for 14 days are performed and then, according to ASTM guidance, the reactivity level of the aggregate is ranked from non-reactive to suspicious, and potentially reactive, aggregate. However, this test is very severe and results in an overestimation of the reactivity of some aggregates (Touma et al., 2001). ASTM C1567 determines the potential ASR deterioration of combinations of cementitious materials and aggregate in mortar bars within 16 days. The ASTM C1567 test method is identical to the ASTM C1260 except that the test mixtures are prepared by replacing a portion of the Portland cement with the SCM being evaluated. In both ASTM C1260 and ASTM C1567, the alkali content of the cement has negligible or only minor effects on the test results. ASTM C1293 requires making concrete prisms with dimensions of 3 inches × 3 inches × 11 inches (76.5 mm × 76.5 mm × 279.5 mm) and storing them over water after curing them in a sealed container at 100°F (38°C). However, this test is time consuming and requires 52 weeks (1 year) to complete and takes 2 years if SCMs are used. For this reason, there are some modifications to this test method to accelerate it and get the results within 26 weeks (6 months) and even 13 weeks (3 months), as Touma et al. (2001) discussed. AASHTO T380 is a combination of the two modifications of ASTM C1293, by storing the samples in 1N NaOH solution at 140°F (60°C) and using miniature concrete prisms, measuring 2 inches × 2 inches × 11.2 inches (50 mm × 50 mm × 285 mm), to obtain results in 8 weeks, or 56 days (ASTM International, 2023). Moreover, the alkalinity of the chemical solution bath used to store specimens in AASHTO T380 was designed to match that of the pore solution of the concrete mixture prescribed in the standard. This preparation was done to minimize the alkalis leaching from or into the samples, which alters the alkali loading of the specimens and thus interferes with the test. Table 1 presents a summary of the active standard test methods for ASR.

Table 1. Standard ASR Test Methods

Standard	Purpose	Procedure	Comment
ASTM C1260	Assess aggregate ASR potential in mortar bars, within 16 days.	• Cast mortar bars, then cure for 24 hours. • Immerse in hot water (80°C) for 24 hours, then in 1N NaOH at 80°C. • Measure expansion periodically up to 14 days.	Rapid yet aggressive test; false positives are not uncommon.
ASTM C1567	Assess ASR potential of aggregate-cementitious system combinations (cement + SCMs) in mortar bars, within 16 days.	• Similar to ASTM C1260 but includes SCMs in the mixture. • Evaluate the reduction in expansion compared with the control mixture. • Typically run for 14 days.	Rapid yet aggressive test; false positives are not uncommon. Used to assess mitigation by SCMs.
ASTM C1293	Assess ASR potential of aggregate-cementitious system combinations (cement + SCMs) in concrete prisms, within 1–2 years (2 years if SCMs used).	• Cast concrete prisms with high-alkali cement. • Store at 38°C over water in sealed containers. • Monitor length change for 1–2 years.	Reliable yet lengthy.
AASTHO T380	Assess ASR potential of aggregate-cementitious system combinations (cement + SCMs) in miniature concrete prisms, within 56 days.	• Cast concrete prisms with high-alkali cement. • Store at 60°C in 1N NaOH. • Monitor length change for 56 weeks.	Reliable and relatively rapid.

1N = one normal; ASR = alkali-silica reaction; NaOH = sodium hydroxide; SCMs = supplementary cementitious materials.

From the aforementioned tests, it is important to note that none of them allow for evaluating the actual concrete mixture to be used in a given project (i.e., the job mix). Instead, ASR reactivity is assessed in standardized concrete compositions and exposure environments designed to minimize alkali leaching by matching pore solution chemistry. However, testing the job mix is highly relevant to practitioners, although this procedure would require tailoring the exposure solution to match the pore solution alkalinity of the job mixture. This concept of matching the alkalinity level between the job mix pore solution and the exposure medium has been proposed in other test methods, and the present study examines this approach (Laskey, 2018; Liu and Mukhopadhyay, 2016; Mukhopadhyay and Liu, 2014; Mukhopadhyay et al., 2018).

AASHTO R 80 and ASTM C1778 methods are currently the best available guidelines on how to address the potential for deleterious alkali-aggregate reaction (AAR) (AASHTO, 2021). It is worth mentioning that both ASTM C1778 and AASHTO R 80 are guidelines rather than specifications or standard test methods (ASTM International, 2024). As stated previously, each test method has some drawbacks. Therefore, advising an appropriate test procedure to inhibit ASR in new construction for a performance-based approach is still a challenge. However, adherence to these guidelines provides a conservative approach and is expected to provide satisfactory resistance to ASR.

The abovementioned statements show that Virginia Road and Bridge Specifications need to be updated to address ASR in VDOT structures and pavements.

PURPOSE AND SCOPE

The purpose of this study is to update ASR provisions in the Virginia Road and Bridge Specifications to align them more closely with current practices and test procedures. The revised provisions should consider the alkali loading of concrete (instead of the alkali content of cement) and incorporate a current, acceptable ASR evaluation test method (instead of a withdrawn standard). This approach will foster the production of concrete using readily available resources in Virginia and mitigate ASR in concrete structures. In turn, this mitigation will promote the use of practical and cost-effective concrete mixtures while enhancing the service life of concrete infrastructure in Virginia. The purpose of this laboratory study will be addressed through the following specific objectives:

1. To determine the ASR distress potential of typical VDOT concrete mixtures (job mix) through accelerated tests.
2. To determine a rapid and reliable test procedure to assess ASR in concrete mixtures, thereby enabling the evaluation of mitigation strategies within a performance specification approach.
3. To compare the effect of the alkali content of cement and alkali loading of the concrete on ASR.
4. To determine the SCM type and dosage necessary to effectively mitigate ASR within a prescriptive specification approach, considering the alkali loading of the concrete.
5. To recommend changes to VDOT Road and Bridge Specifications

METHODS

Overview

To accomplish this study's specific objectives, the researchers performed the following tasks:

1. Literature review.
2. Alkali-silica reactivity test.
3. Preparation of recommended changes to the specifications.

Literature Review

Researchers conducted a literature review to identify the key parameters influencing ASR and to summarize the mitigation strategies other researchers had proposed. In addition, a literature search was carried out to identify existing test methods for ASR mitigation and to recommend appropriate modifications tailored to the needs of VDOT.

Alkali-Silica Reactivity Test

AASHTO T380 was developed to evaluate the reactivity of aggregate or aggregate-cementitious system (i.e., cement + SCMs) combinations in a standardized mixture, rather than to determine the ASR behavior of a specific concrete job mix. Importantly, actual mixtures used in projects can divert significantly from the AASHTO T380 standard mixture in terms of alkali loading, aggregate content and gradation, and water-to-cementitious material ratio, among other relevant parameters, which can significantly affect the development of ASR. This study proposes a modified version of AASHTO T380 that considers using actual job mixtures and compares its results with those from the standard AASHTO T380 procedure (AASHTO, 2019).

This task has three subtasks:

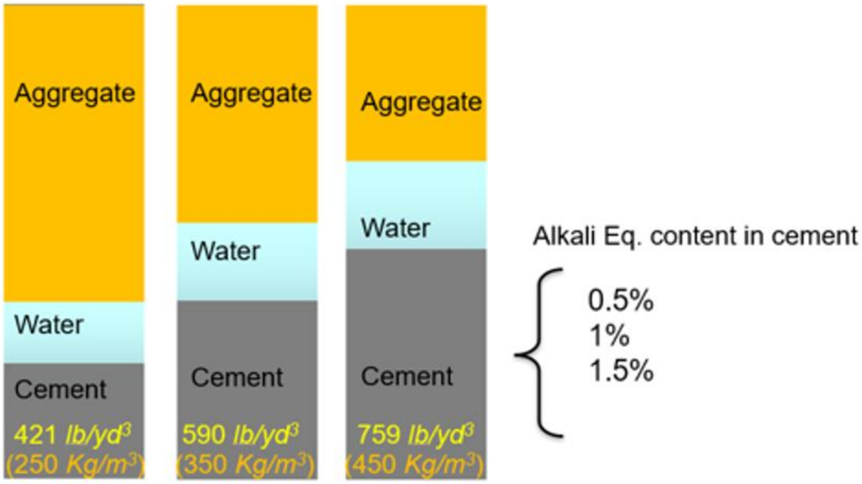
1. Task 2-1: This subtask investigates the goals of objectives 1 and 2 by proposing a modified version of AASHTO T380 as a fast and reliable test for VDOT as a replacement for the withdrawn ASTM C227 (AASHTO, 2019; ASTM International, 2010).
2. Task 2-2: This subtask addresses objective 3 by examining how the total alkali loading in concrete affects ASR, aiming to limit total alkali loading in the mix rather than just the alkali content of cement. Cements with 0.50%, 1.00%, and 1.50% alkali content were used at varying dosages of 421–759 lb/yd³ (250–450 kg/m³) to produce a range of alkali loading levels. All mixtures were tested using the proposed modified AASHTO T380 (AASHTO, 2019). The target cement alkali content levels were achieved by adjusting the cement's natural alkali content with added external alkalis. The study used reactive siliceous aggregates from a Virginia quarry previously identified as ASR susceptible (Lane, 1994).
3. Task 2-3: In this subtask, objective 4 was addressed. SCMs recommended by VDOT specifications—namely Class F coal ash, slag cement, and silica fume—were used at various cement replacement levels and tested for each cement alkali content level.

Prepare Recommended Changes to the Specifications

In this task, the literature review conducted in task 1 and the experimental results obtained in task 2 were analyzed to develop a comprehensive understanding of the ASR mechanism, evaluation methods, and mitigation strategies, while considering VDOT's unique conditions. Based on these findings, changes to the VDOT Road and Bridge Specifications have been recommended.

Experimental Program

In this study, a modification to AASHTO T380 is proposed to enable testing job mixes for both resistance to ASR and sensitivity to alkali loading. To achieve this endeavor, a reactive aggregate was sourced from a quarry in the state of Virginia. The aggregate's reactivity was confirmed using ASTM C1260 and AASHTO T380 (AASHTO, 2019; ASTM International, 2021). For comparison, a known non-reactive aggregate was also tested. For samples being tested with the proposed modified AASHTO T380, a low alkali content cement with Na_2O_{eq} equal to 0.43% was used as a baseline and was boosted to simulate cements with alkali contents of 0.5%, 1.0%, and 1.5% by adding external alkalis. For each simulated cement alkali content, three mixtures with varying cement contents—namely 421, 590, and 759 lb/yd^3—were designed to achieve different alkali loadings, for a total of nine concrete mixtures. Figure 1 illustrates the concrete mixtures experimental matrix.



Variables	*Levels*	*Description*
Groups: *Cement Alkali Content*	*3*	*0.5, 1.0, and 1.5%*
Levels: *Cement content* ***(lb/yd³)***	*3*	*421, 590, and 759*
Total of 9 concrete mixtures		

Figure 1. Concrete Mixtures Experimental Matrix

After fabrication, the specimens were submerged in a base host solution formulated to match the alkalinity of each mixture's pore solution to minimize the leaching of alkalis either from the host solution into the specimens or from the specimens into the solution. This approach ensures that the chemical interactions observed are representative of field conditions. The samples were stored at a temperature of 60°C (140°F), as AASHTO T380 outlines. Further details, including the specific modifications made to AASHTO T380, are provided in the Test Methods section (AASHTO, 2019). The length change of the prisms was monitored for a period of 98 days. The following sections will show that this length of monitoring can be shortened to 84 days.

Materials and Sample Preparation

Cement

Three types of cement were used in this study, with alkali contents of 0.43%, 0.84%, and 1.14%. For testing the reactivity of the aggregates using ASTM C1260 and AASHTO T380, the cements with alkali contents of 0.84% and 1.14% were selected (AASHTO, 2019; ASTM International, 2021). These two cements were chosen because AASHTO T380 recommends using cement with an alkali content of 0.9 ± 0.10% for evaluating aggregate reactivity. A secondary objective was to investigate whether adding external alkalis to cements with different initial alkali contents (0.84% and 1.14%) influences reactivity results and, if so, to quantify the extent of this effect, while adjusting the cements to reach the target alkali content of 1.25% specified in AASHTO T380 for accelerated testing.

The low-alkali cement (Na_2O_{eq} = 0.43%) was included to evaluate the effect of varying alkali contents in the modified AASHTO T380 test by increasing its alkali level with external alkalis to achieve target contents of 0.50%, 1.00%, and 1.50% (AASHTO, 2019). In this phase, SCMs, coal ash, slag cement, and silica fume were included. Table 2 shows the chemical composition of all utilized cements.

Table 2. Summary of the Chemical Composition of the Cements Utilized (% by Mass)

Cement ID	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	Na_2O_{eq}	LOI
OPC (Type I/II)[a]	64.61	17.61	4.17	3.38	2.94	4.75	0.31	0.80	0.84	1.93
High-Alkali Cement[a]	64.20	16.22	4.92	2.66	2.45	5.84	0.35	1.20	1.14	2.14
Low-Alkali Cement[b]	63.28	14.53	3.65	3.37	1.92	3.32	0.02	0.61	0.43	8.61

[a] Used for aggregate reactivity test. [b] Used for making the specimens for alkali-silica reaction testing using the proposed modified AASHTO T380 (AASHTO, 2019). Al_2O_3 = aluminum oxide; CaO = calcium oxide; Fe_2O_3 = iron (III) oxide; K_2O = potassium oxide; LOI = loss on ignition; MgO = magnesium oxide; Na_2O_{eq} = equivalent sodium oxide; OPC = ordinary Portland cement; SiO_2 = silicon dioxide; SO_3 = sulfur trioxide.

Aggregates

Silicious aggregates sourced from a quarry in Virginia were used in this study. A reactive coarse aggregate (R-CA) and a non-reactive coarse aggregate (NR-CA) were collected for ASR testing, in which NR-CA was used to establish a baseline. The reactivity of the aggregates was known from historical performance experience. To verify the reactivity category of the aggregates, ASTM C1260 and AASHTO T380 were conducted (AASHTO, 2019; ASTM International, 2021). Aggregate reactivity results are provided in the relevant section.

R-CA was #8 crushed rock with a nominal maximum aggregate size of 3/8 inches, a saturated surface dry specific gravity of 2.65, and an absorption of 0.3%. The fine aggregate used in this study was a natural concrete sand with an absorption of 0.29% and a fineness modulus of 2.80.

Mix Design

Table 3 presents the mix designs used to prepare the plain concrete prisms for ASR testing. The mixtures were intentionally designed to be slightly coarser than typical concrete. This texture was achieved by using a volume coefficient of 0.67 for dry rodded coarse aggregate, instead of the standard value of 0.46 for a fine aggregate, with Fineness Modulus equal to 2.80 and nominal maximum aggregate size equal to 3/8 inch, as ACI 211.1 indicates (American Concrete Institute, 2022). The adjustment was made to increase the proportion of reactive aggregate in the mixtures—because the reactive coarse aggregate used is expected to have a greater influence than the selected fine aggregate—and thereby enhance the potential for ASR development. The aggregate reactivity test results, provided in the Aggregate Reactivity Test section, support this statement, in which both mixtures contained the same type and quantity of fine aggregate but differed in coarse aggregate type. The mixtures with NR-CA showed lower reactivity, indicating that the fine aggregate had less influence on the expansion results.

Table 3. Plain Concrete Mixture Proportions [lb/yd³]

Level	Cement	Water	w/b	Coarse Aggregate	Fine Aggregate	WR (mL)	External Alkalis to Reach Na_2Oeq = 0.50%		External Alkalis to Reach Na_2Oeq = 1.0%		External Alkalis to Reach Na_2Oeq = 1.5%	
							Added NaOH	*Added KOH*	*Added NaOH*	*Added KOH*	*Added NaOH*	*Added KOH*
1	421	190	0.45	1,869	1,535	1,950	0.41	0	1.56	2.19	2.92	4.09
2	590	266	0.45	1,869	1,199	775	0.57	0	2.19	3.07	8.19	5.74
3	759	341	0.45	1,869	862	75	0.73	0	2.82	3.95	5.26⚙	7.38⚙

⚙ Example of calculation for the amount of external alkalis added for mix Level 3, alkali content of Na_2O_{eq} = 1.5%: Na_2O_{eq} of cement = 0.42538% (A); (B) Na_2O_{eq} of boosted cement = 1.5%; Added Alkalis (% Na_2O_{eq}) = B - A = 1.074%; $Na_2O + H_2O \rightarrow 2NaOH$; 1 mole of Na_2O → 2 moles of NaOH. Then, 61.98 g/mole of Na_2O → 2 × 39.997 g/mole of NaOH. Therefore, 61.98/ (2 × 39.997) = 0.775. It means the amount of Na_2O should be divided by 0.755 to obtain the required NaOH. Na_2O_{eq} = 1.074% × 759 = 8.1517 lb/yd^3. Required NaOH: (50%*8.1517)/0.775 = 5.26 lb/yd^3. Similarly for KOH: $K_2O + H_2O \rightarrow 2KOH$; 1 mole of K_2O → 2 moles of KOH. Then, 94.2 g/mole of K_2O → 2 × 56.17 g/mole of KOH. Therefore, 94.2/(2 × 56.17) = 0.84; $Na_2O = 0.658K_2O$; It means the amount of Na_2O should be divided by (0.84 × 0.658) to obtain the required KOH. Na_2O_{eq} = 1.074% × 759 = 8.1517 lb/yd^3. Required KOH: (50% * 8.1517)/(0.84 × 0.658) = 7.38 lb/yd^3. H_2O = water; KOH = potassium hydroxide; K_2O = potassium oxide; NaOH = sodium hydroxide; Na_2O = sodium oxide; Na_2O_{eq} = equivalent sodium oxide; w/b = water-to-binder ratio; WR = water reducer.

Contrary to the common practice in the literature, in which alkali boosting is achieved solely by adding NaOH or potassium hydroxide (KOH) in the mixing water, this study used a combination of NaOH and KOH to supply the required external alkali. The mass of required NaOH and KOH was calculated by dividing the required external Na_2O_{eq} equally between both alkalis. An example of the calculation has been provided in the footnote of Table 3. This approach of boosting alkali content using both NaOH and KOH was adopted because most cements naturally contain a higher proportion of potassium ion than sodium ion. Boosting exclusively with NaOH would shift the sodium/silicon and potassium/silicon and sodium/potassium balance in the mix, potentially altering the chemical composition and behavior of the ASR gel compared with what is typically observed in the field (Ma et al., 2023; Rajabipour et al., 2015; Shi and Lothenbach, 2019; Wu et al., 2020). To replicate field-like ASR behavior, the sodium content should not be increased to a level that significantly alters the sodium/silicon ratio.

The total alkali loading for each mixture was calculated by multiplying the equivalent alkali content of the cement (Na_2O_{eq}) by the amount of cement used. However, not all the alkalis present are available for reaction. In practice, only about 75% of the cement alkalis are released into the pore solution (Bentz, 2007; Saraswatula et al., 2022). Therefore, to estimate the soluble—or "available"—alkali content, the calculation considered 100% of the added external alkalis and 75% of the cement alkalis. Table 4 provides a summary of both the total alkali loading and the soluble alkali loading for each mixture.

Table 4. Total Alkali Loading and Total Soluble Alkali Loading for Each Mixture

Alkali Content of Cement (%)	Level	Cement lb/yd^3 (kg/m^3)	Total Alkali Loading lb/yd^3 (kg/m^3)	Total Soluble Alkali Loading lb/yd^3 (kg/m^3)
0.50% (Group 1)	1	421 (250)	2.11 (1.25)	1.66 (0.99)
	2	590 (350)	2.95 (1.75)	2.32 (1.38)
	3	759 (450)	3.80 (2.25)	2.99 (1.77)
1.0% (Group 2)	1	421 (250)	4.21(2.50)	3.76 (2.23)
	2	590 (350)	5.90 (3.50)	5.27 (3.13)
	3	759 (450)	7.59 (4.50)	6.78 (4.02)
1.50% (Group 3)	1	421 (250)	6.32 (3.75)	5.87 (3.48)
	2	590 (350)	8.85 (5.25)	8.22 (4.88)
	3	759 (450)	11.39 (6.75)	10.60 (6.28)۞
	4	830(492.4)	12.45 (7.39)	11.57 (6.87)

۞ Sample calculation for the total soluble alkali loading of mix Level 3, alkali content of Na_2O_{eq} = 1.5%;
Available alkalis from the cement: 75% × 759lb/yd3 × 0.43% (alkalis of the cement) = 2.45 lb/yd^3 (A);
Available alkalis from the external alkalis: 100% × 1.074% (total added alkalis) × 759lb/yd3 = 8.15 lb/yd^3 (B);
Total soluble alkalis = A + B = 10.60 lb/yd^3. Na_2O_{eq} = equivalent sodium oxide.

Table 5 summarizes the concrete prism mix designs used for ASR testing according to the proposed modified AASHTO T380 explained in the Test Methods section (AASHTO, 2019). For consistency with the literature, the term *fly ash* will be used throughout this report, although *coal ash* is technically more accurate. For the modified testing protocol, the alkali content of the low-alkali cement mixtures was increased using a combination of NaOH and KOH, whereas specimens were stored in a host solution containing only NaOH, formulated to match the estimated pore solution alkalinity of each mixture. The Test Methods section further explains this procedure. Table 6 does not list the quantities of alkalis added to each mixture. Mixtures were categorized into three groups based on the equivalent Na_2O_{eq} content of the simulated cement (Group 1: 0.5%; Group 2: 1.0%; Group 3: 1.5%). Within each group, three levels were defined according to cement content: Level 1: 421 lb/yd^3; Level 2: 590 lb/yd^3; and Level 3: 759 lb/yd^3. Table 4 presents the alkali loading of the plain concrete mixtures for each group and level.

Table 5. Mix Designs Incorporating Supplementary Cementitious Materials for Evaluating the Effectiveness of Alkali Boosting Compared with Naturally High-Alkali Cement [lb/yd^3]

Mixture	Binder	Cement	SCM	Water	w/b	Coarse Aggregate	Fine Aggregate
C (Plain Concrete)	421	421	0	190	0.45	1,869	1,535
	590	590	0	266	0.45	1,869	1,199
	759	759	0	341	0.45	1,869	862
C + 20% FA	421	337	84	190	0.45	1,869	1,510
	590	472	118	266	0.45	1,869	1,162
	759	607	152	341	0.45	1,869	814
C + 30% FA	421	295	126	190	0.45	1,869	1,496
	590	413	177	266	0.45	1,869	1,143
	759	531	228	341	0.45	1,869	790
C + 40% FA	421	253	168	190	0.45	1,869	1,483
	590	354	236	266	0.45	1,869	1,125
	759	455	304	341	0.45	1,869	766
C + 50% Slag	421	211	210	190	0.45	1,869	1,523
	590	295	295	266	0.45	1,869	1,181
	759	379	379	341	0.45	1,869	839

Mixture	Binder	Cement	SCM	Water	w/b	Coarse Aggregate	Fine Aggregate
C + 60% Slag	421	168	253	190	0.45	1,869	1,520
	590	236	354	266	0.45	1,869	1,177
	759	304	455	341	0.45	1,869	834
C + 10% SF	759	683	76	341	0.45	1,869	837
C + 15% SF	759	645	114	341	0.45	1,869	825

C = low-alkali cement; SCM = Supplementary Cementitious Materials; FA = fly ash; SF = silica fume; w/b = water-to-binder ratio.

Table 6. External Alkalis Added to Each Mixture to Achieve Specified Alkali Contents [lb/yd^3]

Mixture	External Alkalis to Reach Na_2O_{eq} = 0.50%		External Alkalis to Reach Na_2O_{eq} = 1.0%		External Alkalis to Reach Na_2O_{eq} = 1.5%	
	Added NaOH	**Added KOH**	**Added NaOH**	**Added KOH**	**Added NaOH**	**Added KOH**
C	0.41	0	1.56	2.19	2.92	4.09
	0.57	0	2.19	3.07	8.19	5.74
	0.73	0	2.82	3.95	5.26	7.38
C + 20% FA	0.32	0.0	1.25	1.75	2.34	3.28
	0.45	0.0	1.75	2.45	3.27	4.59
	0.58	0.0	2.25	3.16	4.21	5.90
C + 30% FA	0.28	0.0	1.09	1.53	2.05	2.87
	0.40	0.0	1.53	2.15	2.86	4.01
	0.51	0.0	1.97	2.76	3.68	5.16
C + 40% FA	0.24	0.0	0.94	1.32	1.75	2.46
	0.34	0.0	1.31	1.84	2.46	3.44
	0.44	0.0	1.69	2.37	3.16	4.42
C + 50% Slag	0.20	0.0	0.78	1.10	1.46	2.05
	0.28	0.0	1.09	1.53	2.05	2.87
	0.37	0.0	1.41	1.97	2.63	3.68
C + 60% Slag	0.16	0.0	0.62	0.87	1.17	1.63
	0.23	0.0	0.88	1.23	1.64	2.29
	0.29	0.0	1.13	1.58	2.11	2.96
C + 10% SF	0.66	0.0	2.53	3.55	4.74	6.64
C + 15% SF	0.62	0.0	2.39	3.35	4.47	6.27

C = low-alkali cement; FA = fly ash; KOH = potassium hydroxide; NaOH = sodium hydroxide; Na_2O_{eq} = equivalent sodium oxide; SF = silica fume.

Sample Preparation

Coarse and fine aggregates were loaded into the mortar mixer and blended in saturated surface dry conditions for 1.5 minutes. Cement was then added, followed by an additional 30 seconds of mixing. The external alkalis were pre-dissolved in water before mixing. After dry mixing for approximately 2 minutes, one-half of the alkali-water solution was added to the mixer, and mixing continued for 1.5 minutes. The remaining solution was then added, and mixing proceeded until a total mixing time of 7 minutes was reached. A water-reducing admixture was added as needed to achieve sufficient workability for casting.

Pin studs were placed inside the molds to maintain a free distance of 10 inches (254 mm) between them. Concrete prisms measuring 2 inches × 2 inches × 11.2 inches (50 mm × 50 mm × 285 mm) were cast. Fresh concrete was placed into the molds in two layers, with each layer rodded 25 times and consolidated briefly on a vibrating table. Special care was taken to ensure proper consolidation around the studs to fully anchor them in the concrete. The surface of each specimen was finished and covered with plastic. Four replicates were prepared for each mixture. Samples were demolded after 24 hours and prepared for conditioning in hot water and zero-length measurement.

Test Methods

In both ASTM C1260 and ASTM C1567, the alkali content of the cement has been shown to have negligible or only minor effects on test results (ASTM International, 2021, 2025; Laskey, 2018). In contrast, the AASHTO T380 method involves boosting the alkali content of the cement to 1.25% Na_2O_{eq} to match the alkalinity level of the concrete pore solution with that of the host solution. This alignment helps reduce the leaching of alkalis during testing. However, it is important to note that AASHTO T380 is primarily designed to assess aggregate reactivity in a shorter timeframe compared with ASTM C1293, or to evaluate the effectiveness of SCMs for ASR mitigation—not to evaluate actual job mixtures (AASHTO, 2019; ASTM International, 2023).

To address this gap, a modification to AASHTO T380 is proposed in this study to enable the evaluation of a job mix's resistance to ASR (AASHTO, 2019). The specimen dimensions used in this modified test are the same as those in AASHTO T380, utilizing molds measuring 2 inches × 2 inches × 11.2 inches (50 mm × 50 mm × 285 mm). The curing regime also follows AASHTO T380 protocols, including 24-hour initial curing in the mold and the subsequent hot water conditioning phase after demolding.

In the proposed modification, the use of cement is no longer restricted to those with a Na_2O_{eq} of 0.90 ± 0.10%. Instead, any cement—regardless of alkali content—can be used. In addition, unlike the original method, in which cement content is fixed at 708 lb/yd^3 (420 kg/m^3), $w/c = 0.45$, and aggregate gradation is limited, the proposed modified AASHTO T380 lifts these restrictions. This unrestricting allows for testing of actual job mixtures with variable cement types and contents, different aggregate gradations, and other realistic mix parameters. Another modification to AASHTO T380 is extending the duration of the test from 56 to 98 days. The following sections will discuss this extension and will show that it can be shortened to 84 days. For assessing ASR of a mixture, the modified test method adopts the same effectiveness criterion proposed in AASHTO T380, in which an expansion (length change) of less than 0.020% is considered acceptable (AASHTO, 2019). Another study proposed criteria thresholds of length change less than 0.020% or 0.025%, with 0.020% showing a stronger correlation to the results obtained from exposure blocks (National Academies of Sciences, Engineering, and Medicine [NASEM], 2023).

To maintain the test's sensitivity to alkali loading, the concentration of the surrounding solution should be adjusted to match the alkalinity level of the pore solution in the tested mixture. This concept of alkalinity matching between the test medium and the concrete pore solution has also been adopted in other proposed test methods (Ideker et al., 2023; Laskey, 2018; Mukhopadhyay et al., 2018; Shehata and Thomas, 2010). In this proposed test method, the alkalinity level of the host solution was matched with the concrete pore solution. The base host solution was made by using only NaOH, similar to the AASHTO T380 approach. Appendix B provides a detailed guide for calculating the pore solution alkalinity of the proposed concrete mixture. In AASHTO T380, the alkali content of the cement is increased using only NaOH, which is a common practice in the accelerated ASR testing (AASHTO, 2019). In contrast, in the proposed study, when alkali boosting is needed for laboratory testing, such as evaluating different alkali loadings, the alkali content of the mixtures will be increased using a combination of NaOH and KOH. The reason is that the potassium-sodium ratio influences ASR expansion (Leemann and Lothenbach, 2008a). Because most cements contain more potassium sulfate versus sodium sulfate (Rajabipour et al., 2015), boosting alkalis using only NaOH or KOH alters the natural potassium-sodium ratio, potentially changing the ASR behavior of a mixture and consequently misrepresenting field behavior. The literature has suggested that the composition of alkali boosting solutions in ASR studies should be matched to the chemistry of the cement. The required amounts of NaOH and KOH were determined by dividing the needed external alkalis (expressed as Na_2O_{eq}) between the two compounds and calculating their masses based on their respective molar masses. An example of the calculation is provided in the footnote of Table 3.

It is important to acknowledge that no ASR test method is 100% accurate, and no one can fully account for all influencing variables. This limitation also applies to the proposed modifications because the composition of the concrete pore solution is dynamic and evolves over time. Consequently, matching the host solution to the initial pore solution alkalinity of the concrete mixture is only valid for a limited period. However, despite these limitations, altering the chemistry of the concrete pore solution in this way significantly reduces alkali leaching compared with what is observed in ASTM C1260 (ASTM International, 2021). As a result, the proposed test method is expected to offer a more realistic assessment of a mixture’s long-term performance with respect to ASR resistance.

Because ASR testing involves measuring length changes, which can be influenced by both sample and ambient temperatures, all measurements were conducted in a temperature-controlled room. The samples were removed from the host solution one at a time, dried with a towel, and their length was measured using a length comparator. This process was followed by weighing the specimens on a standard scale. After each reading, the specimen was wrapped in a towel until the comparator readings for all other prisms were taken. At the end of the measurement session, all specimens (four replications for each mixture) were returned to the designated host solution. This approach ensured consistent measurements, with minimal impact from thermal effects on specimen length. The measurements were taken 24 hours, 3 days, 7 days, 10 days, 14 days, 21 days, and then once a week until 98 days.

RESULTS AND DISCUSSION

Literature Review

Once the ASR reaction begins, it cannot be fully stopped, although its progression can be slowed (Behravan et al., 2025). However, slowing ASR in existing structures is both challenging and costly (Shi and Lothenbach, 2022). Many state DOTs in the United States have indicated that the primary goal of any repair strategy is to delay the progression of deterioration—mainly to buy time until funding can be secured for the eventual replacement of ASR-affected infrastructure, which is ultimately unavoidable (Behravan et al., 2025). In other words, the complete replacement and reconstruction of affected infrastructure is the most effective method—although often the most expensive—to eliminate ASR (Smith and Van Dam, 2019), suggesting that implementing ASR mitigation measures into practice during construction is more functional and cost efficient. On the other hand, the stages and mechanisms through which ASR expansion occurs are still unknown (Shi et al., 2020). Therefore, the safest approach to prevent ASR development is to use non-reactive aggregates. However, when the use of reactive aggregates is unavoidable, the risk of ASR can be effectively mitigated by incorporating SCMs or by limiting the alkali content of the cement (Muñoz et al., 2021a; Thomas, 2011). Some standards, like ASTM C1260 (ASTM International, 2021), were developed to test the reactivity of the aggregates. However, this test is very severe and results in an overestimation of the reactivity of some aggregates (Touma et al., 2001). Several state DOTs have expressed concerns about frequent false positives associated with the ASTM C1260 testing method (Behravan et al., 2025). These concerns align with other reports (Muñoz et al., 2021a). Although ASTM C1293 has traditionally demonstrated a stronger correlation with field performance (ASTM International, 2023), its reliability has been questioned during the past 5 to 10 years. Some aggregates that passed this test later exhibited signs of ASR in exposure blocks as the concrete continued to age (Konduru et al., 2020; Muñoz et al., 2021b; NASEM, 2023). Moreover, this test is time consuming and requires 52 weeks (1 year) to complete, and if SCMs are used, it takes 2 years. For this reason, some modifications to this test method can accelerate it and produce results within 26 weeks (6 months) and even 13 weeks (3 months), as Touma et al. (2001) explained. It has been shown that the 2-year test program of ASTM C1293 with an expansion limit of 0.04% underestimates the dosage of SCMs needed to suppress expansion in high alkali loading exposure blocks (NASEM, 2023). AASHTO T380 is a combination of the two modifications of ASTM C1293 described previously by storing the samples in 1N NaOH solution at 140°F (60°C) by using the miniature concrete prism test (MCPT) to get the results in 8 weeks (2 months), which is much shorter than the test duration required in ASTM C1293. To eliminate the effect of alkali leaching observed in ASTM C1260, AASHTO T380 requires increasing the cement alkali content to 1.25% by adding NaOH. Appendix A shows a summary of all test methods. When both ASTM C1260 and AASHTO T380 identify an aggregate as reactive, ASTM C1567 may then be applied to establish the necessary SCM dosage, using a 28-day expansion threshold of 0.10% (AASHTO, 2019; ASTM International, 2021, 2025; NASEM, 2023).

Several state DOTs have reported cases in which aggregates passed standard test methods but still exhibited ASR distress after being incorporated into concrete and placed in the field (Behravan et al., 2025). Aggregates in concrete are not entirely inert when it comes to alkali leaching, and as a result, they can affect the overall alkali-silica reactivity of the system (Deschenes, Jr., and Micah Hale, 2017; Ideker et al., 2006). Alkali leaching from fine aggregates is one of the key factors contributing to the differences observed between the physical expansion of concrete specimens containing reactive coarse aggregates and their field performance (Menéndez et al., 2018). For instance, minerals like feldspar—commonly present in many aggregates—can serve as a substantial source of alkalis (Constantiner and Diamond, 2003), illustrating the limitations of evaluating coarse aggregates in isolation and emphasizing the need to assess the actual job mix. Testing job mixtures is essential because ASR depends on factors such as the aggregate's reactivity, the binder's composition, and the environmental exposure conditions. The type of aggregate influences the occurrence of the reaction, whereas the binder's composition affects its severity, and the exposure conditions control how quickly the reaction progresses (Laskey, 2018). Therefore, the need for a new accelerated test method that considers the complete mix design is clear—including alkali loading, the effects of alkali leaching from various aggregates and other mixture components (e.g., SCMs and chemical admixtures), and aggregate gradation, combinations, and particle sizes—to achieve a more accurate and dependable evaluation of ASR potential.

In another attempt to mitigate ASR in newly constructed structures, many state DOTs have made significant efforts to develop specifications that limit the alkali content of the cement because the main alkalis participating in ASR reactions are sodium and potassium, which are primarily obtained from the cement (Behravan et al., 2025). The alkali content of the cement has been limited based on the percentage of Na_2O_{eq}, for which Na_2O_{eq} is calculated as ($\%Na_2O + 0.658 \times \%K_2O$). Unfortunately, restricting the alkali content in the cement specifications has unwanted consequences, such as increasing the final product cost. For example, because of environmental and sustainability concerns, cements with higher amounts of alkali content are produced. It can be expensive to ship cement with low-alkali content from another region to replace a local cement with an alkali content that is higher than the threshold value specified in the specifications. Moreover, it has been shown that the alkali loading—alkali content of cement ($Na_2O_{eq}\%$) times the amount of cement used (kg/m^3 or lb/yd^3)—in the concrete has a considerable effect on initiating ASR (Thomas et al., 2006), meaning that concrete made with a large quantity of low-alkali cement could still have enough alkalis to initiate ASR. In both ASTM and Canadian A23.1-14/A23.2-14 standards, when the potential for ASR exists, the accepted allowable alkali loading of concrete has been limited to the range between 3.0 lb/yd^3 and 5.0 lb/yd^3 (1.8 kg/m^3 and 3.0 kg/m^3) based on the aggregate reactivity, size of the concrete element, and environment (CSA Group, 2004; ASTM International, 2024). Moreover, some SCMs (e.g., Class F coal ash) have higher alkali content compared with the cement, which may increase the total alkali content of the concrete when blended with cement and raise concerns about the effectiveness of the coal ash to mitigate ASR (Schlorholtz, 2015). The previous statements fairly well demonstrate that it is more appropriate to consider the alkali content of mixtures (alkali loading in concrete) instead of the alkali content of the cement when ASR is a concern.

Studies have shown that when the same reactive aggregate was used in two comparable mixtures with similar proportions and different cements but similar alkali contents, the mixtures exhibited different expansion patterns (Leemann and Lothenbach, 2008a). Therefore, it is important to recognize that relying solely on aggregate reactivity and limiting the alkali content of cement may not be sufficient to effectively mitigate ASR. A more comprehensive test method is needed—one that evaluates the reactivity of the specific aggregate (different gradations, sizes, and combinations) used in the concrete mixture while also accounting for the effects of alkali loading. For simplicity, prescriptive specifications may be used with an appropriate factor of safety. When uncertainty exists, performance-based specifications can be considered for a more reliable determination of ASR resistance.

Aggregate Reactivity Test

As Figures 2 and 3 show, both test methods confirmed the reactivity of R-CA. Specifically, based on the ASTM C1260 results, R-CA fell in the R1 aggregate reactivity class according to ASTM C1778, which is indicative of moderate reactivity (ASTM International, 2021, 2024). This level of reactivity is typical for reactive aggregates found in Virginia. On the other hand, the reactivity of NR-CA fell in the R0 category, which is indicative of non-reactive aggregates, as expected.

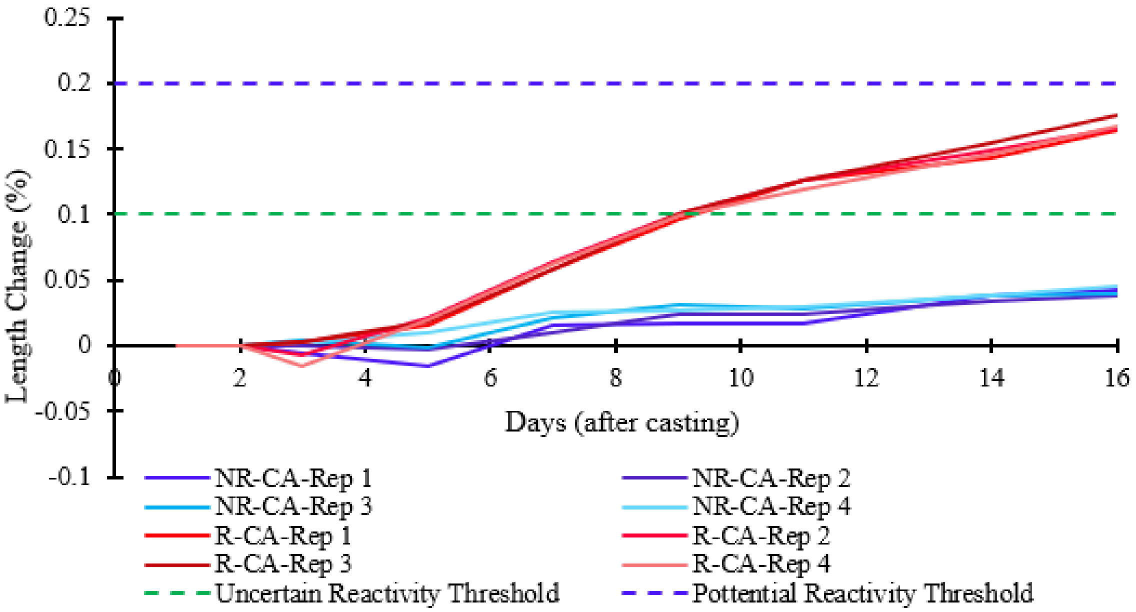


Figure 2. Aggregate Reactivity Test Results Obtained by ASTM C1260 Test Procedure (ASTM International, 2021). NR-CA = non-reactive coarse aggregate; R-CA = reactive coarse aggregate.

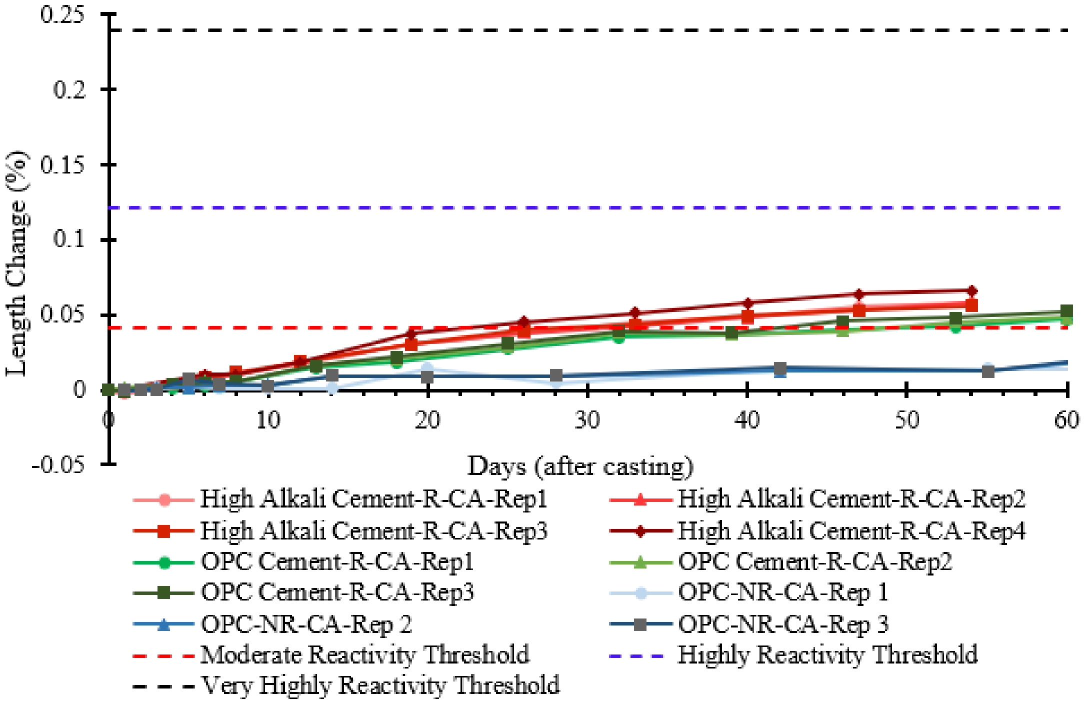


Figure 3. Aggregate Reactivity Test Results Obtained by AASHTO T380 Test Procedure (AASHTO, 2019). NR-CA = non-reactive coarse aggregate; OPC = ordinary Portland cement; R-CA = reactive coarse aggregate.

Modified AASHTO T380 Test

Figures 4, 5, and 6 present the length change results of concrete mixtures made with cement alkali contents of 0.5%, 1.0%, and 1.5%, respectively. Each figure includes the original AASHTO T380 test results as a reference. Although the original AASHTO T380 samples used different aggregate gradations and proportions, comparing the modified AASHTO T380 with the original samples provides better insight into the reactivity behavior of each job mixture and demonstrates that even mixtures with the same aggregate can exhibit different responses (AASHTO, 2019). Because the aggregate source, the reactive aggregate content, and the cement alkali content are constant within each figure, any variation in expansion behavior can be directly attributed to differences in alkali loading and the amount of added external alkalis. The alkali loadings presented in each graph represent the total alkali loading, calculated by multiplying the cement's alkali content (expressed as Na_2O_{eq}%) by the quantity of cement used (in kg/m^3 or lb/yd^3).

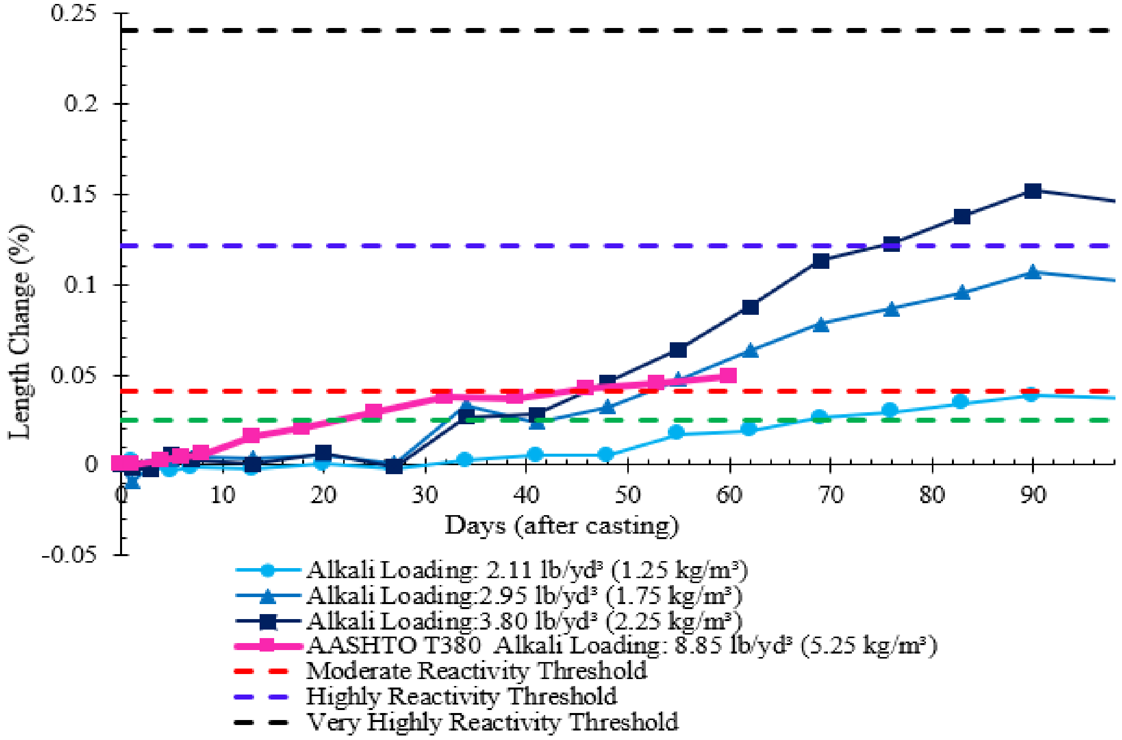


Figure 4. The Length Change Results of Concrete Mixtures Made with Cement Alkali Contents of 0.5% but Varying Alkali Loading

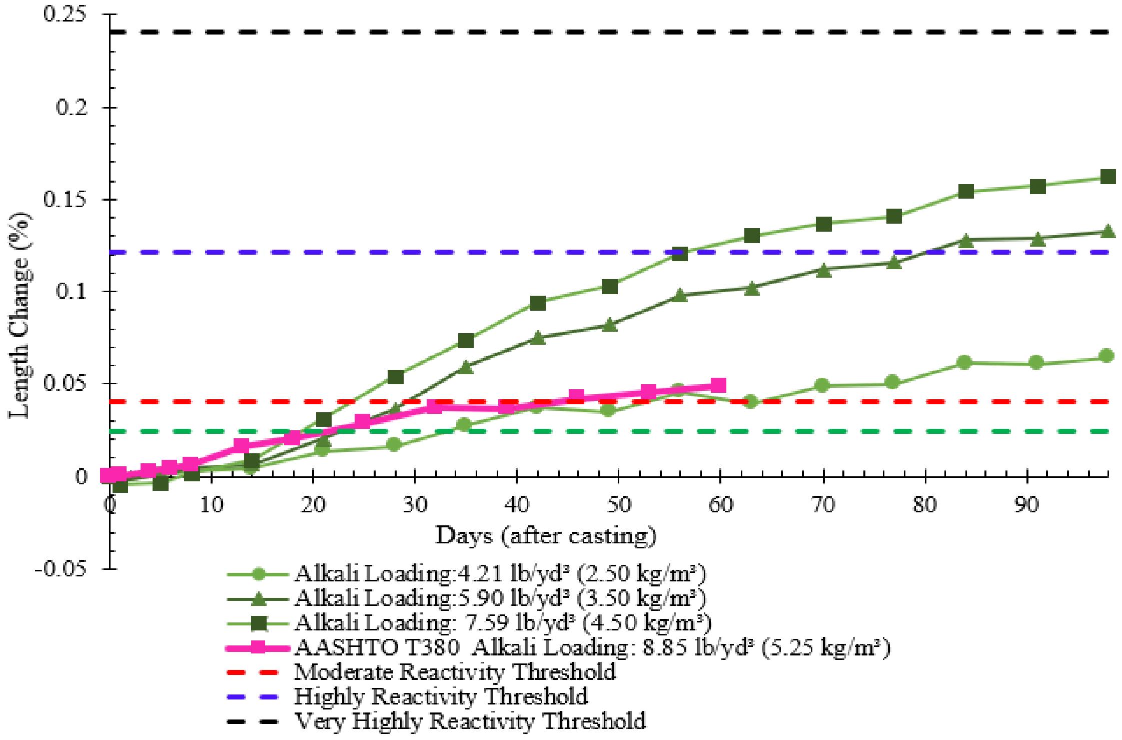


Figure 5. The Length Change Results of Concrete Mixtures Made with Cement Alkali Contents of 1.0% but Varying Alkali Loading

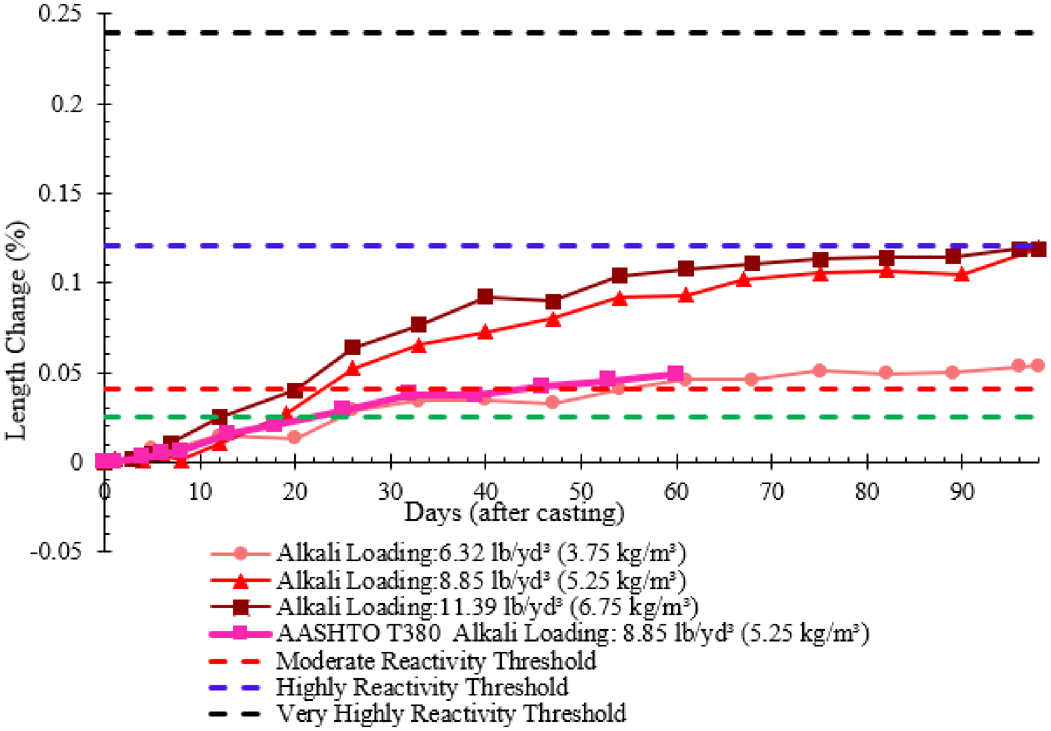


Figure 6. The Length Change Results of Concrete Mixtures Made with Cement Alkali Contents of 1.5% but Varying Alkali Loading

As Figures 4, 5, and 6 show, increasing the alkali loading in each group generally leads to increased expansion in the concrete prisms. Figure 4 shows that even mixtures with low alkali loading of 2.95 lb/yd3 (1.75 kg/m3) can lead to ASR. This observation is consistent with previous findings of ASR occurring with certain aggregates, even under low alkali loading conditions—as low as 2.87 lb/yd3 (1.7 kg/m^3) (Stacey et al., 2016). AASHTO T380 and ASTM C1778 limit the alkali loading of concrete to between 3 and 5 lb/yd^3 (1.8 and 3.0 kg/m^3) Na$_2$O$_{eq}$ (AASHTO, 2019; ASTM International, 2024). However, recent observations of excessive expansion in mixtures with low alkali loading suggest that simply limiting the alkali content of cement or alkali loading of a concrete mixture, irrespective of aggregate type and job mixture, may not be sufficient to prevent ASR. This conclusion aligns with conclusions in other publications (Stark, 1981; Thomas, 1996a). In Figure 6, which presents the results for Group 3 mixtures containing cement with 1.5% alkali content, expansion increased slightly as the alkali loading rose from 8.85 to 11.40 lb/yd^3 (5.25 kg/m^3 to 6.76 kg/m^3). Interestingly, despite the higher alkali content in the cement, these mixtures exhibited less expansion than the corresponding mixtures in Group 2, which had lower alkali loading. To verify this unexpected trend, the Level 2 and Level 3 mixtures in Group 3 were repeated. In addition, a new mixture (Level 4) was prepared using the same cement with 1.5% alkali but with a higher cement content of 830 lb/yd^3 (492.4 kg/m^3), resulting in an alkali loading of 12.45 lb/yd^3 (7.40 kg/m^3). The repeated measurements confirmed the previous expansion results, with no clear explanation for the reduced expansion in Group 3 compared with Group 2. Following sections discuss possible hypotheses and explain the expansion results at 84 days.

Figure 7 compares the expansion results of Level 3 mixtures from each group (with defined cement alkali content) against Level 4 in Group 3. Notably, Level 4 in Group 3—with the highest alkali loading—exhibited greater expansion than Level 3 in Group 3 but less than Level 3 in Group 2. This higher expansion of Level 4 in Group 3 further emphasizes the unexpectedly lower expansion of Level 3 but suggests that the mixtures may have passed the pessimum point compared with Group 2.

A comparison between the modified AASHTO T380 results and the original procedure shows that expansion behavior varies across different mixtures even with the same aggregate type. The original AASHTO T380 method corresponds to an alkali loading of 8.85 lb/yd^3 (5.5 kg/m^3), which is the same alkali loading used in mixture Level 2 in Group 3, yet they exhibit significantly different expansion behaviors (Figure 6). This difference highlights that AASHTO T380 is suitable for evaluating aggregate reactivity but not reliable for assessing the ASR resistance of complete mixtures (AASHTO, 2019). The discrepancy likely stems from differences in aggregate gradation, ratio of alkali to the reactive aggregate in the mixture, and the method of boosting, which can either alter silica dissolution and alkali ions leaching from the concrete or alkali ions diffusion into it.

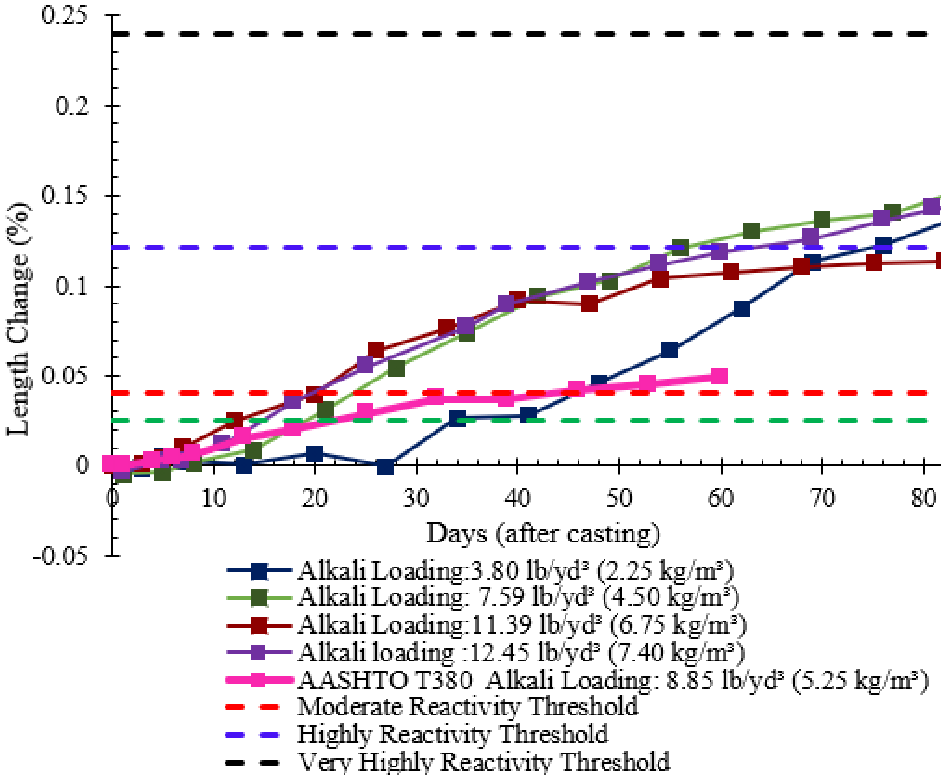


Figure 7. Comparison of Expansion for Level 3 Mixtures in Each Group, All with the Highest Alkali Loading of 12.45 lb/yd^3 (7.40 Kg/m^3)

In Figures 4 through 7, it is evident that expansion changes become minimal after 84 days. Table 7 shows the differences in length change between 84 and 98 days (12 and 14 weeks) for all mixtures. With an average difference of 7.26 % and having an average 2-week rate of expansion equal to 0.004, the test duration can reasonably be shortened to 84 days without compromising the reliability.

Table 7. Comparison of Concrete Prisms Expansion at 84 and 98 Days

Alkali Content of Cement (%)	Level	Expansion at 84 Days (12 weeks) (%)	Expansion at 98 Days (14 weeks) (%)	Change (%)	Average 2-Week Rate of Expansion from 12 to 14 Weeks (%)
0.50% (Group 1)	1	0.034	0.036	6.71	0.001
	2	0.096	0.101	5.93	0.003
	3	0.138	0.145	5.10	0.004
1.0% (Group 2)	1	0.061	0.064	5.26	0.002
	2	0.128	0.133	3.97	0.003
	3	0.138	0.153	11.32	0.008
1.50% (Group 3)	1	0.049	0.054	9.66	0.002
	2	0.107	0.119	11.55	0.006
	3	0.114	0.119	4.16	0.002
	4	0.146	0.159	8.90	0.007

Figure 8 presents a comparison of 84-day expansions for mixtures with varying cement contents. The results clearly demonstrate that increasing cement content—and thus increasing total alkali loading—significantly intensifies expansion because of ASR in each group. In Group 1, increasing the cement content from 421 lb/yd³ to 590 lb/yd³ resulted in approximately a fourfold increase in expansion. Similarly, in Groups 2 and 3, the expansions at 590 lb/yd³ were approximately 2.5 and 2.3 times greater, respectively, than those at 421 lb/yd³. These results highlight the critical influence of alkali loading on expansion behavior. This influence emphasizes that even when using cement with the same alkali content, different alkali loadings can lead to substantially different expansion outcomes. Even when cement content remains constant, variations in cement alkali content continue to influence expansion, underscoring the importance of managing the total alkali input in concrete mixtures. Moreover, it has been demonstrated that cements with similar Na_2O_{eq} values can exhibit significantly different expansion behavior (Leemann and Lothenbach, 2008b). Therefore, relying solely on Na_2O_{eq} as an indicator of the potential reactivity of concrete mixtures may be misleading in some cases (Leemann and Lothenbach, 2008b), suggesting that the current specifications and guidelines that limit Na_2O_{eq} could be reconsidered or removed.

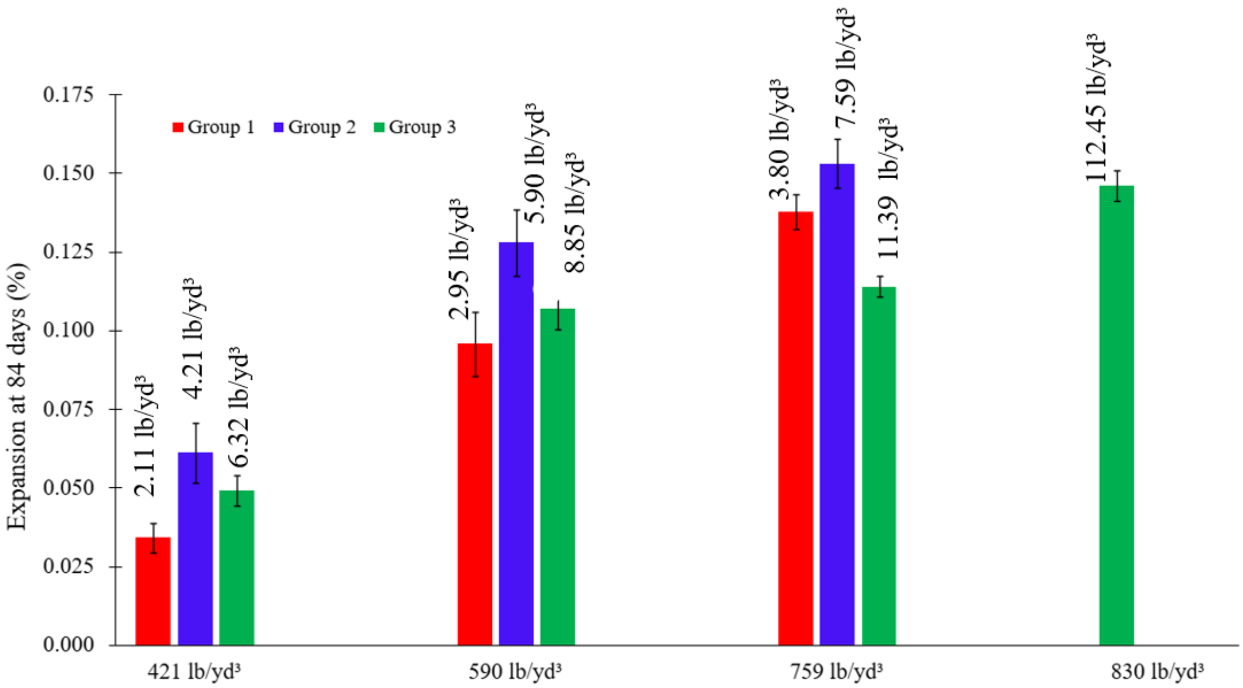


Figure 8. 84-Day Expansions for Mixtures with Different Cement Contents. Group 1 = mixtures with cement having Na_2O_{eq} = 0.5%; Group 2 = mixtures with cement having Na_2O_{eq} = 1.0%; Group 3 = mixtures with cement having Na_2O_{eq} = 1.5%.

However, as Figure 8 shows, increasing the alkali loading across the groups did not result in a consistent increase in expansion, as one might intuitively expect. For instance, Level 1 mixture in Group 2, which had a higher alkali loading of 4.21 lb/yd³, exhibited less expansion than Level 2 mixture in Group 1, which had a lower alkali loading of 2.95 lb/yd³. This trend persisted across other comparisons as well. Notably, for each cement content level, Group 3 consistently showed lower or comparable expansion to Group 2, despite having even higher alkali content. To validate this unexpected observation, mixtures for both Groups 2 and 3 were retested. The repeated experiments confirmed the same expansion patterns, reinforcing initial observations. This result agrees with other studies, which have concluded that excessively high alkali boosting tends to reduce the ASR expansion in concrete samples (Lindgård et al., 2012; Shi et al., 2017; Shi et al., 2018; Wei et al., 2022), suggesting that alkali loading is not the only ASR expansion-determining factor. Three hypotheses can explain the observed expansion behaviors.

1. Effect of excessive alkali boosting: It appears that overly aggressive alkali boosting may distort expansion behavior (Rajabipour et al., 2015), potentially leading to results that do not accurately reflect what happens in the field. The reduced ASR expansion at very high-alkali contents is likely because of the formation of calcium silicate hydrates (C–S–H) instead of ASR products (Lindgård et al., 2012; Matsuyama and Young, 2000; Shi and Lothenbach, 2020; Shi et al., 2017; Shi et al., 2018). These observations could be related to the reduced calcium concentration at very high pH values because calcium is essential for the formation of ASR products (Wang and Gillott, 1991).
2. Influence of boosting method and chemistry of base host solution: The other possible reason is that some KOH has been leached out into the base host solution because a

combination of NaOH and KOH has boosted the alkali, but the host solution is made only with NaOH. Following sections will discuss this outcome further when reviewing the pH results. In addition, it has been shown that a host solution made with NaOH can potentially inhibit the expansion of inherently KOH-boosted samples (Muñoz et al., 2021b). Therefore, for the mixtures in Group 3 that have more KOH used for boosting, the swelling may have been prohibited. The method used for alkali boosting—whether through NaOH, KOH, or a combination of both—along with the chemical composition of the host solution, may need to be reconsidered. These choices could significantly affect the test results and may not fully represent field conditions, particularly in complex binder systems. Another possible explanation is that externally added alkalis become immediately available in the pore solution but are also more prone to leaching or early equilibrium adjustments, particularly during the initial hot-water conditioning, which may limit their long-term aggressiveness.

3. Competing effects of dissolved silicate and aluminum on ASR expansion: Elevated alkali concentrations may inhibit the polymerization of dissolved silicate, as previously proposed (Glasser and Kataoka, 1981). In addition, higher alkali levels facilitate the dissolution of monosulfate phases, thereby increasing the concentration of aluminum in the pore solution. Elevated aluminum concentrations are known to significantly suppress the dissolution of reactive aggregates, thereby mitigating ASR (Chappex, 2012; Chappex and Scrivener, 2013, 2012a). These mechanisms highlight the complex interplay between alkalis and aluminum in influencing ASR. Specifically, although increased alkali levels accelerate the dissolution of reactive silica, the concurrent rise in aqueous aluminum concentrations can counteract this effect. Therefore, in regions of pore solution composition where aluminum's inhibitory influence dominates, ASR expansion may be suppressed. Conversely, in scenarios in which the effect of alkali ions prevails, ASR is more likely to be exacerbated (Wei et al., 2022).

Reliability of External Alkali Boosting in ASR Susceptibility Evaluation

To evaluate the extent to which the proposed modification—boosting the alkali content of cement using both NaOH and KOH while storing samples in a host solution prepared with only NaOH—can simulate the behavior of a high-alkali cement, an additional experiment was conducted. In this test, the alkali content of a low-alkali cement (Na_2O_{eq} = 0.43%) was boosted to Na_2O_{eq} equal to 1.14%, and the resulting expansion was compared with that of mixtures made with cement that intrinsically contained Na_2O_{eq} equal to 1.14%.

Figure 9 presents the expansion results of concrete prisms for a period of 84 days for mixtures prepared with varying cement contents, and consequently, different alkali loadings. As shown, mixtures made with low-alkali cement externally boosted to a target alkali level exhibited lower expansion compared with those produced with naturally high-alkali cement, despite having similar total alkali content. This observation aligns with findings from previous studies, indicating that boosting the alkali content of cements with different Na_2O_{eq} levels to the same target using NaOH does not necessarily yield equivalent expansion behavior (Lindgård et al., 2012). As Table 8 summarizes, mixtures prepared with low-alkali cement had 21% higher total soluble alkali content on average than those made with high alkali cement. Nevertheless, the average expansion of low-alkali mixtures was approximately 19.3% lower. Several factors may explain the lower expansion observed in boosted mixtures, despite their higher soluble alkali content. One possibility is that the increased pH resulting from external alkali addition reduces calcium concentrations in the pore solution, which is critical for the formation of expansive ASR gels (Wang and Gillott, 1991). Another explanation is that the added alkalis increase the sulfate concentration more than the hydroxide content, thereby altering the chemistry of the pore solution in a way that inhibits expansion (Laskey, 2018). In addition, the leaching of KOH and NaOH from the concrete into the NaOH-based host solution could also contribute to this discrepancy. However, the previous discussion shows that when a mixture (without boosting) is being evaluated, the host solution can be prepared using NaOH (for simplicity) without compromising the final evaluation.

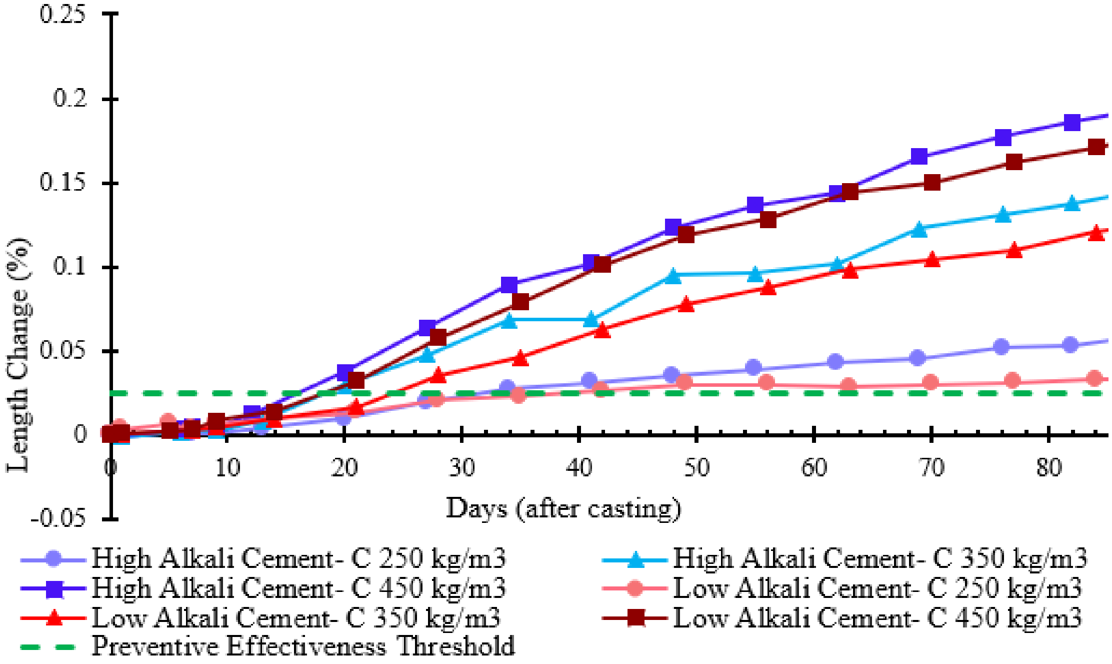


Figure 9. Expansions of the Mixtures with Alkali Content of Equivalent Sodium Oxide = 1.14% Made with Low-Alkali Cement and Added External Alkalis and Naturally High-Alkali Cement with Different Cement Content (Alkali Loading)

Table 8. Comparison between Expansion and Total Soluble Alkali Content of Each Mixture

Cement Content (lb/yd^3)	Expansion of Low-Alkali Cement at 84 Days (%)	Expansion of High-Alkali Cement at 84 Days (%)	Difference (%)	Total Soluble Alkalis in Low-Alkali Cement (lb/yd^3)	Total Soluble Alkalis in High-Alkali Cement (lb/yd^3)	Difference (%)
421	0.0328	0.0527	– 37.66	4.35	3.59	21.13
590	0.1206	0.1374	– 12.21	6.10	5.04	21.07
759	0.1711	0.1858	– 7.95	7.85	6.49	20.78

Figures 10, 11, and 12 present the expansion behavior of mixtures containing various SCMs at different replacement levels, produced with boosted cements to achieve Na_2O_{eq} contents of 0.5%, 1.0%, and 1.5%. A key observation from these figures is that all plain concrete mixtures were susceptible to ASR, and within each group, higher cement content—and consequently greater alkali loading—led to increased expansion in the plain concrete mixtures. However, the magnitude of expansion varied across groups. For example, the plain concrete specimens in Group 3 exhibited lower expansion than those in Group 2.

As Figure 10 shows, when the alkali loading of the plain concrete was below 3.80 lb/yd³ (2.25 kg/m³), all tested SCMs at all evaluated dosages were effective in mitigating ASR. Increased fly ash replacement levels consistently reduced expansion, and 10% silica fume also provided mitigation, although the measured expansions were closer to the threshold of effectiveness (0.0139 versus 0.025) compared with other SCMs.

For Group 2 mixtures, with alkali loadings between 4.21 and 7.59 lb/yd³ (2.5 and 4.5 kg/m³), all SCMs tested remained effective in controlling expansion (Figure 11). However, in Group 3, in which alkali loading ranged from 5.87 to 10.58 lb/yd³ (3.75 to 6.75 kg/m³), 20% fly ash and 10% silica fume failed to prevent deleterious expansion when alkali loading was greater than or equal to 8.85 lb/yd³ (5.25 kg/m³) (Figure 12). This observation aligns well with findings from previous studies, which recommended exercising great caution when using silica fume as the only mitigation strategy, particularly at typical dosage levels of 5 to 10% in concrete mixtures for transportation infrastructure, such as bridges and pavements (ASTM International, 2021). In contrast, 30% fly ash and 15% silica fume were effective. A similar result was observed, indicating that 7% silica fume is ineffective when the alkali loading exceeds 8.43 lb/yd³ (5 kg/m³) (Oberholster et al., 1989). Silica fume with high silica purity is less effective in mitigating ASR compared with alumina-rich fly ash. This difference is primarily related to the availability of soluble alumina. In fly ash, the alumina can dissolve into the pore solution and subsequently participate in pozzolanic reactions, leading to the formation of Al-modified C–S–H, or C–A–S–H, gel. The incorporation of alumina into C–S–H significantly improves its alkali-binding capacity and may also slow down the dissolution of silica, thereby enhancing its effectiveness in controlling ASR (Aquino et al., 2001; Bickmore et al., 2006; Chappex and Scrivener, 2012b; Hong and Glasser, 2002; Shafaatian et al., 2013; Warner, 2012). To refine the minimum effective dosage of fly ash for high-alkali systems, an additional mixture containing 25% fly ash was tested. As Figure 12 shows, this dosage successfully mitigated ASR even in mixtures with high cement alkali content and high alkali loading (> 8.43 lb/yd³[> 5.0 kg/m³]). The findings indicate that as the alkali loading in the mixture rises, a greater proportion of SCM is necessary to suppress expansion within acceptable limits. This trend aligns with results reported in previous research (Fournier et al., 2004).

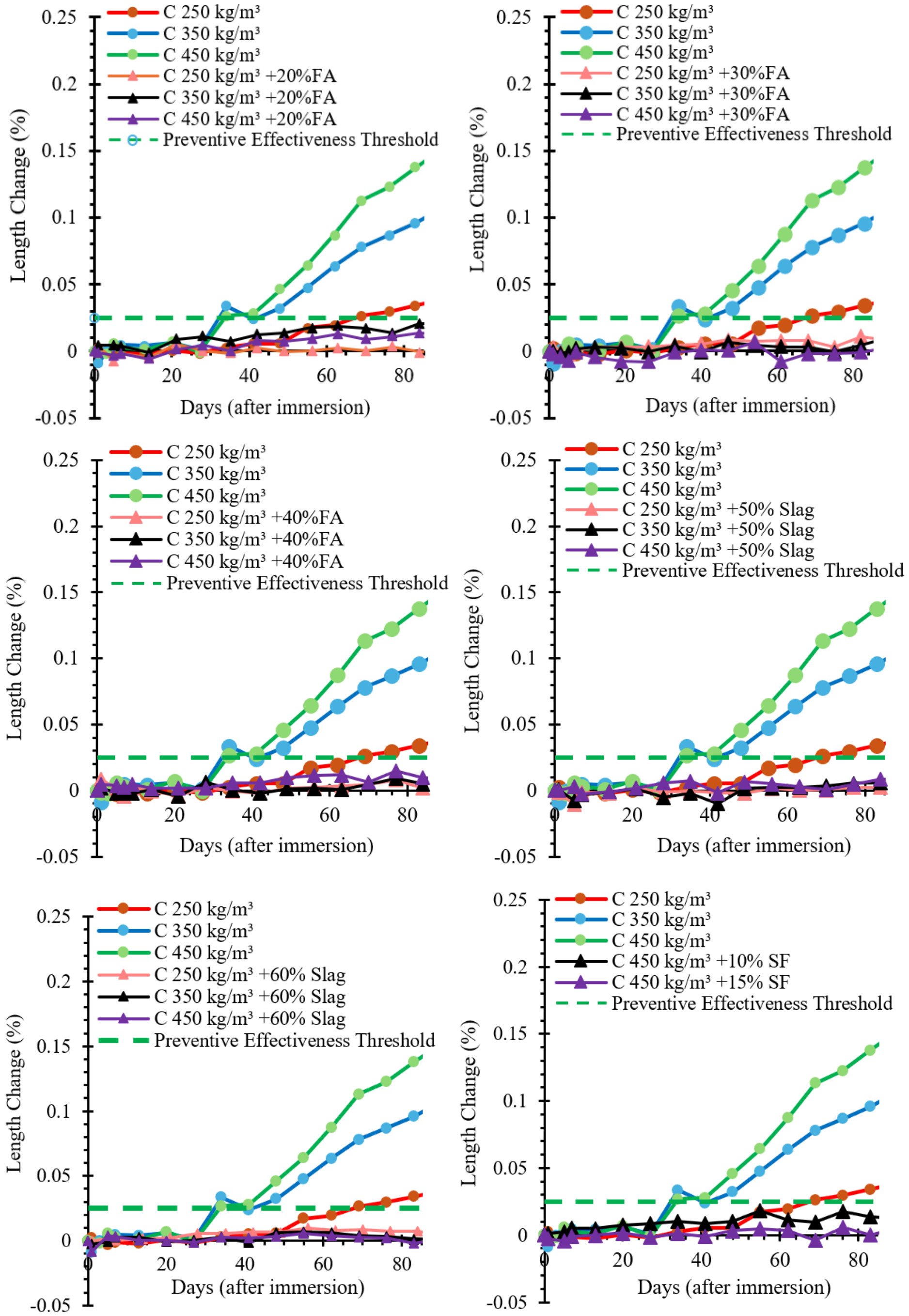


Figure 10. Expansion Results of Mixtures with Boosted Cement (Na_2O_{eq} = 0.5%) Incorporating Different Supplementary Cementitious Materials. C = cement; FA = fly ash; SF = silica fume.

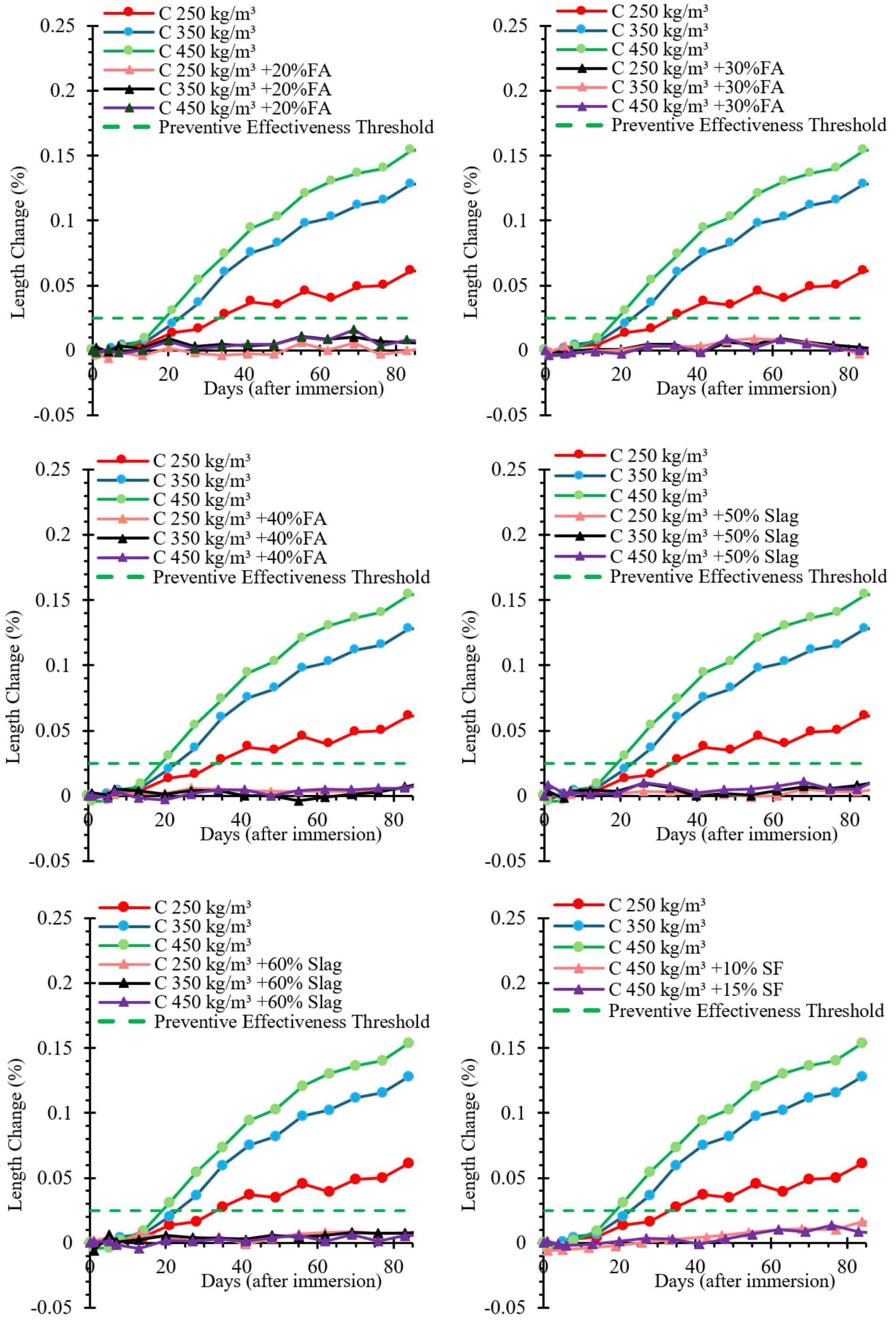


Figure 11. Expansion Results of Mixtures with Boosted Cement (Na_2O_{eq} = 1.0%) Incorporating Different Supplementary Cementitious Materials. C = cement; FA = fly ash; SF = silica fume.

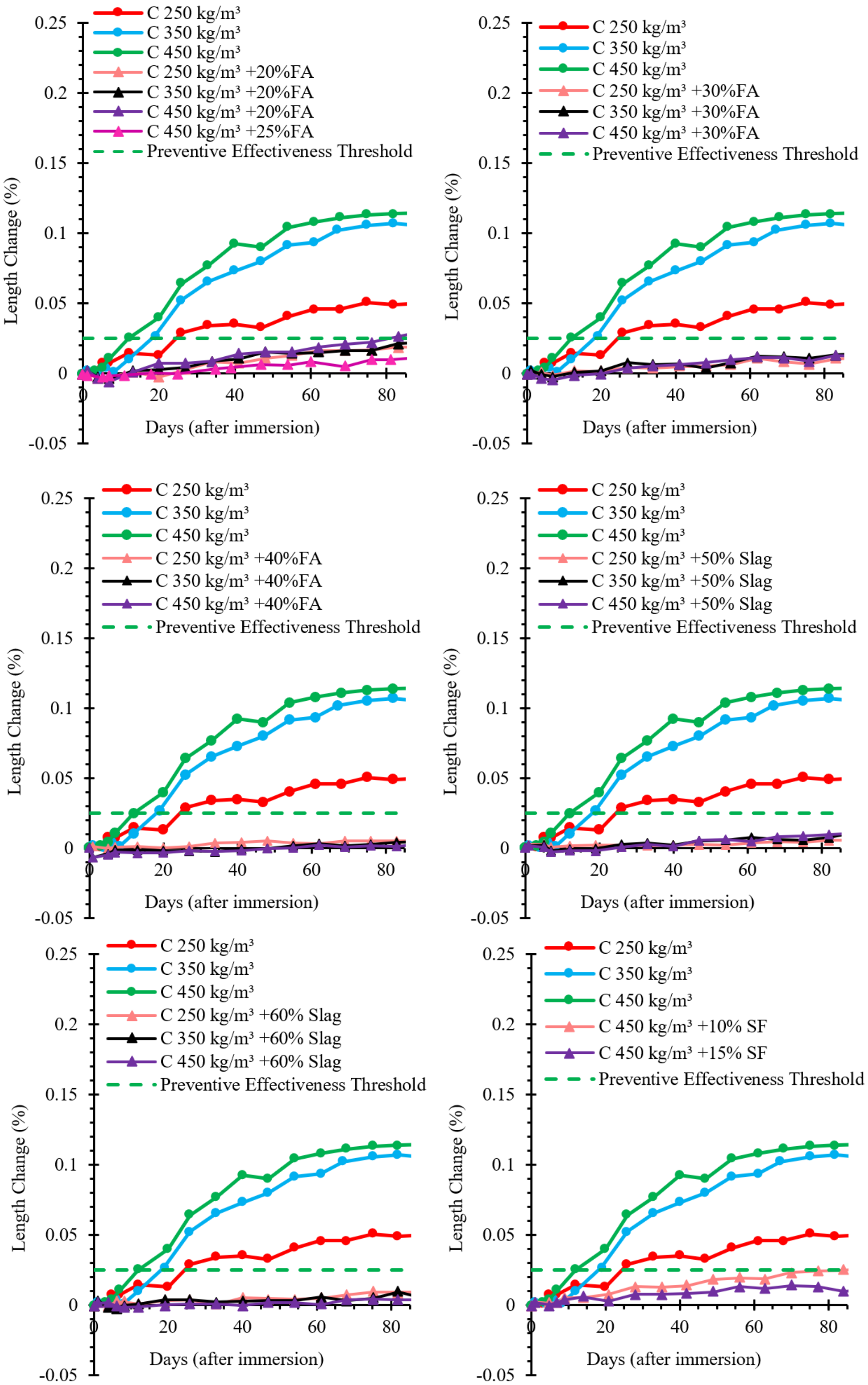


Figure 12. Expansion Results of Mixtures with Boosted Cement (Na_2O_{eq} = 1.5%) Incorporating Different Supplementary Cementitious Materials. C = cement; FA = fly ash; SF = silica fume.

From these results, the minimum effective dosages for high-alkali systems can be recommended as 25% for fly ash and 15% for silica fume. The slag cement at the values tested, 50% and 60%, was also very effective. This study did not examine lower slag replacement levels (e.g., 35%), and therefore, the precise minimum effective dosage for slag could not be determined based on the existing results. The minimum SCM dosages identified in this study are specific to the aggregate sources evaluated. The required quantity of SCM will depend not only on the chemical composition of SCM but also on the aggregate's reactivity, the total alkali contribution from Portland cement and other sources, and potential exposure to external alkalis during service (e.g., from seawater or de-icing salts). Nevertheless, because the aggregate used in this research represents a typical reactive aggregate found in Virginia, the recommended minimum SCM dosages can be considered sufficient to mitigate ASR under conditions commonly encountered in the state.

The findings confirm that, when an adequate quantity of a suitably reactive SCM is used, ASR expansion can be effectively controlled even in concretes containing reactive aggregates and produced with cements of elevated alkali content or mixtures with high alkali loading. This observation suggests that restrictions based solely on cement alkali content or alkali loading could be replaced with mandatory SCM usage requirements.

Importantly, the study also revealed that concretes made with low-alkali cements or low alkali loadings remain susceptible to ASR. Therefore, if plain concrete is to be used, its ASR resistance should be verified experimentally. Furthermore, when aggregates with uncertain long-term field performance are involved, incorporating SCMs is strongly advised.

The reason that SCMs were effective in mitigating ASR is that SCMs primarily bind alkalis, reducing their availability in the pore solution for reaction with reactive aggregates (Boddy et al., 2003; Canham et al., 1987; Shafaatian et al., 2013; Thomas, 1996b, 2011). The effectiveness of SCMs depends on their chemical composition, particularly their alumina content, which contributes to the formation of C–A–S–H phases with increased alkali-binding capacity (Hong and Glasser, 2002; Kawamura and Takemoto, 1988; Thomas, 2011). Moreover, it has been shown that SCM incorporation leads to lower calcium-silicon ratios in C–S–H phases—typical when fly ash is used—which enhance their capacity to retain sodium and potassium ions, thereby further suppressing ASR-related expansion (Bhatty and Greening, 1978; Hong and Glasser, 1999; Thomas, 2011). In addition, the pozzolanic reaction can decrease the permeability of concrete and consequently slow down ion movement and fluid penetration into concrete. This reduction in ion diffusivity becomes particularly important when the structure is exposed to external alkali sources. Furthermore, lowering the hydraulic permeability can limit water ingress, thereby slowing the swelling of ASR gel (Li et al., 2006; Lothenbach et al., 2011). Another contributing factor to the beneficial role of SCMs in controlling ASR is their ability to consume portlandite. Research indicates that the availability of calcium hydroxide, or other soluble calcium sources, is essential for the development of expansive ASR gel. By engaging in pozzolanic reactions, SCMs reduce the amount of portlandite in the system, thereby limiting the calcium available for gel formation (Bleszynski and Thomas, 1998; Chatterji, 1979; Hobbs, 1988).

Even though some SCMs may introduce additional alkalis—sometimes in amounts exceeding those of the cement they replace—the net effect is a reduction in alkalis present in the pore solution because only a portion of the SCMs alkalis are soluble (Diamond, 1981; Thomas, 2011). In some SCMs (e.g., ground glass), the pore solution exhibits higher alkalinity along with increased aluminum concentration (Zheng, 2016). Hydroxide ions associated with alkali cations reduce the solubility of Ca^{2+}, and pozzolanic reactions further consume calcium hydroxide, lowering calcium availability in the system (Zheng, 2016). Regardless of whether alkalinity rises or alkali levels decrease when SCMs have been utilized, the combined effects of limited alkalis, elevated aluminum, and reduced calcium concentrations act to slow aggregate dissolution and, therefore, mitigate ASR.

The aggregate used in this study was moderately reactive. According to ASTM C1778 (ASTM International, 2024), this reaction classifies the aggregate as Type R1. Given that the specimens were exposed to alkalis during the experiment, the corresponding ASR risk level is 4. Depending on the application of concrete, the prevention level associated with Risk Level 4 is W, X, Y, Z, according to Table 4 in ASTM C1778. A comparison of the performance of mixtures containing SCMs tested in this study with the recommendations in Table 6 of ASTM C1778 indicates that the prescribed SCM dosages are generally effective in mitigating ASR. These findings align well with the results obtained in this study. However, the silica fume dosages suggested under Prevention Levels Y and Z may be impractical under conditions of high alkali loading (> 5.0 kg/m^3 [> 8.43 lb/yd^3]).

Moreover, this study demonstrates that the SCM dosages recommended in Table 6 of ASTM C1778 are applicable even when using cements with high-alkali content (Na_2O_{eq} > 1.25%), provided that the aggregate is moderately reactive (ASTM International, 2024). Based on this finding, it is recommended that Table 7 of ASTM C1778 be revised to consider alkali loading (kg/m^3 of binder), rather than just the alkali content of the cement.

CONCLUSIONS

- *According to the literature, when both ASTM C1260 and AASHTO T380 classify an aggregate as reactive, ASTM C1567 can be used to determine the required SCM dosage, applying a 28-day expansion limit of 0.10%.* Literature has shown that results from AASHTO T380 (with an expansion limit of 0.02%) are more reliable than ASTM C1260 to characterize aggregate reactivity (AASHTO, 2019; ASTM International, 2021, 2025).

- *Casting concrete prisms using the same geometry specified in AASHTO T380—but based on the actual job mix design—and immersing them in an alkaline host solution matched to the expected pore solution chemistry of the job mix for 84 days can effectively assess ASR resistance* (AASHTO, 2019). If the prism expansion exceeds the threshold of 0.025%, the mixture is considered susceptible to ASR.

- *Increasing the cement content—and consequently the total alkali loading—leads to higher expansion in the concrete prisms, indicating increased susceptibility to ASR.*

- *Similar to how limiting the alkali content of cement has proven ineffective, placing limits on the total alkali loading of concrete alone does not guarantee ASR mitigation.* Based on the findings, it is proposed that the current limitations on both alkali content and alkali loading in concrete mixtures be revised.

- *SCMs are highly effective in mitigating ASR, even when using cements with high-alkali content or concrete mixtures with high alkali loading.* Therefore, utilizing SCMs should be emphasized. The effectiveness of SCMs is strongly dependent on mix-specific parameters. The required dosage of each SCM varies depending on factors such as total alkali loading, the content and reactivity of the aggregate, and the type of SCM used.

- *Cements with higher alkali contents can be safely used when sufficient amounts of SCMs are incorporated into the mixture, supporting a more flexible and sustainable approach to mix design.*

RECOMMENDATIONS

1. *VDOT's Materials, Structure and Bridge, and Construction Divisions should use the ASTM C1260 test method for evaluating aggregate reactivity* (ASTM International, 2021). If aggregate reactivity is more than moderately reactive (i.e., R1 per ASTM C1778 [ASTM International, 2024]), AASHTO T380 should be conducted. If AASHTO T380 confirms aggregate reactivity level, then the prescriptive method for ASR mitigation of concrete (shown in Recommendation 2) is not applicable, and the performance-based approach should be utilized (AASHTO, 2019).

2. *It is recommended that VDOT's Materials, Structure and Bridge, and Construction Divisions remove the current limitation on the alkali content of cement from the Road and Bridge Specifications.* Instead, in collaboration with VTRC, develop a new prescriptive approach considering the different levels of alkali loading in concrete. Alternatively, performance testing in accordance with the proposed modified AASHTO T380 should be allowed by keeping the threshold of expansion suggested in NCHRP 1083, or ASTM C1567 extended to 28 days per NCHRP 1083 recommendations (AASHTO, 2019; NASEM, 2023).

IMPLEMENTATION AND BENEFITS

Researchers and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and to determine the benefits of doing so. This process is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

Regarding Recommendation 1, VDOT's Materials Division and VTRC will update the next revision of the VDOT Road and Bridge Specifications to incorporate the appropriate test method for evaluating aggregate reactivity within 2 years of the publication of this report.

Regarding Recommendation 2, VDOT's Materials Division and VTRC will include a new section for future revisions of the VDOT Road and Bridge Specifications outlining the proposed test method for evaluating the concrete job mix and determining the minimum effective dosage of SCMs needed to mitigate ASR, even when using cements with higher alkali content. This revision will serve as the performance-based approach. In addition, as a prescriptive approach, a table will be developed specifying the minimum required SCM dosages for varying alkali loading in concrete using non-reactive to moderately reactive aggregates (i.e., R0 to R1 per ASTM C1778 [ASTM International, 2024]). This recommendation will be implemented within 2 years of the publication of this report.

Benefits

Implementing the recommendations outlined in this study offers both economic and environmental benefits for VDOT and the broader transportation infrastructure.

Recommendation 1, which focuses on identifying reactive aggregates using reliable test methods, enables the adoption of appropriate ASR mitigation strategies early in the project. Because ASR cannot be stopped once it begins, early detection is critical. Without proper mitigation, ASR can lead to severe structural deterioration, requiring costly treatments or even full replacement. Although temporary repairs may cost approximately 10% of the total replacement cost, they are often ineffective in the long term and require ongoing maintenance. Considering that, as of 2025 data, the project cost of bridge deck replacement in Virginia is $1,167 per square foot, and the cost of full bridge replacement is $2,556 per square foot, implementing the recommendations from this study can result in substantial savings for VDOT.

Recommendation 2 supports a performance-based approach that allows for the use of cements with higher alkali content and local reactive aggregates, provided proper mitigation strategies—such as the use of SCMs—are applied. This approach not only enhances sustainability by reducing the processing needed in cement manufacturing but also conserves natural resources and lowers transportation costs by utilizing locally available materials. Furthermore, incorporating industrial byproducts like fly ash and slag helps divert waste from landfills and improves the long-term durability and performance of concrete. Overall, these strategies enable the use of broader material sources while effectively mitigating ASR, ultimately reducing lifecycle costs and supporting more resilient and sustainable infrastructure.

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APPENDIX A: SUMMARY OF AVAILABLE ALKALI-SILICA REACTION TEST METHODS

Test Name	Standard Code	Specimen Type	Specimen Size	Temperature	Storage Condition	Test Duration	Failure Criteria	Pros	Cons
AMBT (Shi and Lothenbach, 2019)	ASTM C 1260 and 1567	Mortar (prism)	1″x1″x11.25″ (25x25x285 mm)	80°C	1N NaOH	16 days	> 0.1%	• Useful for aggregates that react slowly or produce expansion late in the reaction.	• Alkali content of the cement is not a significant factor in affecting expansions. • It is not suitable for detecting ACR as aggregates that are alkali-carbonated reactive. • It may not expand when crushed to the gradations used in the test method. • Should not be used to evaluate job combinations of coarse and fine aggregates. • It may give a false-negative result for some slowly reactive aggregates. • It may also provide overly conservative estimates of the amount of SCM to control ASR. • This test method is not suitable for evaluating SCMs with high-alkali contents (fly ash and ground-glass pozzolan with > 4.0 % Na_2O_{eq} and slag cement or silica fume with > 1.0 % Na_2O_{eq}). • It is not suitable for evaluating ASR mitigation by reducing alkali loading.
MCPT (Bentz, 2007)	ASTM C 1293	Concrete (prism)	3″x3″x11.25″	38°C	water	1 year (2 years if	> 0.04%	• The most reliable approach for determining aggregate reactivity.	• Alkali leaches from the sample.

Test Name	Standard Code	Specimen Type	Specimen Size	Temperature	Storage Condition	Test Duration	Failure Criteria	Pros	Cons
			(75x75x285 mm)			SCM was used)		• Suitable for selecting the appropriate level of SCMs. • It is suitable when SCMs with high-alkali content are being evaluated.	• False negatives when SCMs are used. • Long-time testing. • Limits the cement to 708 lb/yd^3 when the performance of SCM is being evaluated.
ACPT-1 (Touma et al., 2001)	Modified ASTM C 1293	Concrete (prism)	3″x3″x11.25″ (75x75x285 mm)	38°C	1N NaOH	6 months	> 0.04%	• Faster than MCPT. • No concern about alkali leachate.	
ACPT-2 (Touma et al., 2001; Mukhopadhyay et al., 2018)	Modified ASTM C 1293	Concrete (prism)	3″x3″x11.25″ (75x75x285 mm)	60°C	water	3 months	> 0.04%	• Faster than MCPT.	• Higher temperatures can cause sulfate ions to replace hydroxyl ions in the pore solution, thus lowering their concentration and pH in the concrete. • High temperature causes reduced expansion compared with that achieved when exposed to 38°C.
Miniature Concrete Prism Test (Ideker et al., 2023)	AASHTO T380 (AASHTO, 2019)	Concrete (prism)	2″x2″x11.2″ (50x50x285 mm)	60°C	1N NaOH	2 months (2.8 months for slow reactive aggregates)	> 0.04% > 0.025 (when effectiveness of ASR mitigation is being evaluate)	• Faster than MCPT. • No concern about alkali leachate.	• Higher temperatures can cause sulfate ions to replace hydroxyl ions in the pore solution, thus lowering their concentration and pH in the concrete.
CCT (Stacey et al., 2016)	Stephen Stacey (UT Austin)	Concrete (cylinder)	6″x11.6″ (150x294 mm)	38°C, 50°C	Water ponded on top	> 5 months 9 months	> 0.04%	• At a higher alkali content, the samples seem to have a more accelerated reaction at 38°C.	• Able to detect expansion with an alkali content > 0.52%.
ACCT (Mukhopadhyay et al., 2018)	Texas DOT	Concrete (cylinder)	3″x6″ (76 x152 mm)	60°C	NaOH + KOH (representative of the	75 days	> 0.04%	• Tests at varying levels of alkali (from 0.82% Na_2O_{eq} to 1.25% Na_2O_{eq}).	• Needs pore solution extraction and analysis of the pore solution.

Test Name	Standard Code	Specimen Type	Specimen Size	Temperature	Storage Condition	Test Duration	Failure Criteria	Pros	Cons
					alkalinity of pore solution)			• No concern about alkali leachate. • No human error (automatic data collection).	• Needs more space due to using VCMD.
UNBCCT (Laskey, 2018)	University of New Brunswick concrete cylinder test	Concrete (cylinder)	5.7″x11.25″ (145x285 mm)	38°C, 60°C	NaOH + KOH (representative of the alkalinity of pore solution)	>180 days (until the length-change reached a plateau)	> 0.04%	• No concern about alkali leachate can detect damage with an equivalent alkali content as low as 0.41%. • UNBCCT yields results more in line with the exposure block than that of MCPT.	• Needs to evaluate mixtures containing SCMs. • Needs pore solution extraction and analysis of the pore solution.
ACPT (Giannini and Folliard, 2013)	Autoclave Concrete Prism Test	Concrete (prism)	3″x3″x11.25″ (75x75x285 mm)	Autoclave for 24 hours at 133°C and 0.20 MPa		4 days	> 0.08%	• Very fast. • Appears to be best suited as a screening test for aggregates and potentially for combinations of aggregates.	• Not likely to be suited to testing mitigation measures. • High alkali content required.
T-FAST for Job Mix (Muñoz et al., 2021a)	FHWA Turner Fairbank	Job mix + synthesized pore solution	50 mL polytetrafluoroethylene test tubes	55 ± 2°C		21 days	RI > 0.45	• Can determine job mix alkali thresholds. • No concern about alkali leachate. • Very fast. • Reliable because it relies on chemical analysis rather than expansion. • Can be used when alkali loading is being evaluated.	• Needs information on pore solution.
T-FAST (NASEM, 2023)	FHWA Turner Fairbank	5 g of coarse or fine aggregate	50 mL polytetrafluoroethylene test tubes	55°C and 80 °C	1N NaOH	21 days	RI > 0.45	• No concern about alkali leachate. • useful in establishing the maximum permissible alkali loading of concrete mixes in the field.	• Needs aggregate crushing. • Needs specific aggregate gradation.

ACR = alkali-carbonate reaction; ASR = alkali-silica reaction; KOH = potassium hydroxide; Na_2O_{eq} = equivalent sodium oxide; NaOH = sodium hydroxide; MCPT = miniature concrete prism test; RI= reactivity index; SCMs = supplementary cementitious materials; VCMD= volumetric change measuring device.

APPENDIX B: CALCULATION OF THE ALKALINITY LEVEL OF CONCRETE PORE SOLUTION

General formula for alkali content of the pore solution:

$$Na_2O_{eq}^{Con} = TSA \qquad \text{Eq. 1}$$

$$Na_2O_{eq}^{Pore} = \frac{Na_2O_{eq}^{Con}}{Vol_{Pore}} \times Vol_{Con} \qquad \text{Eq. 2}$$

$$NaOH_{req} = Na_2O_{eq}^{Pore} \times 1.291 \times Vol_{host} \qquad \text{Eq. 3}$$

Where:

$Na_2O_{eq}^{Con}$ = amount of equal alkalis available in a unit volume of concrete (Kg/m^3).

TSA = total soluble Alkali from all cementitious materials (Kg/m^3).

$Na_2O_{eq}^{Pore}$ = amount of equal alkalis available in a unit volume of concrete pore solution (Kg/m^3).

Vol_{Pore} = volume of the pore solution (m^3).

Vol_{Con} = volume of concrete (m^3).

$NaOH_{req}$ = amount of sodium hydroxide (NaOH) required to make the host solution.

Vol_{host} = volume of host solution (m^3).

The value of 1.291 in Equation 3 is twice the molar mass ratio of NaOH to Na_2O because each mole of Na_2O gives 2 moles of NaOH (Equations 4 through 6). In fact, 1.291 is the coefficient to convert the mass of Na_2O to the mass of NaOH.

$Na_2O + H_2O \rightarrow 2NaOH$ Eq. 4

1 mole of Na_2O → 2 moles of NaOH Eq. 5

61.98 g/mole of Na_2O → 2 × 39.997 g/mole of NaOH Eq. 6

Therefore, 2 × 39.997 / 61.98 = 1.291.

The following equations provide more details to calculate the parameters in each of the previous formulas.

$$TSA = 0.75 \times Na_2O_{eq}^{Cem} \times 0.01 \times C + WSA \times FA + 0 \times Slag + f \times Na_2O_{eq}^{SF} \times 0.01 \times SF + \frac{NaOH^{Boosted}}{1.291} \qquad \text{Eq. 7}$$

$$Vol_{Pore} = \frac{Water\ left}{density\ of\ water} = \frac{Initial\ water - Hydration\ bound\ water + imbibed\ water}{density\ of\ water} = \frac{W - \sum k\alpha B}{density\ of\ water} \qquad \text{Eq. 8}$$

Where:

$Na_2O_{eq}^{Cem}$ = amount of equal alkalis available in cement (%).

C = mass of cement (Kg).
WSA = water-soluble alkalis from fly ash. See Saraswatula et al., (2022) for more details.
FA = mass of fly ash (Kg).
f = the soluble alkali factor for silica fume. The amount of soluble alkali from silica fume reduces from 75% to 45% for silica fume content from 0% to 15% and more (Saraswatula et al., 2022). Therefore, the *f* values should be determined by a linear interpolation. For our study, for the 10% substitution, *f*=0.55, and for the 15% substitution, *f*=0.45.
$Na_2O_{eq}^{SF}$ = amount of equal alkalis available in silica fume (%).
SF = mass of silica fume (Kg).
$NaOH^{Boosted}$ = amount of externally added NaOH to boost the alkali content of the cement.
k = the coefficient for the sum of bound water and imbibed water due to chemical shrinkage accompanying cement and pozzolanic reactions. A sum value between 0.17 and 0.23 is an accepted value for unit mass of binder (Bentz, 2007; Saraswatula et al., 2022). For this study, the authors assumed 0.17 because the samples are at an early age when put in the host solution.
α = degree of hydration. Values of 75%, 10%, and 15% (representative of around 28 days of reaction) are used for cement, Class F fly ash, and Class C fly ash, respectively (Saraswatula et al., 2022). For this study, because the samples are at an early age and were cured for 24 hours in a moist room and 24 hours in hot water (60°C), the authors assumed that the degree of hydration is 0.45.

In Equation 7, the alkali ions present in the slag are assumed to be contained in the slag hydration products and, thus, to have no influence on the pore solution composition (Bentz, 2007). Therefore, a coefficient of "0" was used.

Combining all equations from Equations1 to 8 will produce:

$$\mathrm{NaOH_{req}} = \frac{\mathrm{TSA}}{Vol_{Pore}} \times 1.291 \times 1(m^3) = \frac{\mathrm{TSA}}{\mathrm{W} - \sum \alpha k \mathrm{B}} \times 1.291 \times 1 \times 1000$$

Example of the calculations for mixture Level 1 in Group 1:

Binder = 250 Kg/m^3 = 421 lb/yd^3.
Water = 112.72 Kg/m^3 = 190 lb/yd^3.
$Na_2O_{eq}^{Con}$ = TSA = 0.99 Kg/m^3 = 1.66 lb/yd^3 (Table 3).
$Vol_{Pore} = \frac{112.72 - 0.17 \times .45 \times 250}{1000}$ = 0.0936 m^3.
NaOH $_{req}$ = 0.99/0.0936*1.291*1 (m^3) =13.64, Kg/m^3, or 13.64 g/L.