# Investigation of ASR Expansion Due to Total Alkali and Internal Alkali in the Concrete Mixture

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*Alkali-silica reaction (ASR) in concrete has been studied extensively after it was first recognized by Stanton in the late 1930s as a source of deterioration. However, not much has been done to address the actual job mixture parameters' effects on alkali silica reaction (ASR) related expansion and therefore does not represent true workplace situation. This article presents the influence of total alkali (based on total cement and alkali of the cement and internal alkali (depends on the mix design) in the concrete mixture. It was also aimed to see if the correlation between pore solution (internal) alkalinity (also cement alkalinity) and ASR expansion is linear or not. Good linear correlation was established for pore solution alkalinity and ASR expansion at early stages (within one month) and similarly for cement alkalinity (Na2Oeq%) and ASR expansion. However, the later age expansions showed that ASR expansion is more influenced by high alkaline environment than low alkaline environment and they are not proportional. This also confirms the fact that ASR distress becomes critical at high alkaline environment in the early age of the concrete structure. Total alkali showed a near linear relationship with expansion due to ASR.*

**Field of Research:** Concrete, cement, alkalinity, durability, ASR

## 1. Introduction

Alkali-silica reaction (ASR) is a chemical reaction between reactive silica (SiO2) in certain aggregates (e.g.: chert, quartzite, opal, strained quartz crystals) and alkali hydroxides in the concrete pore solution. The pore solution alkalinity comes from the cement alkalinity (expressed as $Na_2O_{eq}\%$). The alkali-silica reaction (ASR) in concrete was first recognized by Stanton in the late 1930s as a source of deterioration. Researchers have shown that alkali content in the cement greater than 0.60% causes the ASR (Stanton 1940, 1942). However, even with the low alkali cement, ASR can happen with highly reactive aggregates. The reaction (between reactive silica and alkali in the pore solution) produces a hydrous alkali-silica gel, often referred to as ASR gel. Formation of the ASR gel alone does not cause cracking, however when the gel absorbs water it shows significant potential to swell. The resulting expansion often results in pressures greater than what the concrete can withstand, which in turn causes cracks in the concrete. The reaction process can be viewed as a two- step process:

*Step 1:* Silica + Alkali = Alkali-Silica-gel

$SiO_2 + 2NaOH + H_2O = Na_2SiO_3.2H2O$ (2KOH can replace 2 NaOH)

*Step 2:* Gel Reaction Product + water = Expansion

A high-alkali Type I cement and a low-alkali cement were used in this study. In order to assess the influence of total cement content on the test specimen expansion, a series of concrete mixtures with different cement content (600 lb/yd$^3$, 700 lb/yd$^3$, and 800 lb/yd$^3$) were prepared at a constant w/c ratio of 0.45.

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Even though cement alkali content contributes to pore solution alkalinity, it is not fully investigated how the pore solution affects the ASR expansion. This research investigates the influence of internal (pore solution) alkalinity on ASR expansion. Low alkali and high alkali cement based concrete- pore solution was matched by soak solution alkalinity.

## 2. Literature Review

The alkali-silica reaction (ASR) in concrete was first recognized by Stanton in the late 1930s as a source of deterioration [Stanton 1940, 1942]. Over the last few decades considerable volume of research has been conducted to assess potential reactivity of aggregate to cause ASR distress in concrete. Numerous test methods to assess aggregate reactivity have been proposed and standardized in the United States, Canada, Europe, China, Japan, South Africa and others. Of these, the Accelerated Mortar Bar Test (AMBT) (e.g., ASTM C1260, CSA A23.2–25A, RILEM TC191-ARP-AAR2), originally proposed by Oberholster and Davis in 1986 has been widely adopted as an accelerated test method for evaluating alkali-silica reactivity of aggregate for use in concrete [ASTM. 2007a, Canadian Standards Association. 1994a,, RILEM 2000b]. On the other hand, the Concrete Prism Test (CPT), e.g., ASTM C1293, CSA A23.2–14A, RILEM TC191-ARP-AAR3 is recognized as the most reliable test procedure which requires at least one or two years for results depending upon the purpose of the test (CSA A23.2, ASTM C1293, RILEM AAR-3)( ASTM. 2007b, Canadian Standards Association. 1994b RILEM 2000a).

The long duration required in this test method renders this method impractical for use in routine testing and evaluation of aggregate materials. The limitations of ASTM C1260 and ASTM C1293 test method have spurred research in development of new test procedures that are rapid and reliable in evaluating aggregate reactivity and efficacy of ASR mitigation measures.

Miniature Concrete Prism Test (MCPT) was introduced to assess the ASR potential of aggregates with reliability greater than the AMBT method and that correlates well with the CPT method, and with results obtained within 2 months compared to 1 year in the CPT [Latifee 2013]. In this project, MCPT method was employed to assess the influence of total cement content on the test specimen expansion.

It can be noted that Chen and Brouwers (2011) reported a method for alkali concentration only for slag cement. Research conducted by Rivard et al. (2007) showed that in the CPT(ASTM C 1293) the pore solution alkalinity decreased over time which could be attributed to leaching. However, in the MCPT the specimens are kept in soak solution, therefore the alkalinity depleted can easily be replenished by the surrounding soak solution.

## 3. Methodology

### 3.1 Materials:

*Aggregate:* A well-known reactive coarse aggregate Spratt limestone was selected with a known non-reactive aggregate

Reactive coarse aggregate: Siliceous Limestone from Spratt Quarry in Ontario, Canada

Non-reactive fine aggregate: Siliceous sand from Dixiana Plant in Pineridge, South Carolina (Fine Aggregate)

Table 1: Properties of the Aggregates

| Property | Spratt (CA) | Foster Dixiana (FA) |
|---|---|---|
| $SG_{OD}$ | 2.69 | 2.63 |
| $SG_{SSD}$ | 2.71 | 2.64 |
| Absorption, % | 0.46% | 0.44% |
| DRUW (kg/m$^3$) | 1568 | X |
| DRUW (lb./ft$^3$) | 97.91 | X |

*Cement:* A high-alkali Type I cement from Lehigh Cement Company, from Evansville Plant in Pennsylvania was used in this study. The alkali content of the cement was measured at 0.82% $Na_2O_{eq}$. In addition, low-alkali cement from ARGOS Cement company from Harleyville, SC was used in limited studies. The chemical composition of these cements is shown in **Table 2**. The autoclave expansion of both cements was well below 0.80 percent, at 0.03% for low-alkali cement and 0.018% for high-alkali cement.

Table 2: Chemical Composition of High-Alkali and Low-Alkali Cement

| Material | Oxide composition by mass (%) | | | | | | | Specific gravity |
|---|---|---|---|---|---|---|---|---|
| | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ | [$Na_2Oe$] | |
| High-Alkali Cement | 19.78 | 4.98 | 3.13 | 61.84 | 2.54 | 4.15 | 0.82 | 3.15 |
| Low-Alkali Cement | 20.6 | 5.1 | 3.4 | 64.50 | 1.0 | 3.1 | 0.49 | 3.15 |

*Reagents:* Reagent grade sodium hydroxide from Fisher Chemicals was used.

### 3.2 Description of the MCPT Method

Miniature Concrete Prism Test (MCPT) assesses the ASR potential of aggregates with reliability greater than the AMBT method and correlates well with the CPT method, and results are obtained within 2 months compared to 1 year in the CPT. In this method, concrete prisms of dimensions 50 mm x 50 mm x 285 mm (2 in. x 2 in. x 11.25 in.) are used for evaluating the reactivity of both coarse and fine aggregates. Mixture proportions of ingredients used in preparing the MCPT specimens are standardized as follows:

Table 3 – Mixture Proportions for the MCPT Specimens

| Item | Mix Proportion |
|---|---|
| Cement Content of the Mix: | 420 kg/m$^3$ (708 lb/yd$^3$) |
| Water-to-Cement ratio: | 0.45 |
| Coarse Aggregate Vol. Fraction (dry): | 0.65 |
| Maximum size of Coarse Aggregate: | 12.5 mm (1/2 in.) |
| Fine aggregate: | Determined based on ACI 211 Absolute Volume Method, i.e. subtracting the proportions of all the other ingredients from 1 m$^3$ of concrete. |
| Coarse Aggregate Gradation: (% by weight of total coarse aggregate): | |
| 12.5 mm – 9.5 mm: | 57.5% |
| 9.5 mm – 4.75 mm: | 42.5% |

The proportions of aggregate in the 12.5 mm – 9.5 mm fraction and the 9.5 mm – 4.75 mm fraction were selected, based on the assumption of maintaining approximately constant surface area across each of the two aggregate size fractions. To ascertain the coarse aggregate reactivity, a non-reactive fine aggregate is used in the concrete mixture to isolate the effects of the reactive aggregate. Similarly, when the reactivity of a fine aggregate is to be ascertained, a non-reactive coarse aggregate is used. In this protocol, a cement having a high alkali content of 0.9 ± 0.1% $Na_2O_{eq.}$ is required to be used. The alkali content of the concrete is boosted to 1.25% $Na_2O_{eq.}$ by weight of cement similar to the procedure used in the standard ASTM C 1293 test method. The test specimens are demolded 24 hours after casting and after taking the initial length reading the prisms are submerged in water at 60° Celsius for an additional 24 hours. At the end of 48 hours from the time of casting, the zero-day length change reading is taken, before the prisms are transferred to 1N NaOH soak solution that has already been pre-conditioned to 60° Celsius temperature. Subsequent length change readings are periodically taken at 3, 7, 10, 14, 21, 28, 42, 56, 70 and 84 days.

## 4. Results and Discussions:

### 4.1 Alkali Loading

**Table 4** shows six concrete mixtures in which the w/c ratio of the concrete was maintained at 0.45, however the cement alkali content and the cement content of the concrete was varied. A high-alkali cement and a low-alkali cement were used in this study, using three levels of cement content at 356 kg/m$^3$(600 lb/yd$^3$); 415 kg/m$^3$ (700 lb/yd$^3$); and 475 kg/m$^3$ (800 lb/yd$^3$). From these combinations six levels of alkali loading in concrete were generated. These ranged from a low value of 2.94 lb/yd$^3$ to a high value of 10 lb/yd$^3$.
**Table 5** shows the alkali loading in each of these concrete mixtures along with their 56-day MCPT expansion value. **Figure 1** shows a comparison between 56-day % expansion and alkali loading. From this data it can be observed that the correlation

between the alkali loading and the 56-day expansion in the MCPT method is highly linear ($R^2$= 0.99).

Table 4: Alkali loading of different MCPT specimens

| Cement Content (lb/yd$^3$) | Alkali loading, lb/yd$^3$ | |
|---|---|---|
| | Low Alkali , 0.49% $Na_2O_e$ | High Alkali boosted to 1.25% $Na_2O_e$ |
| 600 | 2.94 | 7.5 |
| 700 | 3.43 | 8.75 |
| 800 | 3.92 | 10 |

Table 5: Alkali loading and corresponding 56-day expansions of MCPT specimens

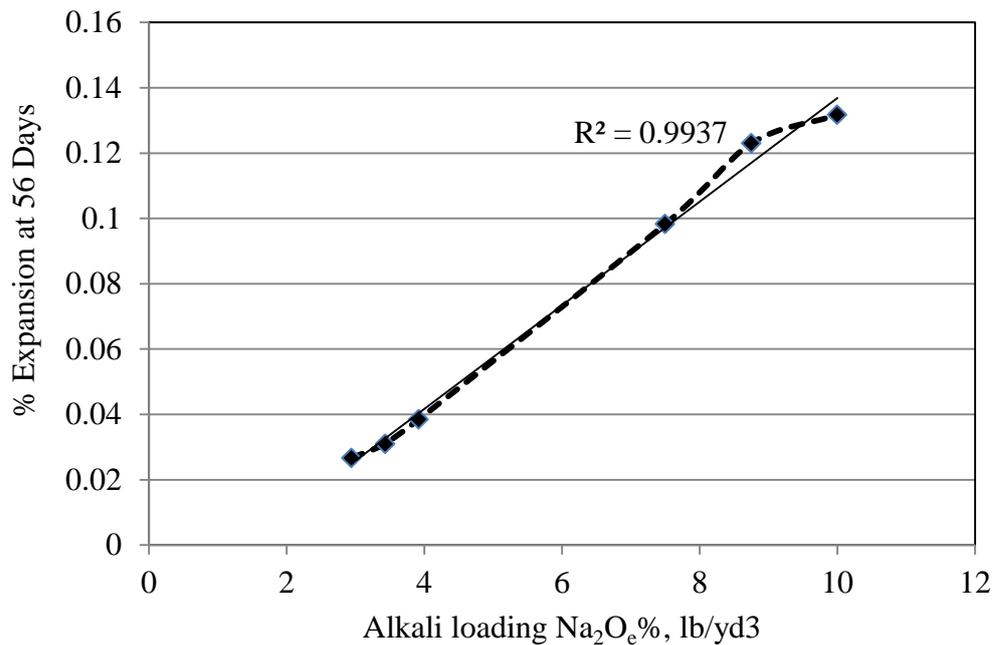| Cement type | Alkali loading, lb/yd$^3$ | 56% Expansion |
|---|---|---|
| Low Alkali , 0.49% Na2Oe | 2.94 | 0.0267 |
| Low Alkali , 0.49% Na2Oe | 3.43 | 0.031 |
| Low Alkali , 0.49% Na2Oe | 3.92 | 0.0385 |
| High Alkali boosted to 1.25% $Na_2O_e$ | 7.5 | 0.0983 |
| High Alkali boosted to 1.25% $Na_2O_e$ | 8.75 | 0.123 |
| High Alkali boosted to 1.25% $Na_2O_e$ | 10 | 0.1317 |

Figure 1: Comparison between alkali loading and 56-day % expansion

## 4.2 Different Alkali Cements and Soak-solutions

Three set of tests were conducted with different cement alkali content in the mix. The concrete prisms made of Spratt limestone were submerged in soak solution matching pore solution alkalinity at 60 degree Celsius. Three concrete prisms were made in each batch. The three tests conditions are as follows- 1. Cement alkali boosted to 1.25% Na2Oeq and 1 N NaOH soak solution matching pore solution 2. Cement alkali of 0.82% Na2Oeq and 0.7 N NaOH soak solution matching pore solution 3. Cement alkali of 0.49% Na2Oeq and 0.45 N NaOH soak solution matching pore solution The expansion curves (% expansion due to ASR vs. Age in days), until 84 days, are shown in Figure 1. The % expansion is highest for Cement alkali (boosted) of 1.25% Na2Oeq and 1 N NaOH soak solution matching pore solution and lowest for Cement alkali of 0.49% $Na_2O_{eq}$ and 0.45 N NaOH soak-solution matching pore-solution, which is expected.
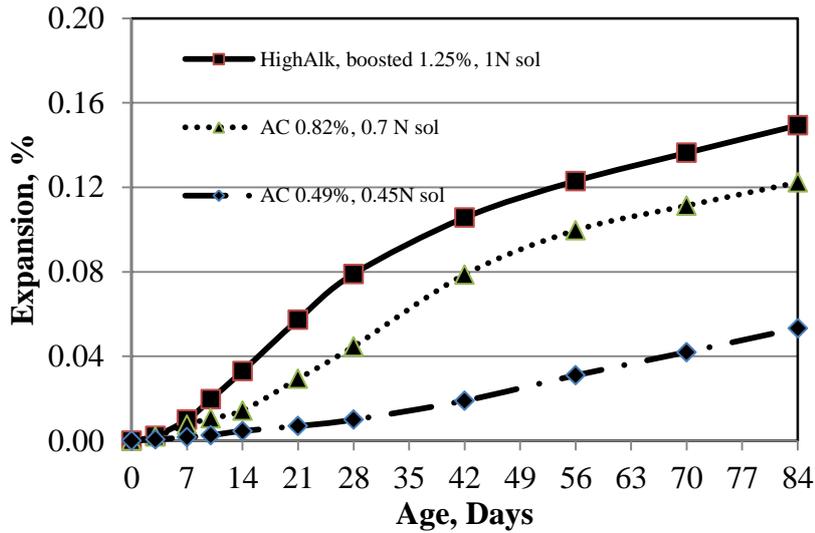
Figure 2: Expansion curves of different cement alkalinity and soak solution alkalinity concrete prisms in the MCPT

However, plotting the 28-day and 56-day % expansion vs. Soak solution alkalinity reveals that there is higher correlation between 28-day % expansion and Soak solution alkalinity than 56 day % expansion and Soak solution alkalinity as shown in Figures 3 and 4.
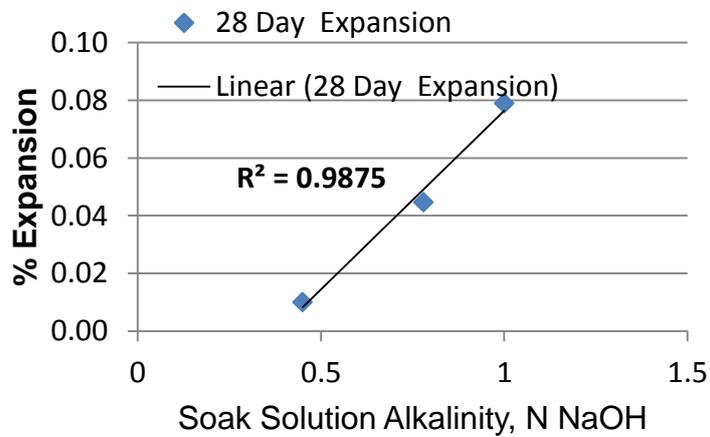


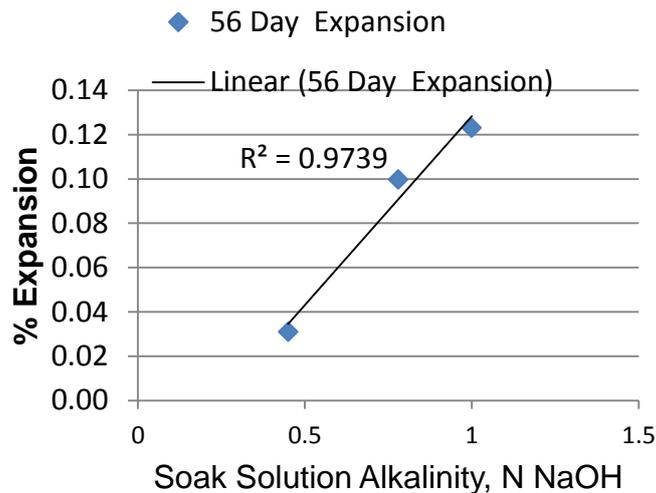Figure 3: 28-day % expansion vs. Soak solution alkalinity

Figure 4: 56-day % expansion vs. Soak solution alkalinity

The early age (28-day) linear behavior or correlation between pore solution (also cement alkalinity) and ASR expansion can be attributed to the fact that the ASR gel formation becomes a function of pore solution and cement alkalinity. At later stage, 56-day, the overall expansion in the high alkaline environment is much higher than low alkaline environment. This can be due to the fact that the average rate of expansion for high alkaline situation during the test period is much higher than the low alkaline situation. However, it is worth to note that at the age from 56-84 days the slope of expansion curve (rate of expansion) for low alkaline environment is increasing and for high alkaline environment it is decreasing. This suggests that even with low alkali cement, sufficient source of alkali can cause ASR problems in the field at later ages.

The relationship can be expressed as a linear form for 28-day and as exponential form for 56-day.

% Expansion at 28-day = 0.1251*Pore soln. alkalinity– 0.451………………… (1)

% Expansion at 56-day = $-0.358x^2$ +0.686x-0.205........................................... (2)
Where, x=Pore soln. Alkalinity(in N NaOH)

## 5. Conclusion

Based on the studies conducted, the following conclusions are drawn.
Increase in the cement content of concrete mixtures increases the percent expansion observed in the MCPT method, and this trend is more significant for the high-alkali cement mixtures than the low-alkali cement mixtures. The difference in the 56-day expansion of test specimens with high-alkali cement contents of 600 and 800 lb/yd$^3$ of high-alkali cement was found to be 0.0334%. The corresponding difference in 56-day expansion of test specimens with low-alkali cement mixtures was 0.0188. It appears that total alkali has a near linear relationship with expansion due to ASR.
The investigation findings corroborates that the influence of total cement content is more significant with the high alkali cement than the low alkali and there is interaction effect between the amount of cement and cement alkalinity on the ASR related expansion.

The experiment showed that the ASR related expansion in concrete is correlated with pore solution alkalinity and cement alkalinity. If we consider cement alkalinity the correlation is almost linear (R2=0.99) at early ages (28-day expansion). The variation starts at later ages (56-days) which indicate that pore solution/cement alkalinity effect is linear within first month and non-linear at later age. Percent expansion of concrete prisms can be predicted based on cement alkalinity, given that the aggregate reactivity of the field matches closely with the one tested in the laboratory. Increasing the temperature in general increases the ASR expansion. The $60^0$ for the experiment was chosen to accelerate the expansion process and in some cases in hot weather conditions the concrete pavement temperature can reach $60^0$. The influence of humidity is important in ASR (some researchers reported 80% RH needed for ASR reaction). In this experiment, the concrete specimens were submerged in alkaline solution so as to avoid storage condition variation and the soak solution could replenish the lost alkalinity in the pore solution.


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