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JOB MIX PARAMETERS' EFFECTS ON ALKALI SILICA REACTIVITY RELATED EXPANSION IN CONCRETE

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Abstract: Numerous test methods to assess aggregate reactivity (for ASR) have been proposed and standardized in the last couple of decades. However, all of the standard test methods can only find ASR potential of aggregates within the scope of the test (with standard test mix proportion) but none of these methods incorporate actual job mix propotions (with job mix w/c, total cement amount and total alkalinity, SCM replacement % etc.) and therefore can not predict correctly the actual concrete expansion potential due to ASR. This article focuses on the job mixture parameters' effects on ASR expansion. Miniature Concrete Prism Test (MCPT)-a rapid ASR test method was employed to evluate the job mix parameters' effects. The factors considered are-influence of i) w/c ratio ii) Cement Alkalinity iii) Total Cement Content iii) Total Alkali Loading. The ASR expansions of concrete specimens (as % expansion) in different variable conditions were measured. Based on the results, it is found that the w/c ratio of concrete has minimal influence on the observed expansions of specimens due to ASR (within the scope of the research), but cement alkalinity and cement content (in terms of alkali loading) has significant effect(within the scope of the research) and there is a very good correlation (near linear) between the total alkali loading and the expansion due to ASR.

Keywords: C*oncrete, cement, aggregate, alkali silica reactivity, job mix, water*

1.0 Introduction

Alkali-silica reaction (ASR) is a chemical reaction between reactive silica (SiO_2) in certain aggregates 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 [1, 2]. Researchers have shown that alkali content in the cement greater than 0.60% causes the ASR [1, 2]. However, even with the low alkali cement, ASR can happen with highly reactive aggregates.

The reaction produces a hydrous alkali-silica gel, often referred to as ASR gel. 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:
Reactive Silica + Alkali = Alkali-Silica-gel
SiO_2 + 2NaOH +H_2O = $Na_2SiO_3.2H_2O$ (2KOH can replace 2 NaOH)

Step 2:
Gel Reaction Product + water = Expansion

Over the last few decades considerable volume of research has been conducted to assess the 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 [3]. 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 C 1293, RILEM AAR-3)[4]. Research conducted by Rivard et al.[5] showed that in the CPT(ASTM C 1293) the pore solution alkalinity decreased over time due to leaching.

In this research, modified MCPT method was employed to evaluate the job mixture parameters which has reliability greater than the AMBT method and that correlates well with the CPT method [6]. In this research, low alkali and high alkali cement based concrete- pore solution was matched by soak solution alkalinity. In order to assess the influence of total alkali content on the test specimen expansion in MCPT, a series of concrete mixtures with different cement content 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) were prepared.

The total alkali loading was found by multiplying the amount of cement in the mix and the alkali level in the cement. This can be expressed as:

Alkali loading, kg/m^3 (lb/yd^3) = Cement content, kg/m^3 (lb/yd^3) x Cement Alkalinity (Na_2O_{eq} %) (1)

2.0 Materials and Methods

2.1 Description of the MCPT Method

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 in the MCPT specimens are standardized in Table 1:

Table 1: 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%

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.

2.2 Modified MCPT Method:

In this method, everything is same except the soak solution (instead of being 1N NaOH), matches the pore solution based on the predictive equation described below. The predicted alkalinity of the pore solution was calculated based on the equation developed by Stark and Diamond in SHRP C-342 [7] as follows:

$$[OH^-] = 0.339\ Na_2O\ \%\ /\ (w/c) + 0.022\ +/-\ 0.06\ mol/L \qquad (2)$$

Also, 56-day expansion data in each case was taken as the specimen percent expansion taken into account. Based on this predictive equation, with a constant w/c of 0.45 used in all cases, for low-alkali cement mixtures (alkali content of the cement was measured at 0.49% Na_2O_{eq}), a pore solution composition of 0.45 N NaOH was determined, while for the high-alkali cement (alkali content of the cement was measured at 0.82% Na_2O_{eq}) a pore solution composition of 0.78 N NaOH solution was established. It can be noted that Chen and Brouwers[8] reported a method for alkali concentration only for slag cement.

2.3 Materials

Aggregate: A well-known reactive coarse aggregate Spratt limestone was selected with a known non-reactive aggregate. Properties of the aggregates are given in Table 2. 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 2: Properties of the Aggregates

Property	Spratt (CA)	Foster Dixiana (FA)
SG_{OD} (Specific Gravity, Oven Dry)	2.69	2.63
SG_{SSD} (Specific Gravity, Saturated Surface Dry)	2.71	2.64
Absorption, %	0.46%	0.44%
DRUW (kg/m^3)	1568	X
(DRUW-Dry Rodded Unit weight)		

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 3. 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 3: 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_2O_{eq}]	
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.
Water: Deionized water was used in all the cases.

3.0 Results and Discussion

3.1 Influence of W/C Ratio on Expansion

In order to assess the influence of w/c ratio on the test specimen expansion in MCPT, a series of trial concrete mixtures with different w/c ratios (0.40, 0.45 and 0.50) were prepared. In this study, the soak solution composition in the high-alkali cement mixtures was maintained at 1N NaOH, while in low-alkali cement mixtures a soak solution composition of 0.45N NaOH was used. This value matches the pore solution alkalinity of a concrete containing low-alkali cement (Na_2O_{eq} = 0.49%), at a w/c ratio of 0.45 w/c. The expansion of prisms for high- and low-alkali cements, with each of the three w/c ratios – 0.40, 0.45 and 0.50 are shown in Figures 1 and 2.

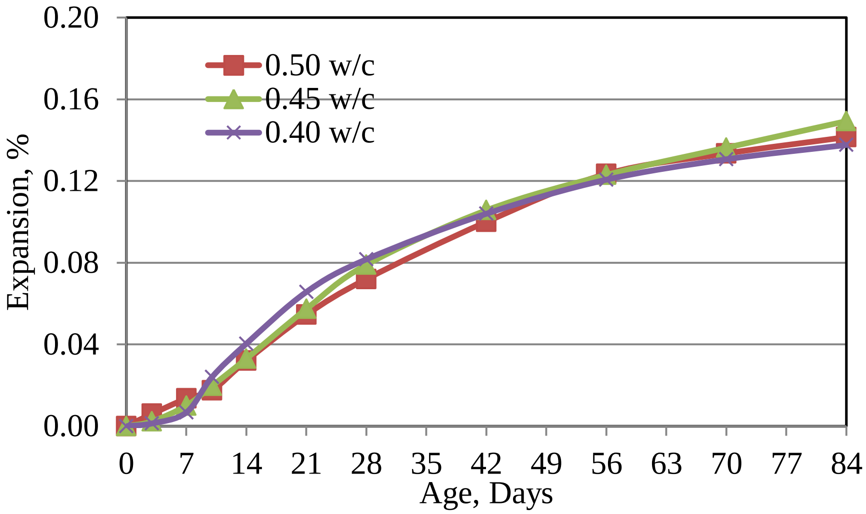

Figure 1: Effect of w/c ratio on the expansion of test specimens in MCPT with high-alkali cement.

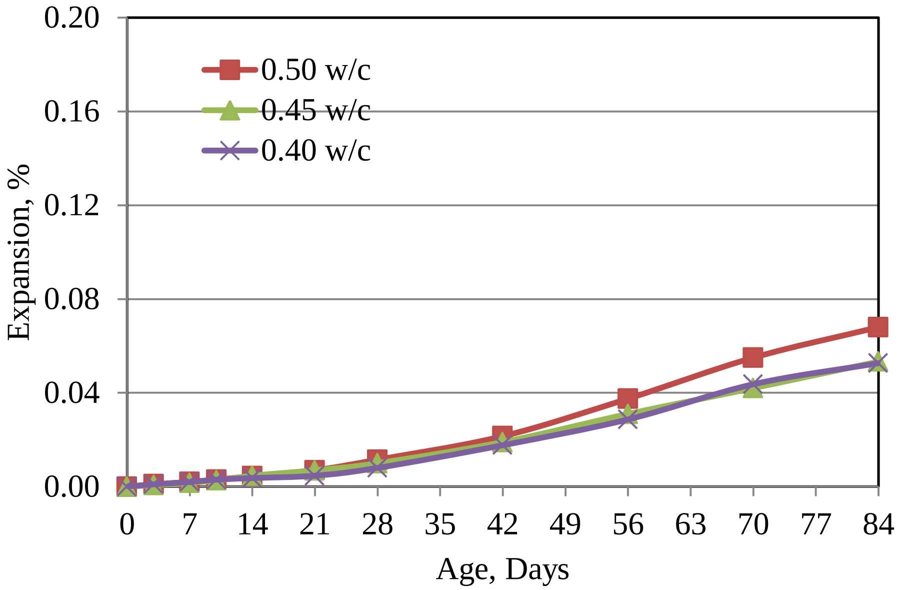

Figure 2: Effect of w/c ratio on the expansion of test specimens in MCPT with low-alkali cement.

In the case of high-alkali cement specimens, the difference between the 56-day expansion of MCPT test specimens with w/c ratio of 0.50 and 0.40 is 0.0028%, and continues to be minimal at later ages and for the low -alkali cement specimens with the 0.40 and 0.50 w/c ratios the 56-day expansions are themselves are very low 0.0287% and 0.0375% (< 0.040% limiting value in MCPT). Based on these results, it appears that the w/c ratio of concrete within the normal operating range of 0.40 to 0.50 may have minimal influence on the observed expansions of specimens in the MCPT method. In these studies, the soak solution concentration used in all of the high-alkali and low-alkali MCPT mixtures were maintained at 1.0N NaOH and 0.45N NaOH, respectively. Having the same soak solution in each set may have reduced the clarity of the impact of interaction between cement alkali content and w/c ratio on the expansion observed in the test specimens. Nevertheless, for the conditions tested in this study the w/c ratio does not appear to have an influence on the MCPT expansion, within the range of 0.40 to 0.50. But, Lingard found that at 0.3 w/c the expansion is lower than 0.45 which may becuase of denser concrete with slower diffusion of water and ion [9]

Figure 3 shows the influence of w/c ratio on the 56-day expansion behavior of test specimens for both high-alkali and low-alkali test specimens. Notice that, the trend lines for both high-alkali and low-alkali cements are almost parallel, indicating that there is no interaction between alkali content of cement and the w/c. In other words, changes in w/c ratio have similar impact on the 56-day MCPT expansion for any given cement alkali content.

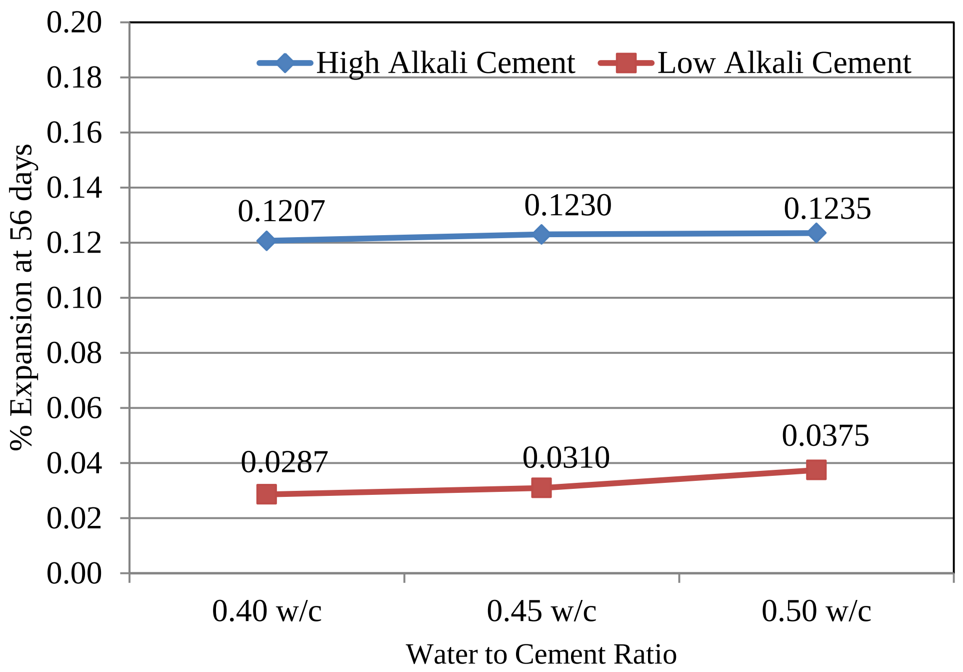

Figure 3: Effect of w/c ratio on the % expansion of test specimens at 56 days in the MPCT with high-alkali and low-alkali cement

Figure 4 and 5 shows the rate (slope) of expansion in MCPT specimens as a function of different w/c ratios for high- alkali cement and low-alkali cements, respectively. The rate of expansion curves show that the high alkali cement specimens have high activity in the initial period, but draws down at the late age, whereas the low alkali cement had little activity at the initial period but continued to grow steadily afterwards. The rate of expansion of high- alkali cement mixtures tends to increase and then decreases at all the three w/c ratios investigated. However, the peak (i.e. highest rate of expansion) occurs at much earlier ages for concrete mixtures having a lower w/c ratio than those with high w/c ratio. For the low alkali cement mixtures, the rate of expansion does not show a peak; rather it continues to grow steadily throughout the test duration. This indicates that with high-alkali cements there is a definite non-linear growth in the test specimens at early ages when the internal pore solution is more dominant in affecting the reaction rate. At low w/c ratio, the pore solution is of higher concentration and the rate of reaction is greater, conversely at high w/c ratio the pore solution concentration is lower and the rate of reaction is slower at early ages. However with increase in age, the micro-environment within the concrete specimens is dominated by the external soak solution alkalinity and masks the influence of any pore solution effects. This trend is more apparent with high-alkali cement than low-alkali cement.

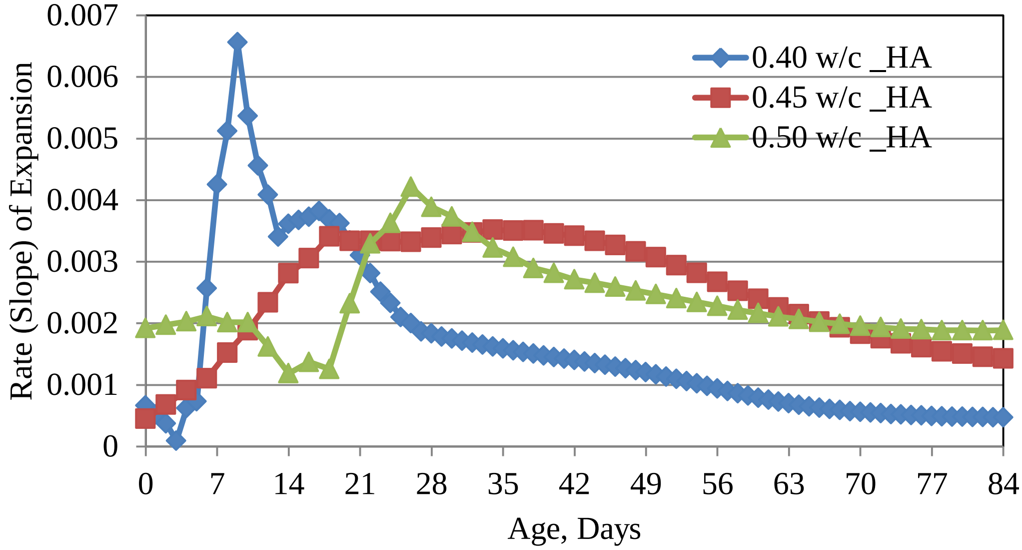

Figure 4: Rate (slope) of expansion of different of w/c ratio with high alkali cement

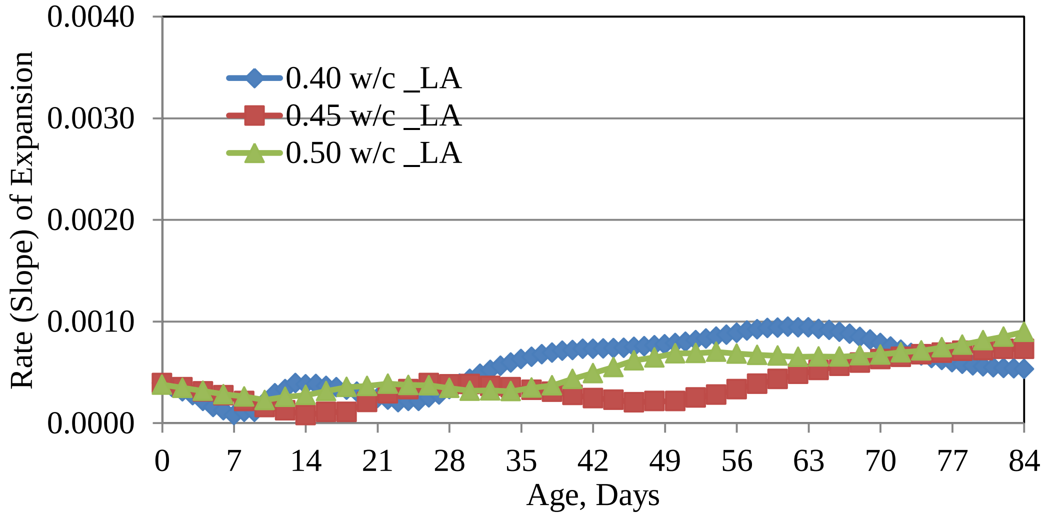

Figure 5: Rate (slope) of expansion of different of w/c ratio with low-alkali cement

3.2 Influence of Total Alkali Loading on Expansion

In order to assess the influence of total alkali content on the test specimen expansion in MCPT, a series of concrete mixtures with different cement content 356 kg/m^3; 415 kg/m^3 ; and 475 kg/m^3 were prepared at a constant w/c ratio of 0.45. The soak solution composition in the high-alkali cement mixtures was maintained at 1N NaOH, while in low-alkali cement mixtures a soak solution composition of 0.45N NaOH (matching the pore solution alkalinity for the low-alkali cement, 0.49%, at 0.45 w/c ratio) was employed. Since the w/c ratio was kept constant at 0.45, the pore solution concentration in each of the mixes was assumed to be constant for a cement of given alkali content.

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 , 415 kg/m^3 , 475 kg/m^3. From these combinations six levels of alkali loading in concrete were generated.

Table 5 shows the alkali loading in each of these concrete mixtures along with their 56-day MCPT expansion value. Figure 6 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). There appears to be a near linear relationship between the total alkali loading and expansion due to ASR

Table 4: Alkali loading of different MCPT specimens

Cement Content (kg/m^3)	Alkali loading, kg/m^3	
	Low Alkali , 0.49% Na_2O_{eq}	High Alkali boosted to 1.25% Na_2O_{eq}
356	1.74	4.45
415	2.03	5.19
475	2.33	5.94

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

Cement type, Cement Content (kg/m^3)	Alkali loading, kg/m^3	56% Expansion
Low Alkali , 0.49% Na_2O_{eq}, 356 kg/m^3	1.74	0.0267
Low Alkali , 0.49% Na_2O_{eq}, 415 kg/m^3	2.03	0.031
Low Alkali , 0.49% Na_2O_{eq}, 475 kg/m^3	2.33	0.0385
High Alkali, 1.25% Na_2O_{eq}, 356 kg/m^3	4.45	0.0983
High Alkali, 1.25% Na_2O_{eq}, 415 kg/m^3	5.19	0.123
High Alkali, 1.25% Na_2O_{eq}, 475 kg/m^3	5.94	0.1317

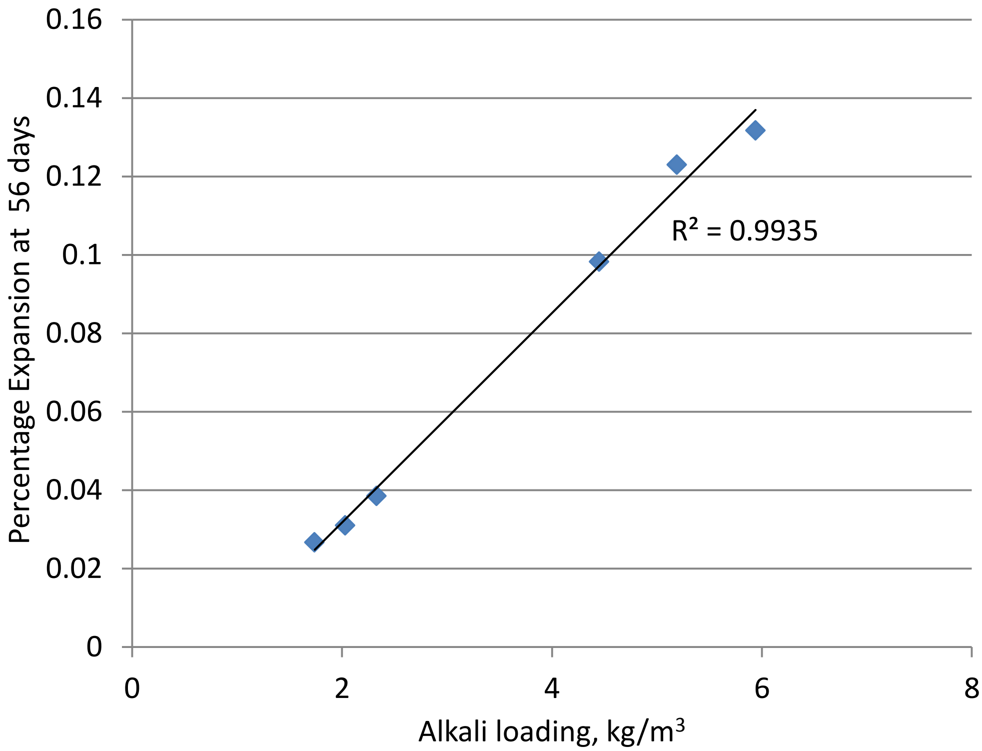

Figure 6: Relation between alkali loading and 56-day % expansion

4.0 Conclusions

Based on the studies conducted on the job concrete mixtures, the following conclusions are drawn:

- Within the normal operating range of w/c ratios between 0.40 and 0.50, the w/c ratio of concrete has minimal influence on the observed expansions of specimens in the MCPT method. This may be because as the w/c ratio is reduced, although the alkali concentration goes up in the pore solution, the strength of the concrete is considerably improved. The strength and the pore solution concentration effects on the ASR-induced expansion in test specimens negate each other within this range. Also, there does not appear to be any interaction effects between alkali content of cement and the w/c on the expansions observed in the MCPT method.

- The rate of expansion of concrete mixtures with high-alkali cements at different w/c ratios shows a maximum value and then decreases with age, whereas for the low alkali cement the rate continues to grow steadily with no discernible maximum. In the case of concrete mixtures with high-alkali cement, the maximum rate of expansion also appears to occur at earlier ages with decreasing w/c ratio, however, the ultimate expansion at later ages is virtually the same regardless of the w/c ratio.

- At a constant w/c ratio, the concrete prism expansions in the MCPT procedure increase with increasing cement content in the mixture from 356 kg/m^3 to 475 kg/m^3. Also, it appears that the cement content of the concrete mixture has more dominant influence on the expansions observed in concrete prisms than the w/c ratio within the typical ranges of values employed.

- 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.

- Total alkali loading correlates excellent (R^2= 0.9935) with % expansion(due to ASR) within the scope of the test range (0.49% to 0.82% Na_2O_{eq} alkalinity and 356 kg/m^3 to 475 kg/m^3 of cement in the job mix).

5.0 Acknowledgements

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