DEVELOPING A RAPID CONCRETE TEST TO ASSESS ALKALI-SILICA REACTION

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Abstract

The concrete prism test (ASTM C 1293) has been considered as a reliable alkali silica reaction (ASR) test method, but long test duration and alkali leaching are the inherent limitations of this method. A rapid concrete cylinder test (RCCT) has been developed to access alkali silica reactivity of aggregates in concrete. In RCCT method, a cylindrical concrete specimen 7.62 x 15.24 cm (3 x 6 inches) is immersed in a soak solution of equal chemistry with pore solution (leach-proof condition) and the length change is measured through LVDT and data acquisition system at 60°C. Cylinders made with highly reactive borosilicate glass balls were tested first to validate the proposed method. The automatic data collection system under constant temperature and leach-proof condition ensure reliability of the RCCT method. RCCT method can be operated at different alkali loadings. The data shows that RCCT method with relatively low alkali loadings (i.e., 2.7 kg/m^3 (4.5 lb/yard^3) as opposed to 5.3 kg/m^3 (8.9 lb/yard^3) in the current ASTM C 1293 method) can effectively be used to assess aggregate reactivity in a relatively short time (i.e., 28-35 days). A favorable comparison between the proposed RCCT and ASTM C 1293 has been observed. RCCT method has shown promises to optimize fly ash contents in order to develop safe ASR-resistant mixes. The RCCT method also has the ability to test job mix.

Keywords: alkali-silica reaction, new rapid test, concrete cylinder test, testing at varying alkali loadings

1 INTRODUCTION

Alkali-silica reaction (ASR) is a deleterious chemical reaction between hydroxyl (OH^-) ions associated with alkalis (sodium and potassium) present in cement or other sources and certain reactive siliceous components that may be present in coarse or fine aggregates, produces a gel. When this alkali-silica gel absorbs moisture, it expands, and eventually produces cracks in aggregate particles as well as in the cement paste in concrete. ASR is recognized as a major concern by several Department of Transportation (DOTs) and new cases of ASR are continuously being reported despite the advancement of the last decades. Aggregates have been found to produce expansive gel even at low alkali loadings.

Since the ASR-related problems were identified in the early 1940s [1], extensive work has been carried out on ASR over the decades. One of the main areas of research was to develop a quick and reliable test method to assess ASR potential of aggregate and concrete based on empirical approach. The main purpose of an ASR test method is to predict aggregate reactivity in a rapid and reliable manner, which ensures developing ASR-resistant mixes. The current approach of ASR testing and mitigating damaging ASR heavily depends on accelerated mortar bar test (AMBT, ASTM C 1260 [2]) and concrete prism test (CPT, ASTM C 1293 [3]). In the AMBT method, aggregate crushing (especially for coarse aggregates) is involved in order to meet the specified aggregate gradation. The mortar bars are soaked in 1N NaOH solution at 80°C and reactivity is determined based on 14-days mortar bar expansion. In the CPT test, NaOH pallets are added to the concrete during mixing in order to enhance concrete alkali level. The concrete prisms are stored above water at 38°C for 1 year and length change due to ASR is periodically measured. The potential of an aggregate to deleterious expansion due to ASR is identified based on 1-year concrete prism expansion. Although these approaches have resulted in significant advances in the avoidance of ASR damage in concrete structures, some of the limitations of the AMBT and CPT methods are well documented by several researchers and agencies [4,5]. The test conditions of AMBT are severe (i.e., 1N NaOH at 80°C) and the test results are unrelated to field performance. Moreover, aggregate crushing in the AMBT method found to be the cause of erroneous reactivity prediction for certain types of aggregates. CPT has been considered as the best index for field performance, but the test duration imposes a major limitation.

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Efforts have been made by different researchers to develop an accelerated concrete prism test (ACPT) by changing the aggregate gradation and temperature of testing of ASTM C 1293 [6-9]. A reasonably good correlation between one year concrete prism expansion at 38°C and two to four months prism expansion at 60°C was observed by these researchers. Although the test duration is shortened by simply increasing the test temperature, a significant reduction in expansion associated with higher alkali leaching in the ACPT than the CPT was noticed [10]. Therefore, the reliability of the modified version of C 1293 is yet to be established. Aggregates belonging to false positive and negative categories based on the current test methods are gradually growing. Therefore, there is a growing demand for a rapid and reliable ASR test method in order to formulate ASR resistant concrete mix. The CPT is not capable to test the effect of cement alkalis and testing at various alkali loadings. Therefore, it would be beneficial if a test can assess the ASR potential of each aggregate at various alkali loadings.

The main objective of this study was to develop a rapid concrete cylinder test (RCCT) method to access ASR. In order to overcome some of the above limitations of the CPT (e.g., alkali leaching, test duration) and come up with a rapid ASR concrete test method, the following steps were undertaken:

a. Eliminating alkali leaching from the concrete specimen during testing
b. Conducting the test inside an oven ensures complete thermal equilibrium of the whole assembled RCCT system.
c. Use of automatic data collection system [i.e., a combination of linear variable differential transducer (LVDT) and data acquisition system] eliminates errors (if any) associated with length change measurement at temperature (e.g., room temperature) different from the testing temperature by the standard comparator method.
d. Testing cylinders made with highly reactive borosilicate glass balls as a proof of concept
e. Making the RCCT capable to test concrete specimens at varying alkali loadings.

2 MATERIALS AND METHODS

2.1 Materials

Cylinders made of borosilicate glass balls and concrete cylinders using aggregates with varying reactivity (Table 1) were tested. The type of reactive siliceous component(s) present in each selected aggregate was determined by petrographic observation (i.e., ASTM C 295) and included in Table 1. Earlier, the authors have developed a device called volumetric change measuring device (VCMD) as a rapid chemical method to determine alkali silica reactivity of aggregate in terms of measuring compound activation energy of ASR within 5 days [11-13]. The VCMD simulates aggregate–pore solution reaction that exists in concrete and measures free solution volume contraction due to ASR over time. The solution volume change over time at multiple temperatures is modeled to determine compound activation energy (CAE) based on the rate theory. The lower the CAE the higher the reactivity is. Researchers have developed a CAE-based aggregate ASR classification system [12]. The CAE values of the studied aggregates are also included in Table 1.

TABLE 1: List of Aggregates with Reactivity Data Based on the Current Methods.

Aggregate	*ASTM C 1260 (14-day Expansion, %)*	*ASTM C 1293 (1-year Expansion, %)*	*ASTM C 295 (Reactive Constituents)*	*CAE [12] (KJ/mole)*
Borosilicate glass	-	-	Amorphous silica	5.53 (VHR)
CA1	0.012	0.027	Few siliceous (e.g., Chert) inclusions in limestone	61.70 (NR)
CA2	0.417	0.078	Acid volcanic, Chert	29.73 (HR)
CA3	0.140	0.020	Few separate chert particle in river gravel	57.03 (NR/VSR)
FA1	0.317	0.058	Low strained QTZ, Chalcedony, Chert	32.64 (R)
FA2	0.381	0.391	Acid volcanic, Chert	26.96 (HR)
FA3	0.079	0.035	Few siliceous (e.g., Chert) inclusions in limestone	60.36 (NR)
FA4	0.242	0.043	High strained QTZ, Chert	36.39 (R)

FA-Fine aggregate, CA-Coarse aggregate, QTZ-Quartz, NR-nonreactive, R-reactive, HR-highly reactive, VHR – very highly reactive, VSR- very slowly reactive.

2.2 Test equipment

Figure 1 shows the setup for the RCCT method. A 7.62 x 15.24 cm (3 × 6 inch) concrete cylinder with cast-in place threaded rod is placed inside the container after 7 days of curing in a moist room (relative humidity (RH) @ 98±2%, temperature @ 23±2°C). The specimen is then immersed in a soak solution of chemistry equal to pore solution alkalinity of the studied concrete. The threaded rod in the specimen is connected to the LVDT rod. During expansion due to ASR the LVDT rod moves inside the LVDT (a maximum range of 5.08 cm (2 inches) with a resolution of 0.0025 cm (0.001 inch)) and creates electrical signals. These signals are converted to LVDT displacements (inch) through the data acquisition system and recorded by the attached computer.

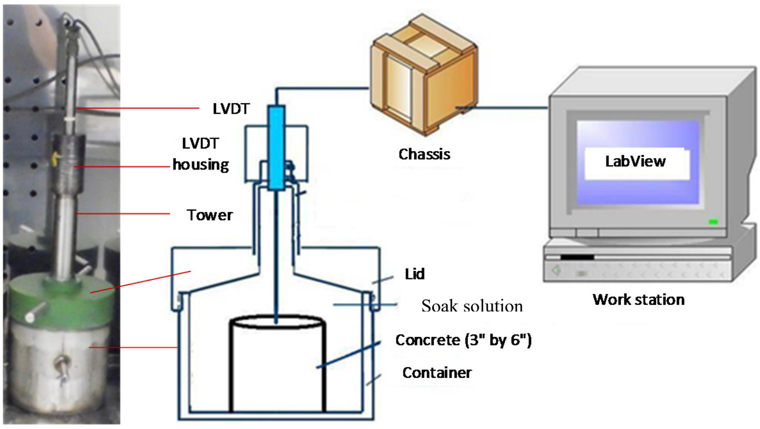


FIGURE 1: The test set up for the RCCT method. Note, the device in the left represents a fully assembled RCCT device placed inside an oven.

2.3 Mix design and specimen preparation

The concrete mix design details are presented in Table 2. The four levels of alkali loadings (i.e., 1.8, 2.4/2.7, 4.0, and 5.3 kg/m^3 (3.0, 4.0/4.5, 6.7, and 8.9 lbs/yard^3)) were selected. Based on judicious use of two Type I/II portland cements [CM 1 - a low-alkali (Na_2O_{eq} = 0.57%) cement, CM2 - a high-alkali (Na_2O_{eq} = 0.82%, CM2)] with varying cement contents (CC) and adding extra NaOH pallets (whenever needed), the four levels of alkali loadings were achieved. The w/c (0.45) and coarse aggregate factor (CAF = 0.76) remain constant for all the mixes. The mixes with high alkali loadings (i.e., alkali boosted mixes with 6.7 and 8.9 lbs/yard3) are similar to standard mixes specified for ASTM C 1293. The purpose of testing mixes with low levels of alkali loadings (i.e., 1.8, 2.4/2.73 kg/m^3 (3.0, 4.0/4.5 lbs/yard^3)) was to verify the efficacy of testing RCCT method at lower levels of alkalinity (no alkali boosting) than that at CCT method. Each concrete (Table 2) was mixed by using the hand mixing procedures in accordance with ASTM C192. Cylinders (7.62 x 15.24 cm (3 by 6 inches)) using each concrete mix were cast followed by curing for 7 days in a moist room (RH @ 98±2%, T @ 23±2°C). The researchers have conducted preliminary investigation using specimens cured at both 7 and 14 days and found no considerable difference in results till 49 days between the specimens of two curing ages and decided to select 7 days curing as a standard practice for the RCCT.

TABLE 2: Concrete Mix Design along with the Corresponding Pore Solution Chemistry Data.

Concrete Mix Design								***Pore Solution Chemistry***				
Mix	CA	FA	Alkali (kg/m^3)	Cement Type	CC (kg/m^3)	Add. NH (kg/m^3)	$Na_2O_{eq.}$ (%)	Na^+ (ppm)	K^+ (ppm)	Na^+ (N)	K^+ (N)	Na^+_e (N)
1a	CA1	FA4	2.4	CM1	420	-	0.57	1800	19000	0.08	0.49	0.37
1b			4.0	CM1	420	1.6	0.95	4898	16100	0.21	0.41	0.46
1c			5.3	CM1	420	2.7	1.25	14132	17300	0.61	0.44	0.88
2a	CA2	FA3	2.4	CM1	420	-	0.57	1800	19000	0.08	0.49	0.37
2b			4.0	CM1	420	1.6	0.95	4898	16100	0.21	0.41	0.46
2c			5.3	CM1	420	2.9	1.25	14132	17300	0.61	0.44	0.88
3a	CA1	FA1	1.8	CM1	312	-	0.57	1539	21031	0.07	0.54	0.38
3b			2.7	CM2	325	-	0.82	4153	31562	0.18	0.81	0.66
3c			5.3	CM2	420	1.8	1.25	12755	31865	0.55	0.81	1.04
4a	CA1	FA2	1.8	CM1	312	-	0.57	1539	21031	0.07	0.54	0.38
4b			2.7	CM2	325	-	0.82	4153	31562	0.18	0.81	0.66

Concrete Mix Design								***Pore Solution Chemistry***				
Mix	CA	FA	Alkali (kg/m^3)	Cement Type	CC (kg/m^3)	Add. NH (kg/m^3)	$Na_2O_{eq.}$ (%)	Na^+ (ppm)	K^+ (ppm)	Na^+ (N)	K^+ (N)	Na^+_e (N)
4c			5.3	CM2	420	1.8	1.25	12755	31865	0.55	0.81	1.04
5	CA2	FA2	2.7	CM2	325	-	0.82	4153	31562	0.18	0.81	0.66
6	CA1	FA3	2.7	CM2	325	-	0.82					
7	CA2	FA3	2.7	CM2	325	-	0.82					
8	CA3	FA3	2.7	CM2	325	-	0.82					

Determination of pore solution alkalinity

The cement paste cylinders (5.08 x 10.16 cm (2 by 4 inches)) corresponding to each mix in Table 2 were cast and covered with plastic foil, and then cured under 98±2% RH at 23±2°C for 7 days followed by de-molding and pore solution extraction by using a high-pressure squeezing method [14]. The extraction method consists of pressing a cement paste cylinder with a loading of 181.4 kg (400 lbs) to extract pore solution (2-5 ml) from the specimen. In order to get a representative and enough quantity of pore solution, pore solution extraction from three cement paste specimens followed by homogeneous mixing of the extracted solution was adopted as a standard practice for each mix. The Na^+ and K^+ concentrations of the extracted pore solutions for each mix were determined by an Atomic Absorption Spectrometer and presented in Table 2. Alkalinity based on the measured concentrations of Na^+ and K^+ were calculated separately and also included in Table 2. The Na equivalent alkalinity (Na^+_e) [14] in Table 2 represents the total combined pore solution alkalinity (PSA)) for each mix. In general, PSA increases with increasing alkali loadings. At the same level of alkali loading, the PSA for the mix with CM2 is in general higher than that of the PSA with CM1. For example, the PSA for the mixes with the alkali loading of 5.3 kg/m^3 (8.9 lbs/yard^3) using CM1 (i.e., 1c and 2c in Table 2) is 0.88N but the PSA for the mixes with the same alkali loading using CM2 (3c and 4c in Table 2) is 1.04N. Therefore, maintaining the same concrete alkali loading doesn't necessarily ensures the same concrete PSA. This is an indication that cement composition (especially the type and amount of alkali-bearing phases) plays the main role on the availability of soluble alkalis in pore solution, which determines the pore solution alkalinity. Therefore, limiting cement based concrete alkali loading (approach of one size fits for all) to a practical lower value (e.g. 2.1-2.4 kg/m^3 (3.5-4.0 lbs/yard^3)) doesn't necessarily ensure universal effective measures to control ASR.

The measured PSA values (Table 2) shows close resemblance to the reported PSA values of similar type mixes in the published literature [15-19]. Soak solution for testing concrete cylinder using each mix in Table 2 was formulated by mimicking the pore solution chemistry (i.e., soak solution alkalinity = pore solution alkalinity) of the corresponding mixes in Table 2. Calcium hydroxide crystals were added to the prepared soak solutions at slightly above saturation (1 gram per liter solution) in order to make Ca^{2+} concentration in soak solution similar to concrete pore solution.

2.4 Test procedure

The RCCT procedure is briefly described below:

- A 27.94-cm (11-inch) stainless steel threated rod was embedded (2.54 cm inside from the top, Figure 1) on top of each concrete cylinder (7.62 x 15.24 cm (3 by 6 inches)) during specimen casting. After casting, the molds were covered with plastic foil and kept inside a curing room with RH @ 98±2% and T @ 23±2°C for 7 days. After 7 days, the concrete cylinders were de-molded and placed inside the container (Figure 1) followed by filling up the container by the prepared soak solutions till the specimen is fully immersed. The purpose of creating soak solution chemistry equals to pore solution chemistry is to prevent alkali leaching from the specimen.
- Place lid, tower, LVDT housing as in Figure 1 and make sure all parts are tightly closed. Place the LVDT through the LVDT housing and press it on the O-ring placed below. Use the side screws in the LVDT housing to ensure a perfect vertical alignment of the LVDT.
- Place the assembled system (Figure 1) inside an oven and start heating to the target temperature at 60°C. Initially the concrete specimen expands due to temperature increase from the starting temperature to the target temperature (60°C). LVDT displacement readings were recorded every 15 minutes automatically through data acquisition-computer system over time.
- Heating inside an oven ensures complete thermal equilibrium of the whole assembled system including LVDT with the set temperature (60°C). When the specimen-soak solution-device attains

a complete thermal equilibrium, the specimen shows a stable target set temperature (takes around 8-9 hours) with completion of thermal expansion. An average LVDT displacement reading (1 hour average) at the stable target temperature is considered as reference (initial) reading for calculating displacement due to ASR. All the subsequent LVDT readings minus the initial LVDT reading represent displacement due to ASR over time. The displacement due to ASR over time divided by the original length at the reference point multiplied by 100 represents the percent expansion of the concrete cylinder due to ASR over time.

3 RESULTS AND DISSCUSSION

3.1 Cylinder test with borosilicate glass balls

The RCCT method was first used to test mortar cylinders (7.62 x 15.24 cm (3 by 6 inches)) made of highly reactive borosilicate glass balls (0.25" dia. with chemical composition SiO_2: 81%, Na_2O: 4%, Al_2O_3: 2%, B_2O_3: 13%) with alkali loading 2.7 kg/m³ (4.5 lb/yard³) and 40% glass (by volume) to verify its applicability to measure ASR expansion before any concrete testing. Figure 2 shows the average expansion of glass-mortar cylinders at 60°C over time (Figure 2a).

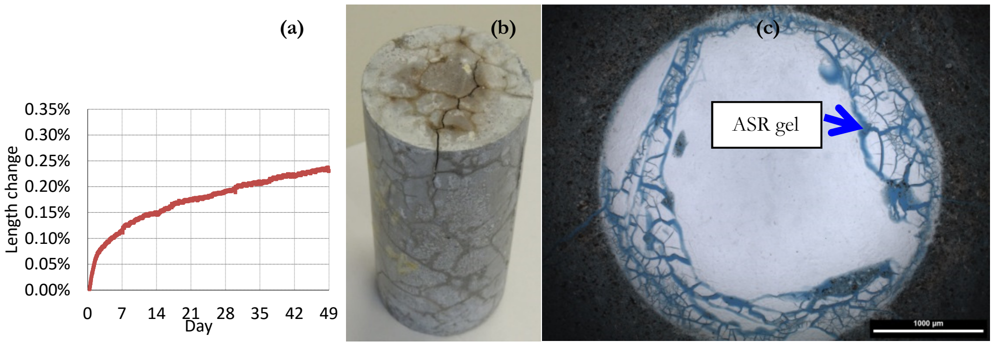
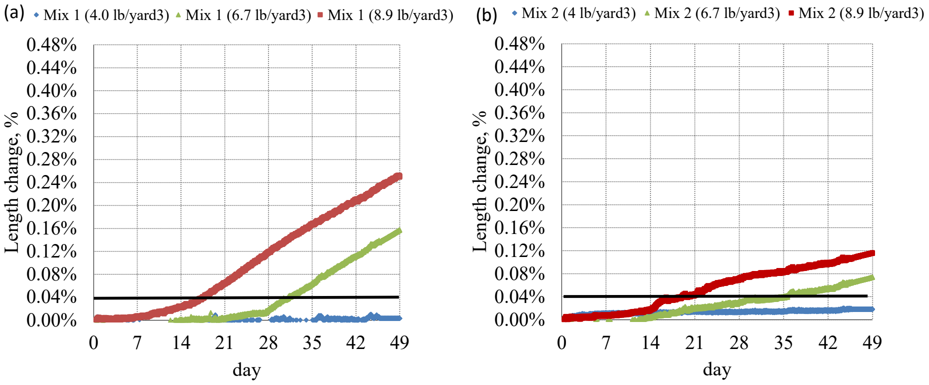


FIGURE 2: Mortar cylinder test using glass balls (a) Expansion over time, (b) Macro-crack pattern in a tested cylinder, and (c) Thin section photomicrograph showing micro-cracks and presence of ASR gel under transmitted light optical microscope.

The following observations supports measuring high expansion (Figure 2a) in the tested glass mortar cylinders: (i) presence of prominent macro-cracking in the tested cylinder (Figure 2b), (ii) presence of intense micro-cracking in the reacted glass balls with presence of ASR gel (Figure 2c) as well as micro-cracks passing through the reacted glass balls to the cement paste, and (iii) presence of ASR gel at the glass ball – paste interfaces and along cracks. Therefore, the proposed cylinder test is capable of measuring ASR expansion in a short period of time. As the data collection in the RCCT method is automatic under constant temperature, the reliability of the RCCT is expected to be high.

3.2 Concrete cylinder test

The selected concrete mixes in Table 2 were tested by the RCCT at varying levels of alkali loading. Figures 3a to 3f show the expansion curves over time at varying levels of alkali loading for the selected mixes in Table 2. For all mixes, the higher the alkali loading the higher the level of expansion is.



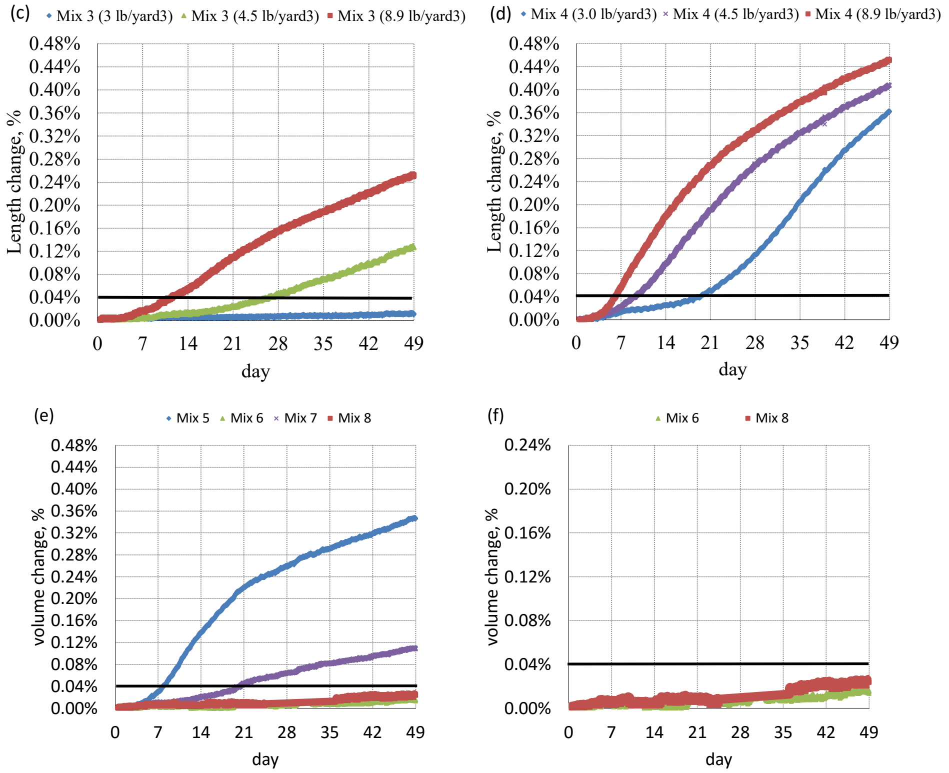


FIGURE 3: Expansion curve of RCCT at studied alkali loadings (a) Mix 1, (b) Mix 2, (c) Mix 3, (d) Mix 4, (e) Mixes 5 to 8, and (f) Mixes 6 and 8.

Mix 4 was used to cast three cylinders at each alkali loading with total three alkali loadings, i.e., 1.8, 2.7, and 5.3 kg/m^3 (3.0, 4.5, and 8.9 lbs/yard^3) to verify the repeatability (within the lab) of the RCCT method. Expansion values of three replicas at different ages were used to calculate coefficient of variation (COV %). The majority of COV% stay below 10% (5-8% after 28-days) for the tested mix at all levels of alkalinity, which indicates that the repeatability (within the lab) of the RCCT method is acceptable. However, more repeatability testing using concrete mixes of varying reactivity is needed in order to establish the repeatability of the RCCT method.

The expansion limit for exposure block/CPT was reported as 0.04% [20], which is chosen for the present study and shown in Figure 3. The RCCT expansion data till 49 days (Figure 3) in comparison with one year CPT (ASTM C 1293) expansion data are presented in Table 3. For all the studied mixes with higher levels of alkali loadings (i.e., 2.7, 4.0, and 5.3 kg/m^3 (4.5, 6.7, 8.9 lbs/yard^3)), the expansion limit of 0.04% is achieved within 36 days. The higher the alkali loading the shorter is the duration to achieve 0.04% limit. It's important to note that PSA is playing the important role to determine when the mixes reach the expansion limit. The mix with 4.5 lbs/yard^3 shows higher PSA (0.66) than the mix with 4.0 kg/m^3 (6.7 lbs/yard^3) (Table 2), which explain why mix with 4.0 kg/m^3 (6.7 lbs/yard^3) taking more time to reach the limit? Therefore, limiting cement based concrete alkali loading alone can't be considered as enough control measure for ASR. The alkali level 5.3 kg/m^3 (8.9 lbs/yard^3) (1.25% Na_2O_{eq}) is equivalent to the level of alkali used in the concrete prism (i.e., ASTM C 1293) test. In RCCT method at 5.3 kg/m^3 (8.9 lbs/yard^3) alkali level, the level of expansion equivalent to ASTM C 1293 1-year expansion is achieved within 35 days (mixes 1c, 2c, 3c, and 4c in Table 3) of testing. This suggests that RCCT method has the potential to be used as a rapid alternative method of concrete ASR testing. Petrographic study (ASTM C 856) was conducted using Mix 4 @ 5.3 kg/m^3 (8.9 lbs/ yard^3) alkali loading to detect the diagnostic ASR features. Figure 4 shows the ASR aggregate cracking and presence of gel under stereomicroscopic examination (Figure 4a) and appearance of gel under scanning electron microscope (SEM) (Figure 4b) with chemical composition by energy dispersive spectroscopy (EDS) (Figure 4c).

TABLE 3: Aggregate Reactivity Based on the RCCT Expansion.

Mix	*Alkali (kg/m^3)*	*$Na_2O_{eq.}$ (%)*	*PSA (N)*	*Time to Reach 0.04% Expansion Limit (Days)*	*Time to Reach CPT 1-year Expansion (Days)*	*ASTM C 1293 1 year Exp. (%)*	*CAE Classification [12]*
1a	2.4	0.57	0.37	DP	NRD	0.043	R
1b	4.0	0.95	0.46	32	32		
1c	5.3	1.25	0.88	18	18		
2a	2.4	0.57	0.37	DP	NRD	0.078	HR
2b	4.0	0.95	0.46	36	49		
2c	5.3	1.25	0.88	20	28		
3a	1.8	0.57	0.38	DP	NRD	0.058	R
3b	2.7	0.82	0.66	27	32		
3c	5.3	1.25	1.04	12	15		
4a	1.8	0.57	0.38	20	NRD	0.391	HR
4b	2.7	0.82	0.66	11	46		
4c	5.3	1.25	1.04	6	35		
5	2.7	0.82	0.66	8	-	NA	HR
6	2.7	0.82	0.66	DP	NRD	0.027	NR
7	2.7	0.82	0.66	21	33	0.078	HR
8	2.7	0.82	0.66	DP	NRD	0.020	VSR/NR
NRD-Not reached ASTM C 1293 1-year expansion till 49 days, DP – Didn't pass till 49 days							

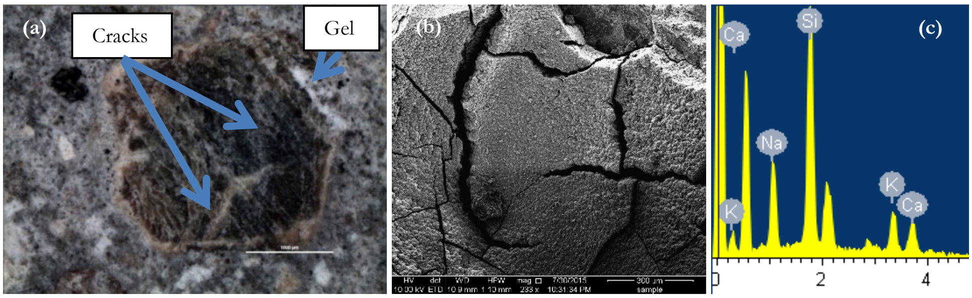


FIGURE 4: (a) Aggregate cracking and presence of gel at aggregate-paste interfaces, (b) Appearance of gel under SEM, and (c) EDS analysis of gel in figure 5b: SiO_2 – 51.48%, Na_2O – 18.76%, K_2O – 15.79% and CaO – 13.97%.

Based on the results in Table 3, it seems that RCCT with relatively low alkali loading (i.e., 2.7 kg/m^3 (4.5 lbs/yard^3)) could be used to pass/fail an aggregate. A concrete mix with a conventional cement content (e.g., 335-362 kg/m^3 (6.0-6.5 sack/yard^3)) will be sufficient to achieve 2.7 kg/m^3 (4.5 lbs/yard^3) alkali loadings if the Na_2O_{eq} of the cement is relatively high (e.g., $0.6 < Na_2O_{eq} \leq 0.82$). However, if the Na_2O_{eq} of the cement is low (e.g., ~ 0.55), a high cement content (~ 362-418 kg/m^3 (6.5-7.5 sack/yard^3)) with or without adding extra alkali may be needed in order to achieve 2.7 kg/m^3 (4.5 lbs/yard^3) alkali loading. Figure 5 shows the expansion curve of mixes 3 to 8 using alkali loading 2.7 kg/m^3. It indicates that the alkali loading of 2.7 kg/m^3 using high alkali CM2 is sufficient to identify the studied reactive mixes within 28 days. The 28-day RCCT expansions (%) are 0.047, 0.269, 0.006, 0.064, and 0.014 for mixes 3, 4, 6, 7, and 8 respectively, which match well with the diagnostic 1-year ASTM C 1293 expansion % i.e., 0.058, 0.391, 0.027, 0.078, and 0.020 respectively. The reactivity prediction based on CAE (i.e., the lower the ASR activation energy the higher the reactivity is) is also supportive to both RCCT and C 1293 data. The coarse aggregate in Mix 8 is a false negative aggregate, i.e., failed by C 1260 but passed by C 1293. It's important to mention here that this coarse aggregate is identified as non-reactive / very slowly reactive by CAE-based classification (Table 3) and non-reactive mix till 49 days by the RCCT method (Figures 3e and 3f, Table 3). This is an indication of the reliability of the RCCT method. Therefore, RCCT with relatively low alkali loadings (2.7 kg/m^3) as opposed to high alkali loadings (i.e., 4.0-5.3 kg/m^3 (6.7–8.9 lbs/yard^3)) in the current CPT test can effectively be used to identify the concrete mixes with varying reactivity in a relatively short period of time. A field mix with relatively high cement content and without any addition of fly ash or other SCMs can have alkali loading close to 2.7 kg/m^3. The testing using mix 3a (Table 3) with a low alkali loading (i.e., 1.8 kg/m^3 (3.0 lbs/yard^3)) was continued for a longer period of time (136 days). Although, this mix didn't achieve 0.04% within 49 days but it crossed this expansion limit by 80 days. This is an indication that if a field mix doesn't show any expansion or show expansion below 0.04% within 80-90 days by the RCCT method, it can be considered as a safe ASR resistant mix. Therefore, the RCCT method has the ability to test job mix and work is under progress to explore this possibility.

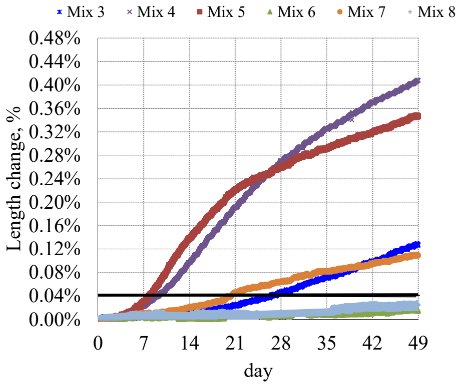


FIGURE 5: Expansion curves of RCCT (mixes 3 to 8 with alkali level 4.5 lbs/yard^3) over time.

3.3 Verification of leach-proof situation

The changes of soak solution chemistry were monitored to verify the leach-proof situation as well as the possibility of ions migration from soak solution to the specimen. An increase of OH^-, Na^+, and K^+ ions concentrations in soak solution after test represents leaching of these ions from the specimen. On the other hand, a reduction in concentration of these ions in soak solution indicates ion migration from the soak solution to the specimen with progress of ASR over time in the specimen. Figure 6 shows the change of OH^-, Na^+, and K^+ concentrations in soak solution of mixes 3 and 4 with alkali loadings 1.8, 2.7 and 5.3 kg/m^3 (3.0, 4.5 and 8.9 lbs/yard^3) after the testing period of 49 days.

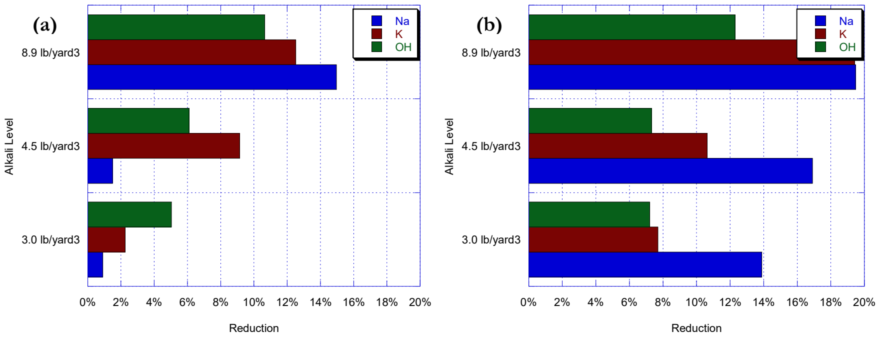


FIGURE 6: The change of Na^+, K^+, and OH^- of soak solution of (a) Reactive mix 3 and (b) Highly reactive mix 4 with alkali levels 1.8, 2.7 and 5.3 kg/m^3 (3.0, 4.5, and 8.9 lbs/yard^3) after testing period of 49 days.

Initially, the ionic concentrations in pore solution and soak solution are equal, which does not allow ion migration between pore solution and soak solution. As ASR progresses, Na^+, K^+, and OH^- concentrations reduce in the pore solution of the specimen, which triggers ion migration from the soak solution to the pore solution. The reduction of Na^+, K^+, OH^- concentrations in soak solution (Figure 6) suggests ion migration from soak solution to the specimen. It seems use of soak solution that is equal to pore solution may have some accelerating effect on the measured expansion for especially the mix using highly reactive aggregates with high alkali loadings. However, the degree of ion migration into the specimen at lower alkali loading (i.e., 2.7 kg/m^3 (4.5 lbs/yard^3)) is not that high (especially for Mix 3, Figure 6). In a separate measurement with different time interval, the reduction of ions in soak solution was found to be negligible before 28 days for both the studied mixes. Therefore, the effect of ion migration into the specimen can be greatly minimized by selecting the testing period between 28-32 days and alkali loading of 2.7 kg/m^3 (4.5 lbs/yard^3).

3.4 Use of RCCT to judge the efficacy of using fly ash

Mix 4b (2.7 kg/m^3, 0.82% Na_2O_{eq}) with and without class F fly ash replacement was tested to verify the effectiveness of RCCT method to determine optimum fly ash content in controlling ASR. The four levels of a Class F ash replacement, i.e., 20%. 25%, 30% and 35% were tested by the RCCT method with soak solution equal to pore solution condition. The pore solution alkalinity (Na^+_e) is reduced from 0.66N (reference sample without fly ash) to 0.44-0.43N with 20-25% fly ash and 0.33N with 30-35% fly ash replacement. Figure 7 shows the expansion curves of mix 4b with different levels of fly ash replacements. At 28 days, the expansion reduced from 0.3% to 0.13%, 0.067%, 0.039%, and 0.004% for the mixes with 20%, 25%, 30%, and 35% fly ash replacement respectively. The higher the level of fly ash replacement the higher is the level of alkalinity reduction in pore solution, which is correlated to higher level of expansion reduction. It is clearly observed that 25% fly ash replacement (conventional practice) is not sufficient to reduce the expansion below 0.04% for Mix 4b made of a highly reactive fine aggregate. The 30% fly ash replacement shows marginal protection (not safe) but the mix with 35% fly ash replacement shows adequate protection (i.e., expansion << 0.04%). Although, the data is limited at this time, the potential of RCCT to do fly ash optimization is high because the RCCT is a concrete test and operates with a relatively mild test condition (0.66N and 60°C) in comparison with ASTM C 1567 (1N and 80°C).

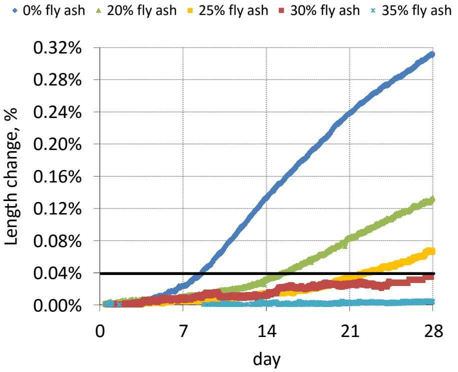


FIGURE 7: Expansion of mix 4b (4.5 lbs/yard^3) with and without fly ash replacement.

4 CONCLUSIONS

Based on the results obtained in this study, the following conclusion can be drawn:

- The RCCT method was developed to determine the length change of concrete cylinder (7.62 x 15.24 cm (3 by 6 inches)) due to ASR at a temperature of 60°C. RCCT with relatively low alkali levels (2.7 kg/m^3 (4.5 lbs/yard^3)) as opposed to high alkali levels (i.e., 4.0-5.3 kg/m^3 (6.7–8.9 lbs/yard^3)) in the current CPT test can effectively be used to pass/fail a concrete mix in a relatively short time (e.g. ≥ 28 days) with an expansion limit of 0.04%. More testing at 2.7 kg/m^3 (4.5 lbs/yard^3) using cements with varying alkali levels and aggregates with wide range of reactivity is needed in order to ascertain the testing time, which is under progress.
- In an earlier research [21], the effect of specimen dimension has been studied in a similar set up, i.e., use of LVDT to measure length change of mortar cylinder in 1N NaOH solution. The maximum aggregate size (2.54 cm) for the tested coarse aggregates in this study allows using the 7.62 x 15.24 cm (3 x 6 inches) concrete cylinder as the lowest possible dimension. The expansion difference between 7.62 and 10.16 cm (3 and 4 inch) dia. specimens was found to be smaller in the above study [21]. Therefore, RCCT based on 7.62 x 15.24 cm (3 x 6 inch) cylinder should be acceptable. However, the use of 10.16 x 20.32 cm (4 x 8 inches) cylinder will also be verified in our future study.
- The reliability of the RCCT method is high because of (i) elimination of alkali leaching from the concrete specimen during testing, (ii) use of LVDT based automatic data collection system under constant stable temperature inside an oven, (iii) verification of the RCCT method by testing cylinders made with highly reactive borosilicate glass balls as a proof of concept, (iv) establishing a favorable comparison between RCCT and ASTM C 1293 method, (v) making the RCCT capable to test concrete specimens at varying alkali loadings, and (vi) consistent identification of a mix with a false negative aggregate (failed passed by C 1260 but passed by C 1293).

- RCCT has the potential to determine optimum content of fly ash and / or other SCMs in order to develop safe ASR-resistant mixes. More testing using different types of fly ashes is needed in order to validate this expectation, which is under progress.
- The proposed RCCT has the ability to emerge as a potential method to test job mix (e.g., a mix with typical ASR mitigation measures) in the laboratory and serve as an alternative method to validate an ASR-resistant mix. Work is under progress to explore this possibility under an ongoing research project.
- Calibration and validation of the RCCT method by using field exposure block data – A comparative assessment of expansion data between field exposure bock and lab cylinder for some selective studied mixes will be undertaken in the ongoing project.

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