

RAPID CHEMICAL METHOD FOR DETERMINATION OF AGGREGATE ALKALI
SILICA REACTIVITY

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PRESENTED FOR THE
2014 FAA WORLDWIDE AIRPORT TECHNOLOGY TRANSFER CONFERENCE
Galloway, New Jersey, USA

August 2014

ABSTRACT

The main objective of this study was to develop a fast, reliable test method to determine the aggregate alkali-silica reactivity (ASR) with respect to the overall alkalinity of the concrete. A device, called volumetric change measuring device (VCMD), which measure volume change over time due to ASR was used in this research. The VCMD simulates the aggregate-pore solution reaction 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 (E_a) based on the rate theory. The VCMD-based test can reliably predict aggregate alkali silica reactivity in a short period of time (5 days) in terms of measuring compound activation energy. A representative E_a can be determined by testing as-received aggregates (i.e., field aggregates) with 0.5N NaOH + Ca(OH)₂ solution (similar to concrete pore solution) and with permissible repeatability. Researchers have developed an E_a -based aggregate classification system, which can serve as a potential screening parameter in an aggregate quality control program. A relationship between E_a and alkalinity is developed, which became the basis to determine threshold alkalinity. The proposed method has the potential to be considered as an alternative method to the current accelerated mortar bar test (AMBT) method. An effective way of tailoring mix design depending on the level of protection needed is developed based on activation energy, threshold alkalinity, pore solution chemistry.

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.

Alkali-silica reaction (ASR) is recognized as a major concern for the Texas Department of Transportation (TxDOT) and other DOTs. New cases of ASR are continuously being reported despite the advancement of the last decades. In the past 5.5 years, the Texas Department of Transportation (TxDOT) spent approximately \$2 million for recasting precast concrete products that had alkali-silica reaction (ASR). TxDOT realized that options 7 (i.e., concrete total alkali should not exceed 3.5 lbs/cy) and 8 (i.e., ASTM C 1260 14 days expansion should not exceed 0.08) in Special Provision (SP) 421 did not provide enough protection, and some aggregates have been found to produce expansive gel even at low alkali loadings.

Since the ASR-related problems were identified in the early 1940s, 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 access ASR potential of aggregates and concrete through a simulative (empirical) type of approach. The main purpose of an ASR test method is to measure aggregate reactivity prior to their use in concrete structures and develop ASR-resistant mixes. The current approach of ASR testing and mitigating damaging ASR heavily depends on accelerated mortar bar test (AMBT, ASTM C 1260 [1]) and concrete prism tests (CPT, ASTM C 1293 [2]). Aggregate are crushed to meet the specified gradation in order to cast mortar bars according to AMBT. The mortar bars are soaked in 1N NaOH solution at 80°C for 14 days. Based on the 14-day expansion, the aggregate reactivity is identified. In CPT test, concrete prisms are cast with

additional alkalinity (i.e., adding NaOH pallets in the mix) in order to boost the alkalinity in concrete. The prisms are stored above water at 38oC for 1 year. Based on the 1-year expansion, the potential of an aggregate to deleterious expansion due to ASR is identified. Although these approaches have resulted in significant advances in the avoidance of ASR damage in concrete structures, the limitations of the AMBT and CPT methods are well documented by several researchers and agencies. The test conditions of AMBT are severe (i.e., 1N NaOH at 80oC) and the test results are unrelated to field performance. CPT has been considered as the best index for field performance, but the test duration imposes a major limitation. 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. It would be beneficial to accurately, fairly, and rapidly assess the ASR potential of each aggregate at various alkali loadings.

ASR is a kinetic type of chemical reaction. Many researchers in the past have applied kinematic type models to characterize AMBT expansion over time and determine a rate constant. The separation between reactive and non-reactive aggregates based on rate constant criteria was much better than that based on expansion criteria [3, 4]. This indicates that the rate of expansion can serve as effective criteria to assess ASR potential rather than a single value of expansion. The main purpose of these kinematic approaches was to provide a better interpretation of the AMBT data through kinematic approach but not intended to improve the test procedure.

OBJECTIVES

The main objective of this study was to develop a rapid (within 5 days) and reliable chemical test method to determine aggregate alkali-silica reactivity based on the time-dependent nature of the onset and rate of reaction

APPROACH FOR DEVELOPING A RAPID CHEMICAL TEST METHOD

It is known that some threshold values of alkalinity and moisture need to be satisfied in order to initiate ASR and make ASR expansive. A simple chemical test by simulating aggregate-pore solution reaction that exists in concrete and measuring solid/solution volume change over time will be appropriate to determine rate of reaction and ASR activation energy (E_a). Activation energy (E_a) of ASR can serve as a single chemical material parameter to represent the combined effects of alkalinity, temperature, and moisture and can be used as a measure of alkali silica reactivity of aggregate.

A device called volumetric change measuring device (VCMD) has been developed at Texas A&M Transportation Institute (TTI) where as-received aggregates were immersed in alkaline solution of varying concentrations and allowed to react at different temperatures. The device measures solution volume contraction over time (till 4–5 days) as the reaction between aggregate and solution proceeds. A new model has been developed that characterizes the measured volume change over time and calculates reaction rate. The reaction rates at multiple temperatures allowed to calculate ASR compound activation energy (E_a) based on Arrhenius rate theory. E_a is used as a measure of alkali silica reactivity of aggregate.

EXPERIMENTAL PROGRAM

Materials and Experimental Design

Total fifteen aggregates (both coarse and fine) covering a wider range of reactivity, mineralogy and geographic locations were selected to test in this study. All tested aggregates were washed, dried, and sieved before testing. A fixed aggregate gradation which meets ASTM C 33 specification was selected for both fine and coarse aggregates in order to compare the results between different aggregates. Table 1 provides detailed information on the 15 selected aggregate sources. The coarse aggregates CA6 and CA7 belong to false positive (i.e., passed by ASTM C 1260 but failed by ASTM C 1293) and the coarse aggregate CA5 belong to false negative categories. The selected and collected aggregates were evaluated in terms of overall mineralogical composition, type, and distribution of the reactive components through petrographic examination of thin sections (ASTM C 295). The types of reactive constituents present in each aggregate are also included in Table 1. The experimental design (significant factors and their levels) for aggregate testing are presented in Table 2. For each source, the required amount of materials (determined based on the full factorial experimental design presented in Table 2) have been collected. It was decided to test borosilicate glass balls (pure phase) using the proposed test methods for validation purposes (as a proof of concept). The required amounts of highly reactive borosilicate glass balls were also collected.

The 1 N, 0.5N and 0.25N NaOH (NH) solutions are prepared by diluting 40, 20 and 10g of sodium hydroxide crystals into 0.9 liter of distilled water. Water is added to raise the total volume of solution to 1 liter. $\text{Ca}(\text{OH})_2$ (CH) crystals are then added (1g per liter solution) to the above respective NaOH solutions slightly above saturation in order to prepare an alkaline solution saturated with calcium hydroxide. Adding CH crystals slightly above the saturation point ensures presence of undissolved CH crystals, which represents a situation similar to concrete pore solution.

Test methods and equipment

The VCMD consists of a pot, a Teflon[®]-coated brass lid, a hollow tower, and a steel float (Figure 1). The pot and tower are made of stainless steel whereas the lid is made of naval brass. At the top of the tower, a casing is installed to ensure proper alignment of the linear variable differential transducer (LVDT) and the float. The LVDT used is the Schaevitz[®] Model HCA-1000 HCA, which has a maximum range of 2 inches. The LVDT is placed with an O-ring located at the bottom of the casing and secured with six set screws through the side of the cylinder.

As the chemical reaction between aggregate and the test solution (NH + saturated CH) progresses, the volume of test solution in the pot changes and the float sitting in the solution also moves. As the float moves, the stainless steel rod moves inside the LVDT and generates electrical signals (Figure 1). Therefore, the physical phenomenon (i.e., movement of the rod) is converted into a measurable signal. All LVDT signals are amplified through the use of signal conditioners and then transferred through a USB cable to a workstation where a program in LabVIEW was developed to display, analyze, and store the generated data (Figure 1).

Table 1.
Reactive Components, Mineralogy, and Other Relevant Aggregate Data.

Aggregate	Rock Type	ASTM C 1260 (14D)	ASTM C 1293 (1YR)	Dominated Reactive Constituent
FA1	RS	0.554	-	Acid volcanic + high strain QTZ + Chert
FA2	RS	0.334	0.171	High strained QTZ + Chalcedony + chert
FA3	RS	0.317	0.058	Low strained QTZ + Chalcedony + Chert
FA4	LS	0.242	0.043	High strained QTZ + Chert
FA5	LS	0.079	0.035	Few siliceous (e.g., Chert) inclusions
FA6	RS	0.381	0.391	Acid volcanic + Chert
CA1	RG	0.417	0.078	Acid volcanic + Chert
CA2	LS	0.250	0.047	High strained QTZ + Chert
CA3	LS	0.227	0.071	Chalcedony + Chert
CA4	RG	0.179	0.149	Chalcedony + Chert
CA5 ^b	LS	0.14	0.02	limestone + limited separate Chert
CA6 ^a	LS	0.1	-	Low strained QTZ + siliceous inclusions
CA7 ^a	RG	0.04	0.129	chalcedony + chert
CA8	LS	0.012	0.027	Few siliceous (e.g., Chert) inclusions

FA: fine aggregate; CA: coarse aggregate; LS: limestone; RS: River sand; RG: river gravel;
QTZ: quartz;

^a Passed by 1260 but failed by 1293

^b Failed by 1260 but passed by 1293

Table 2.
Experimental Design with the Factors and Levels for Aggregate Testing.

Factors	No. of Levels	Level Description
Material type	15 aggregates	Borosilicate glass, 6 fine aggregates, and 8 coarse aggregates in Table 1
Temperature	3	(1) 60°C, (2) 70°C, and (3) 80°C
Solution normality	2/3	(1) 0.5N and (2) 1N NH with CH (3) 0.25N NH with CH for some selected aggregates

Mostly 18 test runs per aggregate (i.e., 3 temperatures, 2 levels of alkalinities, and 3 replicas) were conducted. For some limited aggregates, 27 test runs (i.e., 3 temperatures, 3 alkalinities, and 3 replicas) per aggregates were also conducted. Eight VCMDs were simultaneously run inside two ovens for 4 days.

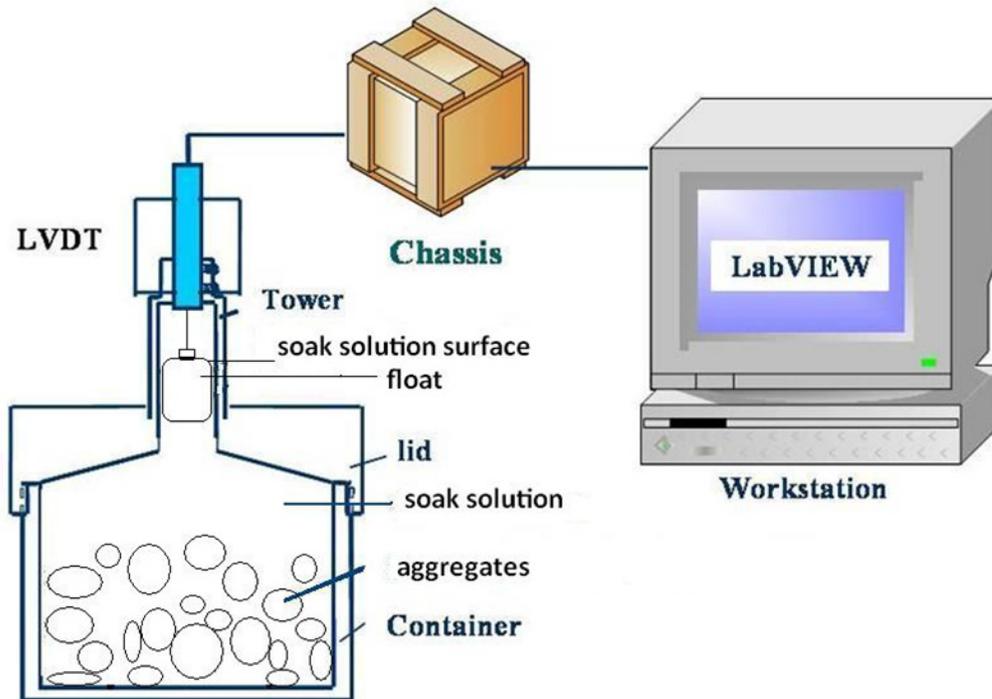


Figure 1. VCMD Test Setup.

Equipment Calibration

Calibration testing using water or alkaline solution at any of the selected temperatures (e.g., preferably at 80°C) is conducted to check smooth float movement and ensure that the device is leak-proof. A stable LVDT displacement output (e.g., flat line output with no such fluctuation) at stable target temperature indicates leak-proof situation. Obtaining very close values of change in LVDT displacement (Δh) with a constant change in temperature change (ΔT) between the VCMDs indicates smooth float movements. A one-time calibration testing is recommended. However, it is necessary to repeat the calibration testing whenever there is a change in float and / or a repair in the device.

Testing

The VCMDs are filled up with as-received aggregate (approximately 8–9 lbs) and alkaline solution of different concentrations (e.g., 1N, 0.5N, and 0.25N NH + CH) and tested at different temperatures (e.g., 60°, 70°, and 80°C) inside an oven according to the experimental design in Table 2. The weight of the oven-dried material corresponded to the 80 percent volume of the VCMD pot. Researchers used a constant aggregate/solution volume ratio and gradation for all the aggregate testing.

VCMDs are filled up with clean and dried aggregate and alkaline solution overnight at room temperature to allow maximum saturation of aggregates voids by alkaline solution. In the next day, vacuuming under mild vibration is applied (2.0 hours) to remove entrapped air bubbles from the solution as well as enhance further aggregate saturation (i.e., void filling) by alkaline solution. The next step is heating the VCMDs inside an oven until they reach a selected temperature (i.e. 60°C) and then apply a second stage vacuuming (45 minutes) at elevated

temperature under vibration to ensure a near completion of aggregate saturation. It is justified to say that aggregates attain the maximum possible saturation by the end of this second stage of vacuuming and further aggregate saturation during testing would be very negligible. It is reported that concrete aggregates that have high absorption capacity reach 95% saturation within 24 hours of soaking in water [5]. In the next step, the VCMDs are placed inside an oven, whose temperature was then raised to the selected target temperature (i.e. 60 or 70 or 80°C). Solution volume changes as the chemical reaction between aggregate and alkaline solution progresses (4 days), which are recorded as LVDT displacement readings over time in a computer through the data acquisition system.

LVDT displacement readings at the stable target temperature (i.e., average of 2 hours data) represents the reference (initial) LVDT reading for calculating displacement due to ASR. This ensures separation of thermal solution volume expansion (due to heating to the target temperatures) from solution volume change due to ASR. All subsequent LVDT readings (i.e., after reference reading) minus the reference LVDT reading represent displacement due to ASR over time. The percent volume change of solution due to ASR is calculated by using Equation (1).

$$V(\%) = \frac{\Delta V_{ASR}}{V_{Aggregate}} \times 100 \quad (1)$$

$V(\%)$ = Percent volume change of solution due to ASR

ΔV_{ASR} = Solution volume change due to ASR

$V_{Aggregate}$ = Initial volume of aggregate.

TEST RESULTS

Borosilicate Glass Balls

Borosilicate glass balls (SiO₂: 81%, Na₂O: 4%, Al₂O₃: 2%, B₂O₃: 13%) were tested at three levels of temperatures and at 0.5N NH + CH, 1N NH + CH, and 1N (NH + KOH) + CH alkalinities. A net solution volume contraction over time due to ASR between glass balls and alkaline solution was invariably observed for all the tests at different levels of temperatures and alkalinities. Note that glass balls are non-porous and there was no effect of absorption on the measured net solution volume contraction over time. This observation suggests that the VCMD in closed system set up measures net solution volume contraction over time due to ASR. The glass ball solid volume increases (verified in a separate experiment based on Archimedes' principle) but the net solution volume decreases.

Aggregates

All aggregates were tested using the VCMDs according to the experimental design in Table 2 and net solution volume change over time was measured. Figure 2 shows the measured net solution volume change over time (the red curves) at three levels of temperatures (60°, 70°, and 80°C) at 1N NH+CH for FA1 as an example. Measurement of net solution volume contraction over time was also invariably observed for all other aggregates (irrespective of coarse or fine

aggregates). It is pointed out earlier that aggregates attain maximum saturation during sample preparation time and the effect of further continuation of aggregate saturation (if any during testing period) on net solution volume contraction measurement would be very negligible. The dominant phenomenon is net solution volume contraction over time due to ASR.

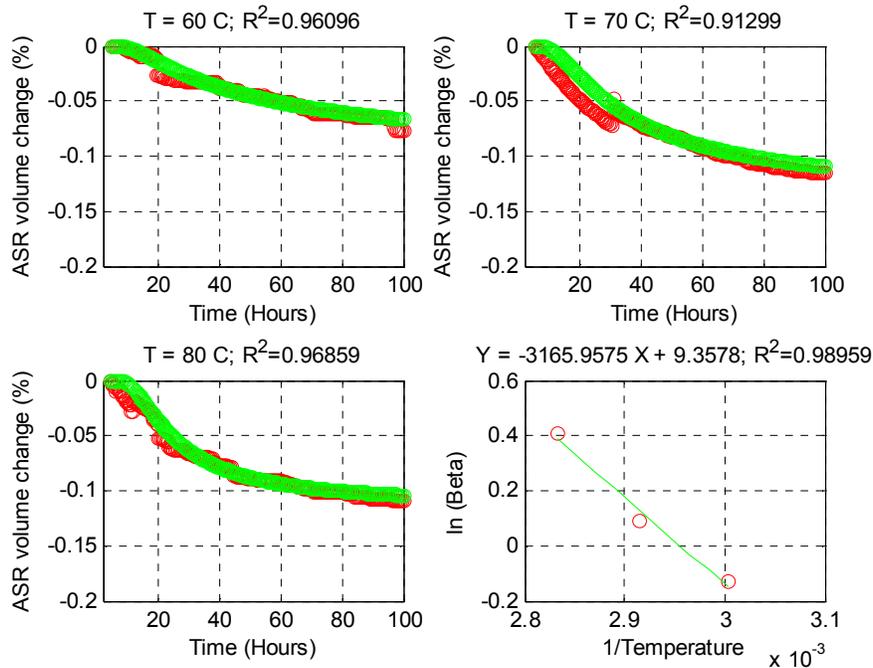


Figure 2. Measured (red) and Calculated (green) ASR Solution Volume Change Over Time and Activation Energy Calculation for FA1 at 0.5N NaOH + Ca(OH)₂.

Geiker and Kundsén [6] measured chemical shrinkage (CS) in fine aggregate-alkaline solution closed system set up (10N NaOH solution at 50°C) over time and used CS as a measure of aggregate reactivity, i.e., the higher the CS, the more reactive the aggregate is. The CS measurement in their work (a widely used test in Denmark for fine aggregate) and solution volume contraction measurement in our work are similar in nature and supportive to each other.

The measurement of solution volume contraction over time was also commonly observed in our previous study [7]. Interestingly, an approach of subtracting water curves (i.e., net water volume change over time in parallel aggregate-water test) from the solution curves (i.e., net solution volume change over time in aggregate-solution test) was used to determine net solid volume increase (expansion) due to ASR indirectly in the previous study. Based on the detailed investigation in this study, a consistent trend of upward movement after deducting the water curves from the solution curves was not obtained. It is unlikely that aggregate-water system remains inert at high temperatures and water curves obtained from aggregate-water tests may not serve as a good reference curves. This explains the inconsistency of the results. Therefore, it is concluded that simply deducting a water curve from a solution curve of an aggregate does not necessarily provide a measurement of solid volume increase (i.e., expansion) invariably.

Characterizing net solution volume contraction over time to determine rate constants at different temperatures followed by measuring activation energy can be a sound scientific approach to measure aggregate ASR reactivity.

Measurement of ASR Activation Energy

A kinetic-type model (Equation 2) was developed to model measured non-linear type solution volume change data over time [8]. By fitting the model (Equation 2) to the measured data over time, the characteristics parameters (i.e., ε_0 , β , t_0 , ρ) are calculated.

$$\frac{1}{\varepsilon} = \frac{1}{\varepsilon_0} \cdot e^{\left(\frac{\rho}{t-t_0}\right)^\beta} \quad (2)$$

ε_0 = Volume change due to ASR

β = Rate constant

t_0 = Initial time of ASR expansion (hr)

ρ = Time corresponding to a volume change ($\varepsilon_0 / \varepsilon$)

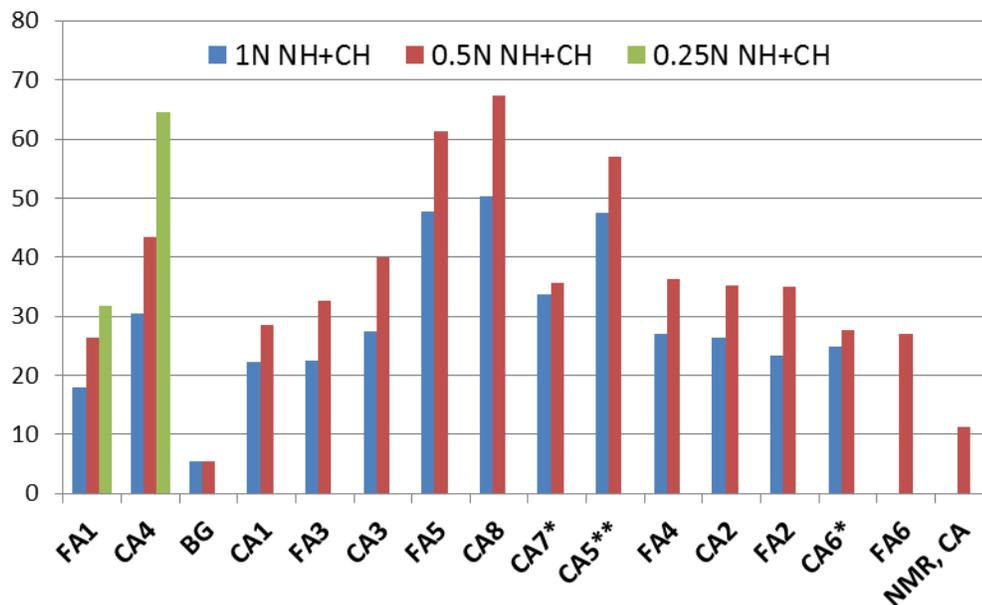
The β values at multiple temperatures (minimum 3 temperatures) are then determined and activation energy is calculated by plotting $\ln(\beta)$ versus $(1/T)$. Based on rate theory [9], the slope of the linear regression is equal to $(-E_a/R)$ where R is the universal gas constant and E_a is the activation energy. For ASR, E_a is considered as the minimum energy required to initiate ASR, taking into account the combined effect of alkalinity, temperature, and time. It is important here to mention that the ASR E_a should be considered as a compound activation energy as aggregate is a heterogeneous material that is often composed of different mineral phases, i.e., reactive phases (one or more phases) and non-reactive phases (crystalline minerals). Moreover, net solution volume change over time represents a combined effect of the different steps in alkali silica reaction (i.e., Si-O-Si bond breaking, dissolution, and product formation). The concept of ASR compound activation energy was introduced as a representative single parameter of alkali silica reactivity of minerals and aggregates earlier [10, 11].

The NEWTON numerical approach [8] was developed based on the model in Equation 2 to predict solution volume change over time. Figure 2 shows the measured (red) and calculated (green) volume change over time at three different temperatures (60°, 70°, and 80°C) for FA1 as an example. At the best fit between the predicted and measured data over time, the characteristics parameters (i.e., ε_0 , β , t_0 , ρ) are determined [8]. The reaction rates at studied 3 temperatures were used to calculate ASR compound activation energy (E_a) based on Arrhenius rate theory. The E_a calculation based on $\ln(\beta)$ versus $(1/T)$ plot is also presented in Figure 2. The activation energies were determined for all the tested aggregates and borosilicate glasses based on the above procedure at multiple levels of alkalinity and are presented in Figure 3. Activation energy vs. ASTM C1260 14-day expansion (%) is presented in Figure 4.

Figures 3 and 4 show the following important observations:

- Activation energy is a measure of aggregate reactivity. The lower the E_a values the higher the reactivity is.

- In general, C 1260 14 day expansion values are well correlated (negatively) with E_a values, i.e., E_a decreases with increasing C 1260 14 days expansion. A high reactivity is indicated by a lower value of E_a or higher C 1260 expansion. Similarly, a low reactivity is indicated by a higher value of E_a or lower C 1260 expansion. This indicates that a VCMD-based test procedure can reliably measure aggregate reactivity within a short period of time (i.e., 5 days).
- Consistently identified the aggregates belong to false positive and negative categories – For example, aggregates CA7 and CA6 are passed by C 1260 but failed by C 1293 (false positives) but these aggregates are identified as reactive based on E_a values. Similarly, CA5 aggregate is failed by C 1260 but passed by C 1293 (false negatives) but this aggregate is identified as non-reactive or slowly reactive based on E_a . Therefore, E_a based reactivity prediction shows better correlation with C 1293 than C 1260 for these mismatch aggregates. Therefore, the main benefits of the E_a based method is consistent identification of the aggregates belong to false positives and negatives in a short period of time.
- A representative E_a can be determined by testing aggregate with a test solution of 0.5N NH + CH alkalinity (close to concrete pore solution alkalinity), which offers a great advantage of the proposed method. The favorable points of testing with 0.5N + CH are (i) repeatability is better than testing with 1N NH+CH, (ii) data are less noisy and smooth, (iii) E_a values are well separated - facilitates assigning effective E_a ranges to categorize aggregates based on their reactivity, and (iv) test solution alkalinity is pretty close concrete pore solution chemistry.



*Passed by ASTM C1260 but Failed by ASTM C1293

** Failed by ASTM C1260 but Passed by ASTM C1293

Figure 3. Measured Compound Activation Energy for the Tested Aggregates at Different Levels of Alkalinities.

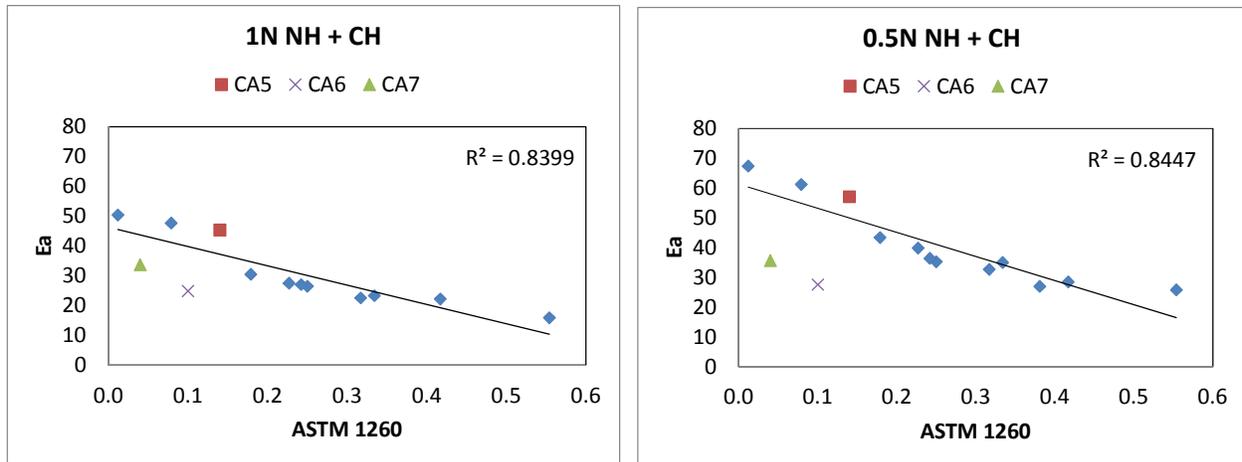


Figure 4. Correlation Between ASR E_a and ASTM C1260 Expansion (14 days) for the Tested Aggregates.

Repeatability

Each test run (a particular combination of T and alkalinity) was repeated three times to verify the repeatability (within the lab) of the VCMD test results. Three rate constants (β) corresponding to the three replicas were used to calculate the coefficient of variation (COV) and the results are presented in Figure 5. The COV are mostly within 10 percent for the tested aggregates at all levels of alkalinity, which indicates that the results are highly repeatable.

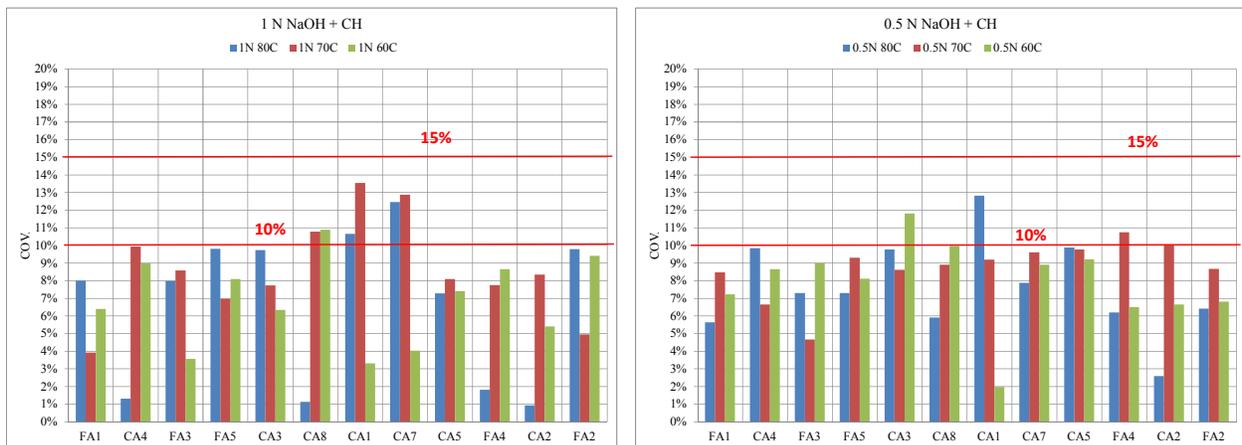


Figure 5. Percentage Coefficient of Variation (COV) Based on Reaction Constant (β) from the Repeated Tests for All the Tested Aggregates.

Determination of Threshold Alkali Level

An apparent relationship between compound activation energy (E_a) and alkalinity is evident from the results of the studied aggregates (Figure 3). The higher the alkalinity, the lower the E_a is. An attempt was made to establish a mathematical relationship between E_a and alkalinity. The following model (Equation 3) was used to establish a relationship between E_a and alkalinity:

$$E_a = E_{a_0} + \frac{C_1}{C^n} \quad (3)$$

Where: E_a is Activation energy (KJ/mol)

E_{a_0} is Activation energy – theoretical threshold (KJ/mol)

C_1 is Activation energy curvature coefficient (KJ/(mol)¹⁻ⁿ)

n is Activation energy curvature exponent

C is Alkalinity (mol)

The predicted relationship between E_a and alkalinity for aggregate FA1 is presented in Figure 6 as an example. The plots show that as alkalinity increases, the E_a decreases. A good fit between the measured and predicted E_a values is manifested, and this demonstrates the applicability of the proposed model. The existence of a characteristic threshold alkalinity for each aggregate was manifested from the plots of alkalinity vs. E_a (e.g., green curve in Figure 6) of the tested aggregates. All TH_A are mathematically calculated (using MATLAB program) from the E_a vs. alkalinity plot (Figure 6) and is summarized in Table 4. When two tangent lines (e.g., two blue lines in Figure 6, one started from the upper vertical portion of the green curve and another one started from the lower horizontal portion of the green curve) intersect on the green curve (or close to the green curve), the alkalinity at the intersection is considered as a TH_A . In general, the higher the reactivity, the lower the TH_A is, except for CA6 and CA7. The activation energy values for these two aggregates do not show a good relationship with alkalinity (a minor change in E_a for a large change in alkalinity), which caused the TH_A value moving towards lower side. The addition of one more data point at a relatively low alkalinity (e.g., 0.25-0.3N NH + CH) will possibly help to improve the TH_A determination for these two aggregates. Additionally, the effectiveness of calculating TH_A from E_a vs. alkalinity relationship needs further critical evaluation, which is continuing.

DEVELOPMENT OF AN E_a -BASED ASR CLASSIFICATION SYSTEM

An activation energy-based aggregate classification system is developed based on the number of aggregates that are tested in this study and presented in Table 5. The ranges are arbitrary in nature at this time. To establish an effective ASR aggregate classification system, assignment of more refined activation energy ranges through testing greater number of aggregates is highly warranted. It is recommended to use the classification system based on activation energy at 0.5N NH + CH (close to concrete pore solution alkalinity, i.e., field levels of alkalinity) in all practical purposes.

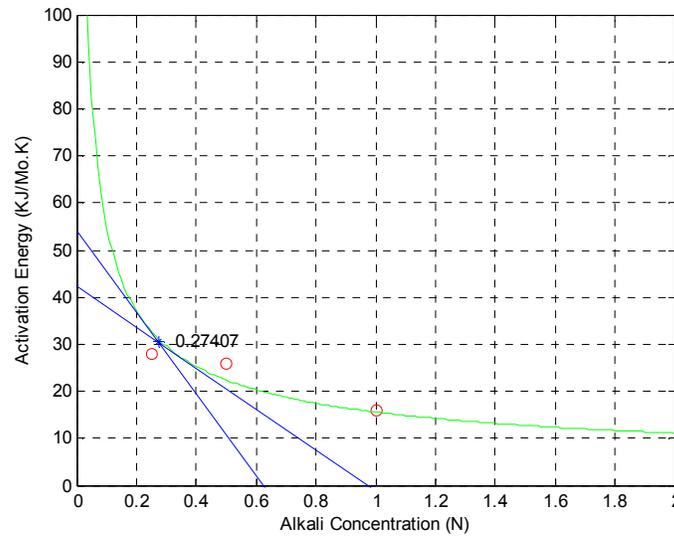


Figure 6. Alkalinity versus activation energy for FA1.

Table 4.

Summary of Threshold Level of Alkalinity (TH_A).

Aggregate	TH_A (N)	E_a (1N)	E_a (0.5N)
FA1	0.27	15.882	25.811
FA2	0.46	23.254	34.979
FA3	0.47	22.485	32.640
FA4	0.46	26.980	36.391
CA1	0.37	22.164	28.499
CA2	0.59	26.437	35.244
CA3	0.50	27.486	39.864
CA4	0.52	30.409	43.365
CA5	0.49	45.279	57.091
CA6	0.20	24.783	27.602
CA7	0.17	33.641	35.655

Table 5.

 E_a -based Aggregate Classification System.

Activation Energy Range		Reactivity
1N NaOH + CH	0.5N NaOH + CH	
< 25	< 30	4 (highly reactive)
25–35	30–45	3 (reactive)
35–45	45–60	2 (potential/slow reactive)
1N NaOH + CH	0.5N NaOH + CH	1 (nonreactive)

APPROACH FOR ASR RESISTANT MIX DESIGN DEVELOPMENTS

After measuring E_a and TH_A of an aggregate, the following steps can be used to develop an ASR resistant mix:

- Develop a mix based on the guidelines presented in Table 6 - as activation energy based reactivity prediction is reliable and dependable, an expert can design ASR resistant mix by selecting appropriate mix design controls and special protection measures (as needed) depending on E_a -based reactivity and TH_A .
- Adjustment of the developed mix (above) based on pore solution alkalinity (PSA) and TH_A relationship (below). It is necessary to extract pore solution from representative mortar/paste specimens by pore solution extraction technique and analyze by some suitable chemical analysis technique.
 - If the pore solution alkalinity (PSA) is lower than TH_A , the mix should perform well in the field without any ASR - A reactive aggregate can practically behave as non-reactive or very slow reactive if concrete pore solution alkalinity can be maintained below the threshold level of alkalinity.
 - If the PSA is higher than TH_A , the mix needs adjustment by both mix design controls (help to reduce the pore solution alkalinity) as well as special protection measures (help to make gel less expansive and/or increasing the space for gel accommodation).
 - If the PSA is equal to TH_A , the mix may not need any further adjustment under mild ambient conditions. However, special protection measures may be needed under severe ambient conditions.

SUMMARY AND CONCLUSIONS

- The VCMD-based test can reliably predict aggregate alkali silica reactivity in a short period of time in terms of measuring activation energy. This test has the ability to test as-received aggregates (i.e., field aggregates) and determine activation energy (reactivity) matching with the field level of alkalinity. This reduces the gap between lab and field.
- The experiments with pure glass balls support solution volume contraction over time and used to validate the VCMD procedure.
- The majority of COV based on rate constant is within 10 percent, which indicates the results are highly repeatable.
- The VCMD based test method has consistently identified the aggregates belong to false positive and negative categories in a short period of time. This is the main benefit of the VCMD-based method. More aggregates that belong to the false positive and negatives categories need to be tested in order to establish the above benefit of the VCMD-based

Table 6.
Guidelines Through Examples for Development of ASR-Resistant Mixes.

E_a -Based Aggregate Reactivity (Table 5)	TH_A	Severity of Ambient Conditions	Mix-Design Controls	Special Protection Measures (SPM)
High	Low (i.e., low alkali tolerance)	High	(i) Low alkali cement (must), (ii) relatively low cement factor (CF), (iii) higher amount (25–35%) of good quality fly ash (FA), and (iv) low w/c	Highly needed - (i) Use of ternary / quaternary blends instead of fly ash alone, (ii) use of 100% or higher dosage of $LiNO_3$, (iii) use of porous light weight aggregate (LWA) and/or aggregate blend.
High	Low	Low	Same as above	Use of lower dosage of $LiNO_3$ may be needed depending on TH_A
Low	High (i.e., high alkali tolerance)	High	Conventional mix design practice – (i) cement with relatively high alkali content can be allowed, (ii) medium quality fly ash can be used	Use of ternary blends may be needed depending on the severity of ambient conditions
Low	High	Low	Conventional mix design practice	No need

procedure.

- The ASR activation energy (E_a) will serve as a single chemical material parameter to represent alkali silica reactivity of aggregate. The E_a -based aggregate classification will serve as a potential screening parameter in aggregate quality control program.
- A procedure to determine threshold alkalinity of aggregate has been developed based VCMD testing at different alkali levels. A chemical approach based on E_a , TH_A and pore solution chemistry is proposed to develop an ASR resistant mix without depending on a long lasting concrete testing.
- The VCMD-based test shows potential to be used as an alternative to ASTM C 1260. However, more testing covering large number of aggregates with varying reactivity is needed in order to conclude VCMD-based method as a valid alternate rapid and reliable test.

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