Malaysian Journal of Civil Engineering 27(2):180-192 (2015)

PREDICTING ASR LONG TERM EXPANSION THROUGH EXISTING TEST METHOD

Enamur R. Latifee[1]* & Md Rashedul Kabir[2]

[1] *Graduate Student, Glenn Dept. of Civil Engineering, Clemson University, S. Palmetto Blvd., Clemson, SC 29634, USA*
[2] *Lecturer, Department of Civil Engineering, Ahsanullah University of Science and Technology, Dhaka, Bangladesh*

*Corresponding Author: *erlatifee@gmail.com*

Abstract: Alkali-silica reaction (ASR) related distress in the concrete is considered as the second most important concrete durability issue after corrosion. The modeling of ASR distress and prediction of ASR expansion in the real-life concrete structure is a matter of great difficulty. In this research article, the prediction equations were derived using a special mathematical function known as Spline. The equations were based on the actual expansion curves of known reactive aggregates, and of the mitigation measures (e.g., fly ash, slag etc.). The experimental expansions in the extended period, i.e., beyond 84 days, through the Miniature Concrete Prism Test (MCPT) method were compared with the predicted expansions matching the experimental age. The results indicated that the experimental and the predicted expansions matched very well with R^2 value close to 1. It was also found that the reaction reached at a steady state condition after certain curing days and this steady state condition continued throughout the extended test period. Also, for the mitigation measures using low lime fly ashes, meta-kaolin and slag at certain percent replacement levels of cement by weight; the experimental expansion correlated well with the predicted expansion. Therefore, the expansion prediction can be used confidently for both reactive aggregates and the mitigation measures.

Keywords: *Alkali-silica reaction, concrete, durability, cement, prediction*

1.0 Introduction

Alkali-silica reaction (ASR) is a chemical reaction between reactive silica, SiO_2 in certain aggregates such aschert, quartzite, opal, strained quartz crystals and alkali hydroxides in the concrete pore solution (Li *et al.*, 2000; Gao, 2010). The pore solution alkalinity comes from the cement alkalinity which is expressed as percentage of $Na_2O_{eq.}$ The 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 hydrophilic 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 (Fecteau and Fournier, 2012). The complex reaction process can be simplified as a two- step process:

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

SiO_2+2NaOH+H_2O = Na_2SiO_3.2H_2O (2KOH can replace 2 NaOH) (1)

Step 2: Gel Reaction Product + water = Expansion

Though the main cause of the ASR distress is well understood, the micro and macro structural effects including concrete matrix are very complex since the expansive growth is a function of the induced stress. The stress can develop on the periphery of the aggregate due to the expansion of reaction rim absorbing water or it can generate within the reactive aggregate and crack inside the aggregate ultimately, the combined stresses give the expansive strain or percentage expansion as measured in the standard test methods like Concrete Prism Test (CPT), Accelerated Mortar Bar Test (AMBT). The Accelerated Mortar Bar Test (ASTM C 1260) 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 (Fertig and Tanner, 2012; Johnston and Fournier, 2000; Johnston *et al*., 2000; ASTM, 2007). However, the results from this test method can be unreliable due to the aggressive conditions used in the test. On the other hand, the Concrete Prism Test (ASTM C1293) 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 (ASTM, 2007b). 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 the ASTM C1260 and ASTM C1293 test methods have spurred research in the development of new test procedures that are rapid and reliable in evaluating aggregate reactivity and efficacy of ASR mitigation measures. The Miniature Concrete Prism Test (MCPT) was developed incorporating selected features of the ASTM C1260 and ASTM C1293 test methods to ensure a reliable prediction of the performance of aggregate and ASR mitigation measures while obtaining the results within a reasonable time frame (56- days for most cases and 84 days for low/slow reactive aggregates) that is of value to the construction industry. In this research, the MCPT method is followed.

Several researchers have tried to model the ASR expansion with numerical model (Uomoto *et al*., 2992). Larive *et al*. (2000) proposed a model equation that leads to the classical S-shaped curve for ASR. A variation of this equation has been proposed by Baghdadi (2008) to predict continuous growing of expansion observed in affected concrete. A mechanical model for Alkali-reaction was proposed by Laurent and Alain (2012) inspired by that of Bažant *et al*. (2000) and Riche (2003) to produce the usual ASR sigmoid expansion curve.

Salles *et al*. (2012) inspected alkali-aggregate reaction in the concrete of a Hydropower plant water intake almost 30 years after its conclusion which indicated increasing trend of crack opening suggesting that the alkali-aggregate reaction is evolving. The opening movement was linear and increasing, with no tendency to stabilize. Rodríguez *et al*. (2012) studied a double curvature arch dam in northwest Spain. They observed swelling phenomena from a relatively early stage and it continued even after 50 years later. A numerical model of the dam was prepared implementing the model by Saouma and Perotti (2006). They found, even under considerable compression in all directions, swelling decreased but did not vanish.

Also it was reported that large ASR affected dam pushes for a continuous expansion at constant rate without showing any sign of slowing down (Charlwood, 2011). Given the fact the ASR expansion continues within the real structures even after 50 years, in this research the focus is to verify the assumption that ASR expansion will continue at a constant rate after reaching steady state. For this purpose, experimental data are gathered at ages beyond the test scope, i.e. 84 days and compared that expansion with the predictive expansion. Prediction equations are developed from the experimental data after the steady state has been reached.

Known reactive and non-reactive aggregates are tested in the MCPT beyond the standard time, i.e., 84 days. These included three reactive (two coarse and one fine) and two non-reactive (one coarse and one fine) aggregates. Also, supplementary cementitious materials (SCM) at different replacement level by percentage of weight cement are used for the mitigation of ASR. These included Slag (40%), Meta-kaolin (10%), and three different low lime fly ashes (two at 25% and one at 35% dosage).

In this research, Spline function is used to generate the parametric curve whose shape closely follows the sequence of the actual input, called control points. Spline functions are defined as piecewise polynomials of degree n. the pieces join in the control points or knots and fulfill continuity conditions for the function itself and the first n-1 derivatives. Thus a Spline function of degree n is a continuous function with n-1 continuous derivatives. Spline functions are considered the most successful approximating functions for practical applications, where ordinary polynomials are inadequate in many occasions.

2.0 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 in Table 1.

Table 1: MCPT Specimen Mixture Proportion

Item	**Mix Proportion**
Cement content of the mix	420 kg/m^3 (708 lb/yd^3)
Water-to-cement ratio	0.45
Coarse aggregate volume fraction (dry)	0.65
Maximum size of coarse aggregate	12.5 mm (1/2 in.)
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%
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

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.

3.0 Materials

3.1 Aggregates

A number of well-known reactive and non-reactive aggregates are chosen for the experimental investigation of their reactivity characteristics. The properties are given in Table 2.

3.1.1 Reactive Aggregates

Two reactive coarse aggregates and one reactive fine aggregate are selected in the preliminary investigation. Siliceous limestone from the Spratt Quarry in Ontario, Canada and Rhyolitic gravel from the Las Placitas Pit in Bernalillo County, New Mexico is picked as reactive coarse aggregates. The only reactive fine aggregate is from Jobe, Texas, USA.

3.1.2 Non-reactive Aggregates

Stones from Big Bend, Kentucky and Siliceous sand from Dixiana Plant in Pineridge, South Carolina are used as the non-reactive coarse and fine aggregate correspondingly. Dixiana sand is used with the reactive coarse aggregates and Big Bend, Kentucky stone is used with the reactive Texas sand.

3.2 Cement

A high-alkali (0.82% $Na_2O_{eq.}$) type I Portland cement is selected for this study. Chemical compositions of the Portland cement are provided in Table 3.

3.3 NaOH and Water

A reagent grade sodium hydroxide is applied to boost the alkali level of concrete to 1.25% $Na_2O_{eq.}$by the weight of the cement. De-ionized water is used in all the tests.

3.4 Mitigation Materials

A slag meeting the Grade 120 specification of ASTM C 989 is used in this study at 40% cement replacement level by mass of cement. A commercially produced meta-kaolin is used at a cement replacement level of 10% by mass. The chemical compositions of slag and meta-kaolin are provided in Table 3. Furthermore, low lime fly ashes as a substitute of cement in various percentages are used as mitigation measures. Table 4 illustrates the proportion of different chemicals present in fly ashes.

Table 2: Properties of the Aggregates Used

Property	Big Bend, KY (CA) ****NRA-I**	Spratt (CA) ***RA-I**	Jobe- TX (FA) ***RA-II**	New Mexico (CA) ***RA-III**	Foster Dixiana (FA) ****NRA-II**
SG_{OD}	2.66	2.69	2.58	2.6	2.63
SG_{SSD}	2.70	2.71	2.55	2.63	2.64
Absorption, %	1.27%	0.46%	1.52%	1.09%	0.44%
DRUW (kg/m^3)	1455.9	1568	---	1585.3	---
DRUW ($lb./ft^3$)	90.89	97.91	---	98.97	---

*Note: CA= coarse aggregate; FA= fine aggregate; **NRA= non-reactive aggregate; *RA= reactive aggregate, SG_{SSD} = specific gravity based on saturated surface dry weight, SG_{OD}= specific gravity based on oven dry weight*

Table 3: Chemical Composition of Cement, Slag and Meta-kaolin

Oxides (%)	Cement	Slag	Meta-kaolin
SiO_2	19.74	38.17	51.0 – 52.4
Al_2O_3	4.98	7.31	42.1 – 44.3
Fe_2O_3	3.13	0.78	0.30 – 0.50
CaO	61.84	39.12	0.019
MgO	2.54	12.48	0.119
SO_3	4.15	2.56	---
Mn_2O_3	---	0.40	---
Na_2O equivalent	0.82	---	0.21
K_2O	---	0.34	---
Insoluble Residue	0.25	---	---
Specific Gravity	3.15	2.92	2.2
Loss on Ignition (LOI)	1.9	---	0.6-0.9

Table 4: Chemical Composition of Fly Ash (Low Lime) Used

Fly Ashes	% cement replacement by mass	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Total Alkalies (as Na_2O) (%)	Specific gravity
*FA-I	25	61.63	24.86	4.56	1.4	0.23	0.21	NA	2.09
*FA-II	35	57.49	29.29	2.95	6.06	1.36	0.41	NA	1.97
*FA-III	25	60.30	28.60	3.20	1	0.00	0.00	NA	2.20

*Note: *FA= fly ash*

4.0 Experimental Program

Reactive and non-reactive aggregates are tested in the MCPT beyond the standard time, 56 or 84 days depending on the situation and the % expansions are recorded at different days. To determine the rate of change of % expansion and to find out when the rate becomes constant a mathematical function called Spline function is used. Spline generates piecewise polynomials and the zero value obtained by double derivative of expansion graph indicates the constancy of expansion rate. First the Spline curve is generated from the experimental curve (84 days % expansion data). Then the first derivative curve is generated and finally the double derivative curve. The sample graphs of RA-I % expansion, corresponding Spline curve, first derivative and second derivative are given in Figure 1 through Figure 4 accordingly. Table 5 shows the experimental % expansion data for RA-I. The same process is employed to find the number of days required to reach constant rate of change. In all cases including mitigations, the rate becomes constant at or below 56 days. Given that, constant rate portion (56 to 84 days) of the Spline curve is used to find out the prediction equation. This prediction equation is used to find the predicted % expansion values at the desired number of days matching the experimental number of days. The prediction curve example for RA-I is given in Figure 5.

Table 5: Experimental Percent Expansion Data for Reactive Aggregate-I

Days	% Expansion	Coefficient of variation (CV)
0	0.000	
3	0.002	24.744
7	0.010	10.000
10	0.020	12.796
14	0.033	10.497
21	0.057	5.607
28	0.079	7.905
42	0.106	5.782
56	0.123	6.138
70	0.136	6.815
84	0.149	6.873

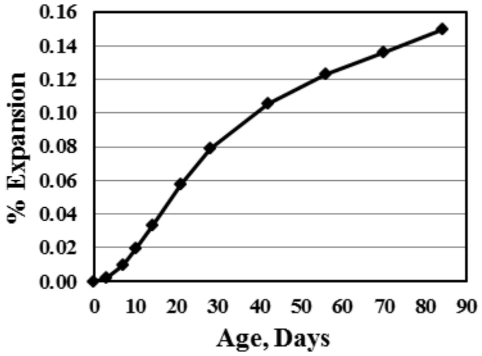

Figure 1: Experimental Percent Expansion Curve for Reactive Aggregate-I

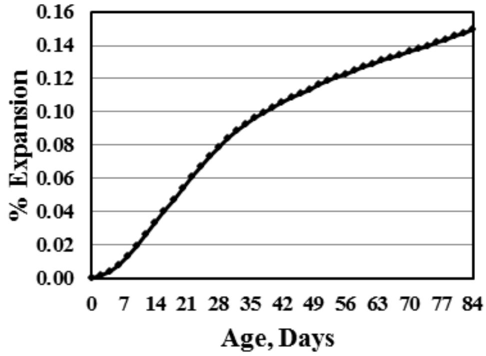

Figure 2: Generated Spline Curve for Reactive Aggregate-I Expansion

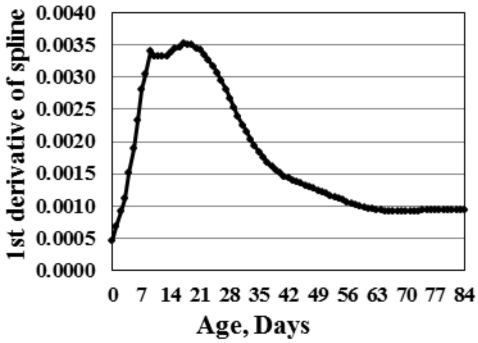

Figure 3: 1st Derivative (slope) of Spline Curve for Reactive Aggregate-I Expansion

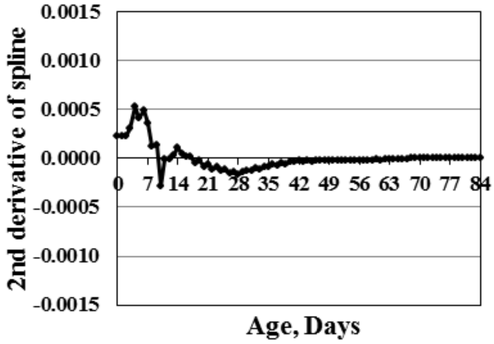

Figure 4: 2nd Derivative of Spline Curve for Reactive Aggregate-I Expansion

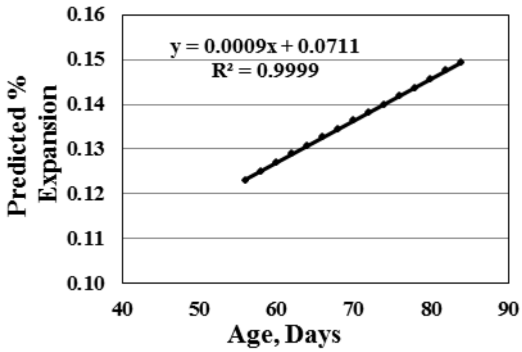

Figure 5: Predicted Percent Expansion Curve for Reactive Aggregate-I (56 to 84 Days)

5.0 Results and Discussion

The experimental data and predicted percent expansion for three reactive aggregates and one non-reactive aggregate is given in Table 6. The R^2 values show that the prediction curve is essentially linear and has constant rate of change. Figure 6 shows the correlation between predicted and experimental percent expansion for these reactive and non-reactive aggregates. The correlation is excellent (R^2 value is 0.992).

Table 6: Experimental and Predicted Percent Expansion for Reactive and non-reactive Aggregates only (without mitigation)

Aggregate Type	Age, Days	Predicted % Expansion	R^2 (for predicted curve)	Experimental % Expansion
NRA-I	112	0.037	0.997	0.038
	140	0.047		0.048
	168	0.057		0.057
	196	0.066		0.060
	410	0.141		0.135
RA-I	112	0.175	0.999	0.161
	250	0.304		0.240
RA-II	561	1.331	0.999	0.822
RA-III	112	0.201	0.990	0.196

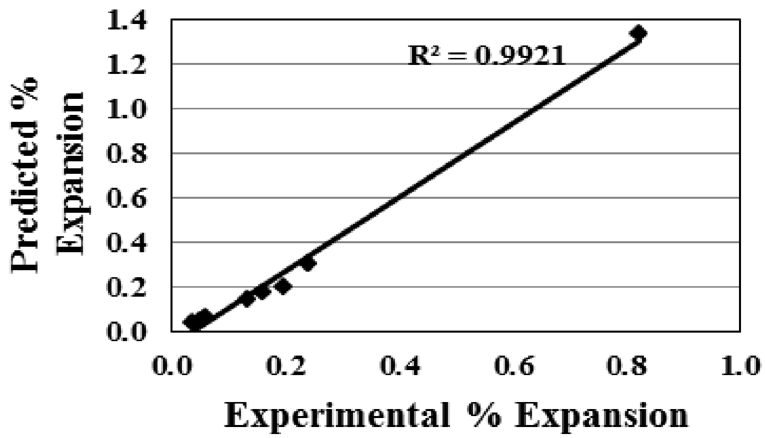

Figure 6: Comparison of Percent Expansion for reactive and non-reactive Aggregates

The experimental data and predicted percent expansion for the different mitigation measures (slag, Meta-kaolin, three low lime fly ashes) for a known reactive aggregate (Spratt) are given in Table 7. The R^2 values show that the prediction curves are almost linear with constant rate of change. The correlation between predicted and experimental percent expansion for these reactive and non-reactive aggregates after mitigation are shown in Figure 7. The correlation is also satisfactory (R^2 value is 0.982).

Table 7: Experimental and Predicted Percent Expansion with SCMs Mitigation

SCM Type (replacement level)	Age, Days	Predicted % Expansion	R^2 (for predicted curve)	Experimental % Expansion
Slag (40%)	112	0.030	0.978	0.025
	140	0.037		0.035
	168	0.045		0.046
	182	0.049		0.047
Meta-kaolin (10%)	112	0.038	0.995	0.039
	140	0.049		0.050
	168	0.060		0.061
	182	0.065		0.067
FA-I (25%)	206	0.045	0.951	0.037
FA-II (35%)	309	0.063	0.992	0.071
FA-III (25%)	519	0.110	0.990	0.142

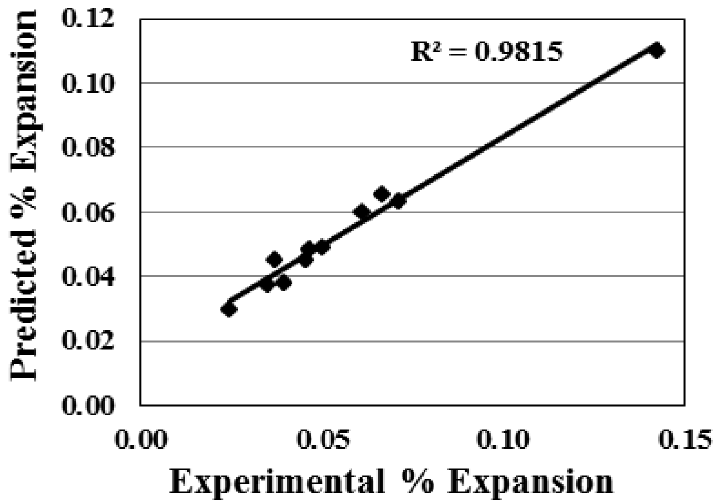

Figure 7: Comparison of Percent Expansion with SCMs Mitigation

Figure 8 shows the Combined Comparison of Percent Expansion for different Aggregates and expansions with Mitigation measures. Again, the correlation is excellent (R^2 value is 0.986).

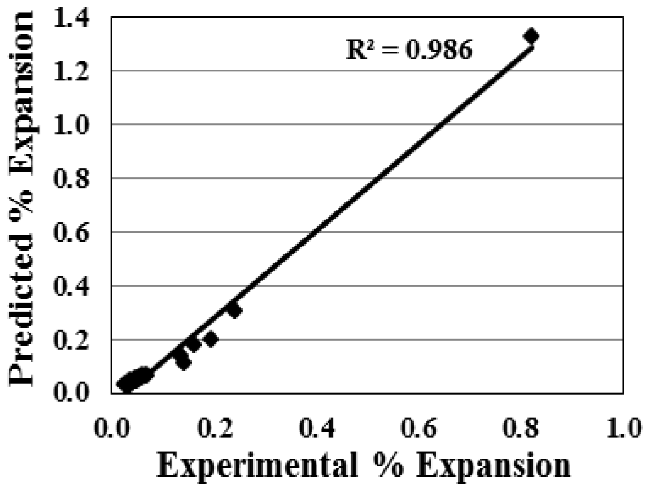

Figure 8: Combined Comparison of % Expansion for Aggregates and Aggregates with Mitigation

Results of experimental and predicted expansions showed excellent correlation between the two data sets (R^2 value close to 1). Therefore, it can be concluded that the ASR expansion due to reactive aggregates did not show any sign of slowing down, rather continued at constant rate, even at longer age under the laboratory test condition. This is in harmony with the fact observed in some real life structures such as arch dam discussed by Rodríguez *et al*. (2012). Also, the constant rate of expansion that was found in our experiment is in harmony with the observation by Charlwood (2011) for ASR affected dam continues to expand at constant rate even after 50 years.

From the data analysis of this research, it is found that the expansion curve including long term expansion does not flatten out and is not similar to classical "S-shaped" model as proposed by Larive *et al*. (2000) rather it continues to grow more as upward-positive slope linear at the extended age. However, since all the aggregates are unique in mineral composition and the type and amount of reactive silica varies over a wide range therefore the best solution will be to analyze the data for prediction with that particular potentially reactive aggregate.

6.0 Conclusion

Based on the analysis, the following conclusions can be drawn:

- From the expansion data of the known reactive aggregates, it is found that the rate of expansion due to ASR becomes constant after certain curing days. This indicates that the alkali silica reaction activity reaches a steady state condition within the concrete matrix, i.e., the reaction rate between the OH^- ions in the pore solution and reactive silica reaches a steady level.

- This steady state condition apparently continues at a constant rate without any sign of slowing down for the reactive aggregates, which is rich in reactive silica. Therefore, reactive silica from the aggregates and OH^- ions from the pore solution are abundant in the system to promote the ASR expansion.
- The mitigation measures, including three different low lime Fly ashes, Slag, and Meta-kaolin all showed similar nature of constant expansions at later stages of curing days. This indicates that, even with the mitigation measures, the rate of expansion becomes constant or the activity within the concrete matrix reaches a steady level.
- The prediction data matching the experimental data corroborates the fact that the rate of expansion in the range from 56 to 84 days in the MCPT method can be confidently used to predict the long term expansion in the specimen.
- This prediction was found valid for both the reactive aggregates and the mitigation measures. Therefore, for the actual job mixtures, the ASR expansion potential for long term can also be predicted using similar method.

References

ASTM (2007a) *Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method),* ASTM C 1260, ASTM International, West Conshohocken, PA.

ASTM (2007b) *Standard Test Method for Concrete Aggregates by Determination of Length Change of Concrete Due to Alkali-Silica Reaction,* ASTM C 1293, ASTM International, West Conshohocken, PA.

Baghdadi, N. (2008) *Modélisation du couplage chimico-mécanique d'un béton atteint d'une réaction sulfatique interne [Modeling of chemical mechanical coupling of concrete suffering from internal sulphate reaction],* Ph.D. thesis, École nationale des ponts et chausses[National School of Bridges and Roads], France.

Bažant, Z. P., Zi, G. and Meyer, C. (2000) Fracture Mechanics of ASR in concretes with waste glass particles of different sizes, *Journal of Engineering Mechanics,* 126(3): 226-232.

Charlwood, R. G. (2011) Managing AAR affected dams, *Proc. 6th Int. Conf. on Dam Engineering,* Lisbon, 15-24.

Charpin, L. and Ehrlacher, A. (2012) A linear elastic Fracture Mechanics-based study of the influence of aggregate size and gel mechanical properties during Alkali-Silica Reaction, *Proceedings of the 14th ICAAR, International Conference on Concrete Alkali Aggregate Reactions,* Austin, Texas, USA.

Fecteau, P. L. and Fournier, B. (2012) Residual expansion testing: new aspects on cores extracted from exposure blocks submitted to environmental conditions, *Proceedings of the 14th ICAAR, International Conference on Concrete Alkali Aggregate Reactions,* Austin, Texas, USA.

Fertig, R. and Tanner, J. (2012) Evaluation of ASR potential in Wyoming aggregates using multiple accelerated tests, *Proceedings of the 14th ICAAR, International Conference on Concrete Alkali Aggregate Reactions,* Austin, Texas, USA.

Gao, X.X. (2010) *Contribution to the requalification of Alkali Silica Reaction (ASR) damaged structures: Assessment of the ASR advancement in aggregates,* PhD thesis, University of Toulouse, France.

Johnston, D. and Fournier, B. (2000) A kinetic-based method for interpreting accelerated mortar bar test (ASTM C1260) data., *11th International Conference on Alkali-Aggregate Reaction,* Quebec, CA.

Johnston, D., Stokes, D. and Surdahl, R. (2000) A Kinetic-Based Method for Interpreting ASTM C 1260, *Cement Concrete Aggregate,* 22(2): 142-149.

Laurent C., Alain E. (2012), ‘A computational linear elastic fracture mechanics-based model for alkali-silica reaction’, Cement and Concrete Research, Elsevier, 2012, 42, pp.613-625.

Larive, C., Joly, M., and Coussy, O., (2000) “Heterogeneity and anisotropy in ASR-affected concrete - Consequences for structural assessment”, Proc. 11th Int. Conf. AAR, Quebec, Canada, 919-928.

Li, K. F., Ulm, F. J., Coussy, O., Larive, C. and Fan, L. (2000) Chemoelastic modelling of Alkali-Silica Reaction in concrete, *11th ICAAR, International Conference on Alkali Aggregate Reaction in Concrete,* Quebec, pp. 989-998.

Riche, J. (2003) *La réaction alcali-silice: approche cinétique et mécanisme d’expansion. Étude du système silex-chaud-potasse à 80°C. [The alkali-silica reaction: kinetic approach and expansion mechanism. Study flint-hot-potash system at 80 ° C],* PhD Thesis, University of Lille, France.

Rodríguez, J., González, P., Martínez, F. and Martí, J. (2012) Concrete swelling in a double curvature dam, *Proceedings of the 14th ICAAR, International Conference on Concrete Alkali Aggregate Reactions,* Austin, Texas, USA.

Salles, F. M., Pínfari, J. C., Kuperman, S. C., Mizumoto, C. and Bernardes, H. M. (2012) Jaguari Hydropower plant - evaluation, diagnosis and control of a structure affected by Alkali-Aggregate Reaction, *Proceedings of the 14th ICAAR, International Conference on Concrete Alkali Aggregate Reactions,* Austin, Texas, USA.

Saouma, V. and Perotti, L. (2006) Constitutive model for alkali-aggregate reactions, *ACI Materials Journal,* 103(3): 194-202.

Stanton, T. E. (1940) Expansion of concrete through reaction between cement and aggregate, *Proceedings, American Society of Civil Engineers,* pp. 1781-1811. (Reprinted with discussion and closure in Transaction, ASCE, 107: 54-126.)

Stanton, T. E. (1942) California experience with the expansion of concrete through reaction between cement and aggregate, *ACI Journal Proceedings,* 38: 209.

Uomoto, T., Furusawa, Y. and Ohga, H. (1992) A simple Kinetics Based Model for predicting Alkali Silica Reaction, *Proceedings of the 9th International Conference on Alkali Aggregate Reaction in Concrete,* London, England, 2: 1077-1084.