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KINETIC MODEL TO PREDICT ULTIMATE MORTAR EXPANSION

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This study reports the prediction of ultimate mortar expansion (UME) due to alkali-silica reactivity. The investigated sixteen aggregate groups with a wide range of geology and mortar expansion that were utilized in this study were obtained from two existing experimental studies. The expansions over the 28-day testing period were fitted with the ASR decay model to predict the UME and time required to reach 50%, 75%, 90% and 95% of UME. The study showed that the ultimate mortar expansion varied with aggregate mineralogy. Finally, aggregates susceptible to alkali-silica reactivity were determined based on the proposed limit of ultimate mortar expansion, and they were compared with the results obtained by the aggregate geology and expansion limits at test durations of 14 and 28 days.

Keywords: Alkali-silica reaction, Test durations, Aggregate mineralogy, Failure limits.

1 INTRODUCTION

Alkali-silica reaction (ASR) is one of the most deleterious chemical phenomena in concrete structures. It has become a major concern in many countries since its discovery in 1940s. ASR can cause significant expansion and cracking in concrete (Touma 2000, Ghafoori and Islam 2010, Islam 2010, Islam and Akhtar 2013, Ghafoori and Islam 2013, Islam and Ghafoori 2013a, 2013b, Islam 2014). Among all the standard methods to evaluate the ASR of an aggregate, the ASTM C 1260 (2007), well known as accelerated mortar bar test (AMBT), is the most widely-used test to determine the reactivity of an aggregate due to its short duration of time (Johnston 2000, Golmakani 2013).

Since ASR is a kinetic-type reaction, Mukhopadhyay et al. (2005) and Ghanem (2010) demonstrated that a kinetic model can be implemented to evaluate the ASR-induced expansion characteristic. Concrete at nuclear power plants has shown to be decayed, a great concern for nuclear safety authorities (MacLeod 2012). Most recently, Islam (2015) proposed the ASR decay model (ADM), shown in Eq. (1), to determine the ultimate mortar expansion (UME) and time to reach the UME:

$$\varepsilon_t = \varepsilon_0[1 - e^{(-\lambda\, t)}] \tag{1}$$

where, ε_0 is the ultimate mortar expansion; t is the test duration in days; ε_r is the residual expansion at t days; λ is the first order rate constant, which has a unit of 1/t. A decay model for alkali-silica reaction has not been fully investigated in previous studies. As such, utilizing ADR on mortar expansion to determine UME, and time differentials for different percentages of UME, is a important topic which needs to be incorporated.

2 RESEARCH SIGNIFICANCE

The use of an ASR kinetic model to predict the UME is a new technique that can be used by researchers to reduce the test duration. The ASR classifications of the aggregates were determined using the limit of the ultimate mortar expansion, and they were compared with the results generated from the aggregate geology and the expansion limits at the test durations of 14 and 28 days.

3 PREVIOUS EXPERIMENTAL STUDIES

The database used in this study was compiled from two existing experimental studies conducted by Touma (2000) and Islam (2010). The raw materials utilized in this study consisted of sixteen aggregate groups – nine from Touma (2000) and seven from Islam (2010). The identification and rock type of the investigated aggregate groups are shown in Table 1. The susceptibility of the aggregates to ASR was then determined according to the aggregate's geological nomenclature, as described in the studies conducted by Islam (2010), Ghafoori and Islam (2010), Islam and Ghafoori (2013) and Islam and Akhtar (2013). The results are also presented in Table 1. The compositions of Portland cement used in the studies are shown in Table 2. The expansion reading of mortar bar was taken at the test durations of 0, 4, 6, 10, 14, 21, and 28 days.

Table 1. Identification, rock type and ASR potential of investigated aggregate groups.

Previous Studies	**Aggregate Id**	**Rock Type**	**Potential ASR Reactivity**
	A1-WY	Rhyolite	0.050 (I)
	A9-NE	Granite	0.233 (I)
	B4-VA	Quartz	0.502 (R)
	C2-SD	Quartz	0.117 (I)
	D2-IL	Dolomite	Innocuous
	E2-IA	Shale	0.599 (R)
	E4-NV	Natural siliceous	1.185 (R)
	E6-IN	Natural siliceous	0.109 (I)
Touma (2000)	E8-NM	Rhyolite, andesite	Reactive
	SN-A	Dolomite	Innocuous
	SN-C	Dolomite-Limestone	Reactive
	SN-D	Dacite	Reactive
	SN-E	Dolomite	Innocuous
	SN-G	Andesite	Reactive
	NN-B	Andesite	Reactive
Islam (2010)	NN-C	Basaltic-andesite	Reactive

Table 2. Composition of Portland cement used in the study.

Studies	SiO_2	Al_2O_3	Fe2O3	CaO	MgO	Na_2O*	SO3	LOI
Touma (2000)	20.90	4.43	3.01	62.65	2.97	1.14	3.06	1.68
Islam (2010)	21.00	3.60	3.40	63.10	4.70	0.84	2.60	1.30

*$Na_2O_{eq} = Na_2O + 0.658 \times K_2O$

4 RESULTS AND DISCUSSIONS

4.1 Mortar Expansion over the Test Duration

Figure 1 shows the progression of mortar expansion of the sixteen selected aggregates. As can be seen, the expansion increased with an increase in test durations. The rate of mortar expansion was extensive and faster for the reactive aggregates as compared to that of innocuous aggregates.

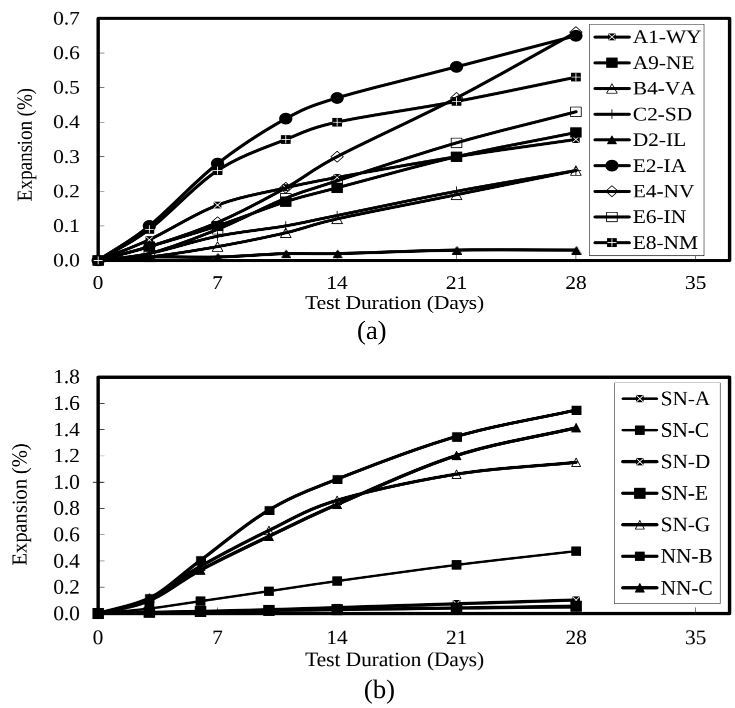


Figure 1. Progression of mortar expansions for the aggregates obtained from a) Touma (2000) and b) Islam (2010).

4.2 ASR Decay Model

The mortar expansion over the test duration of 28 days was fitted with Eq. (1), and the values of coefficient ε0 (UME) and λ, their t-ratio, Prob(F) and R^2, were determined. Time required to reach 50%, 75%, 90% and 95% of UME was also determined. The results are shown in Table 3. As can be shown, a strong correlation existed with R^2 values of 0.850~0.999, with an average of 0.950. Additionally, another parameter for multiple regression models of R^2_{adj} was shown to be very close to the R^2 value. Again, the absolute value of the t-ratios was more than 1.00, and Prob(F) was shown to be very low (close proximity to 0.0000). These indicate that the mortar expansion over the test duration showed a very good fit with the ADM model.

Table 3. Statistical analysis of ADM model (Eq. (1)), ultimate mortar expansion (ε_0) and time required to reach 50%, 75%, 90% and 95% of ε_0.

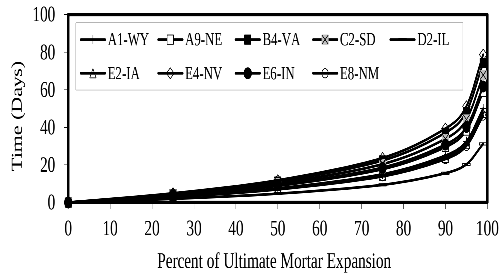
Agg. ID	**Regression Coefficients (RC)**		**t-ratio of RC**		**Prob(F)**	$\mathbf{R^2}$	$\mathbf{R^2_{adj}}$	$\mathbf{t_{1/2}}$[a] **(Days)**	$\mathbf{t_{3/4}}$[b] **(Days)**	$\mathbf{t_{9/10}}$[c] **(Days)**	$\mathbf{t_{19/20}}$[d] **(Days)**
	Λ	ε_0	**λ**	ε_0							
A1-WY	0.0921	0.3703	-22.58	-24.41	0.0000	0.993	0.992	7.53	15.05	25.00	50.00
A9-NE	0.0781	0.4245	-8.92	-9.48	0.0007	0.957	0.947	8.88	17.75	29.48	58.97
B4-VA	0.062	0.3053	-11.14	-6.78	0.0025	0.920	0.900	11.18	22.36	37.14	74.28
C2-SD	0.0679	0.2952	-12.63	-8.20	0.0012	0.944	0.930	10.21	20.42	33.91	67.82
D2-IL	0.1475	0.0418	-8.70	-4.72	0.0092	0.848	0.810	4.70	9.40	15.61	31.22
E2-IA	0.0966	0.6976	-10.65	-33.32	0.0000	0.996	0.996	7.18	14.35	23.84	47.67
E4-NV	0.0585	0.7541	-3.09	-7.47	0.0017	0.933	0.917	11.85	23.70	39.36	78.72
E6-IN	0.0746	0.5098	-6.44	-8.32	0.0011	0.945	0.932	9.29	18.58	30.87	61.73
E8-NM	0.0996	0.5488	-16.86	-32.64	0.0000	0.996	0.995	6.96	13.92	23.12	46.24
SN-A	0.083	0.0498	-61.41	-19.41	0.0000	0.990	0.987	8.35	16.70	27.74	55.48
SN-C	0.0712	0.5475	-6.44	-8.68	0.0010	0.950	0.937	9.74	19.47	32.34	64.68
SN-D	0.0589	0.1168	-23.22	-7.27	0.0019	0.930	0.912	11.77	23.54	39.09	78.19
SN-E	0.0642	0.0589	-56.90	-14.73	0.0001	0.982	0.977	10.80	21.59	35.87	71.73
SN-G	0.1234	1.4660	2.86	-10.52	0.0005	0.965	0.956	5.62	11.23	18.66	37.32
NN-B	0.0988	1.8678	6.20	-11.19	0.0004	0.969	0.961	7.02	14.03	23.31	46.61
NN-C	0.0897	1.7226	4.26	-8.02	0.0013	0.941	0.927	7.73	15.45	25.67	51.34

[a]Time (days) required to reach 50% of ultimate mortar expansion; [b]Time (days) required to reach 75% of ultimate mortar expansion; [a]Time (days) required to reach 90% of ultimate mortar expansion; [a]Time (days) required to reach 95% of ultimate mortar expansion.

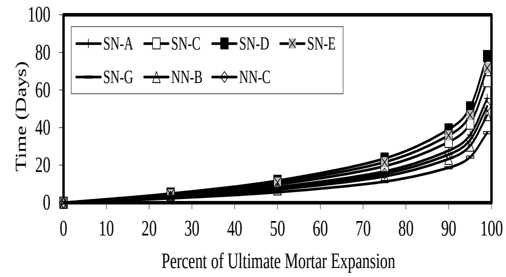
Fig. 2 shows time needed to reach a percentage of UME for the investigated aggregate groups. As can be demonstrated, the 50%, 75%, 90% and 95% of UME occurred from 4.70 to 11.85 days with an average of 8.68 days, from 9.40 to 23.70 days with an average of 17.35 days, from 15.61 to 39.36 days with an average of 28.81 days, and from 31.22 to 78.72 days with an average of 57.63 days, respectively. It gives an idea that time required to reach a given fraction of UME depends on the aggregate geology.

4.3 ASR Classifications of the Aggregates

Table 3 shows the ASR classifications of the aggregates based on the aggregate geology and expansion limits at the ages of 14 and 28 days. Additionally, the results obtained by the failure limit of ultimate mortar bar were also evaluated, and were presented in Table 3. The 14-day failure criteria of the ASTM C 1260 resulted in some innocuous aggregates as reactive. As compared to the results obtained at 14 days, the limit at the extended age of 28 days showed more liable. Finally, the ultimate expansion limit underestimated some reactive aggregates as innocuous. The reason can be stated that the mortar expansion data up to the 28-day testing period was not sufficient for the ADM model to predict the UME. The expansion data at the extended testing period of at least 56 days would better predict the UME of aggregates, and hence, the ASR classifications of the aggregates can be improved.



a) Touma (2000).



b) Islam (2010).

Figure 2. Time required to reach percent of ultimate mortar expansion.

Table 4. ASR classifications based on the expansion limits of mortar bars.

Agg. ID	**Aggregate Mineralogy**	**14-Day**	**28-Day**		**Limit of UME**
		(0.10%)[a]	**0.28%[b]**	**0.33%[c]**	**(0.64%[d])**
A1-WY	I	R	R	R	0.3703 (I)
A9-NE	I	R	R	R	0.4245 (I)
B4-VA	R	R	I	I	0.3053 (I)
C2-SD	R	I	I	I	0.2952 (I)
D2-IL	I	I	I	I	0.0418 (I)
E2-IA	R	R	R	R	0.6976 (R)
E4-NV	R	R	R	R	0.7541 (R)
E6-IN	I	R	R	R	0.5098 (I)
E8-NM	R	R	R	R	0.5488 (R)
SN-A	I	I	I	I	0.0498 (I)
SN-C	R	R	R	R	0.5475 (R)
SN-D	I	I	I	I	0.1168 (I)
SN-E	I	I	I	I	0.0589 (I)
SN-G	R	R	R	R	1.4660 (R)
NN-B	R	R	R	R	1.8678 (R)
NN-C	R	R	R	R	1.7226 (R)

[a]Failure limit recommended by ASTM C 1260; [b]Failure criteria suggested by Islam (2010)
[c]Failure limit proposed by Hooton and Rogers (1993); [d]Failure limit suggested by Islam (2015)

5 CONCLUSIONS

The existing ASR decay model was very suited with the expansion of mortar bars over the 28-day test duration. The predicted UME and time required to reach 50%, 75%, and 90% of the UME varied mainly on aggregate mineralogy. When compared to the early age expansion limit, the proposed failure criteria of ultimate mortar expansion showed a better correlation with the outcomes obtained from the previously suggested 28-day failure criteria in determining the ASR classifications of the investigated sixteen aggregates. However, it is highly recommended that the expansion data for an extended testing period of at least 56 days would best be utilized for the ADM to predict the UME.

References

ASTM Standard C1260, Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method). ASTM International, West Conshohocken, PA, 2007.

Ghafoori, N., and Islam, M. S., Time Series analysis for prediction of ASR-induced expansions. Constr Build Mater, 49:194-200, 2013.

Ghafoori, N., and Islam, M. S., Evaluation of alkali-silica reactivity using mineralogy of aggregates and the expansion tests, Proceedings of the 5th International Structural Engineering and Construction Conference, pp. 467-472, Las Vegas, September 22-25, 2009.

Ghanem, H., Zollinger, D., and Lytton, R., Predicting ASR aggregate reactivity in terms of its activation energy. Constr Build Mater, 24:1101-1108, 2010.

Golmakani, F., Possible modifications to the Accelerated Mortar Bar Test (ASTM C1260). Master's Thesis, 117 pp, University of Toronto, 2013.

Hooton, R. D., and Rogers, C. A., Development of the NBRI rapid mortar bar test leading to its use in North America. Constr Build Mater, 7(3):145-148, 1993.

Islam, M. S., Performance of Nevada's aggregate on alkali-aggregate reactivity of Portland cement Concrete, Doctoral Dissertation, University of Nevada, 362 pp, Las Vegas, 2010.

Islam, M. S., and Ghafoori, N., Evaluation of alkali-silica reactivity using ASR kinetic model, Constr Build Mater, 45:270-274, 2013.

Islam, M. S., and Ghafoori, N., Evaluation of Alkali-Silica Reactivity Using Aggregate Geology, Expansion Limits of Mortar Bars and Concrete Prisms, and Kinetic Model, Journal of Materials Science Research, 2(2), pp. 103-117, 2013.

Islam, M. S., and Akhtar, S. A., Critical Assessment to the Performance of Alkali-Silica Reaction (ASR) in Concrete, Canadian Chemical Transactions, 1(4), pp. 253-266, 2013.

Islam, M. S., Prediction of ultimate expansion of ASTM C 1260 for various alkali solutions using the proposed decay model, Journal of Construction and Building Materials, DOI: 10.1016/j.conbuildmat.2014.12.087, 2015 (in press).

Islam, M. S., and Ghafoori, N., Relation of ASR-induced Expansion and Compressive Strength of Concrete, Journal of Materials and Structures, Vol. 48, 2014 (in press).

Islam, M. S., Comparison of ASR mitigation methodologies, International Journal of Concrete Structures and Materials, 8(4), pp. 315-326, 2014.

MacLeod, I., Decaying concrete raising concerns at Canada's aging nuclear plants, National Post News, July 8, 2012. Retrieved from http://news.nationalpost.com/2012/07/08/decaying-concrete-raising-concerns-at-canadas-aging-nuclear-plants/ on August 2, 2012.

Mukhopadhyay, A. K., Zollinger, D. G., and Shon, C. S., Evaluation of Alkali Silica Reactivity of Mineral and Aggregate Using Dilatometer Method. An Innovative Pavement Research Foundation (IPRF) Research Report, Report No. IPRF-01-G-002-02-5.1, 27 pp., Skokie, IL, USA, 2005.

Touma, W. E., Alkali-silica reaction in Portland cement concrete: testing methods and mitigation alternatives. Doctoral Dissertation, 520 pp, University of Texas, 2000.