16th International Conference on
Alkali-Aggregate Reaction in Concrete
Lisboa | LNEC | Portugal | 31 May - 2 June 2022
http://icaar2020-2022.lnec.pt

Impact of NaOH addition on the ASR expansion of ternary concrete incorporating Ground Glass

Isabelle Fily-Paré(1), Benoît Fournier(2), Josée Duchesne(3), Arezki Tagnit-Hamou(4)
(1) Université Laval, Québec, Canada, Isabelle.fily-pare.1@ulaval.ca
(2) Université Laval, Québec, Canada, benoit.fournier@ggl.ulaval.ca
(3) Université Laval, Québec, Canada, josee.duchesne@ggl.ulaval.ca
(4) Université de Sherbrooke, Sherbrooke, Canada, Arezki.Tagnit-Hamou@USherbrooke.ca

Abstract

NaOH addition is a current practice in most ASR test methods. If it provides severe conditions for the aggregates and accelerates their reactivity, its potential interaction with supplementary cementitious materials (SCM) is a matter of concern. In this study, concrete prisms were manufactured from ternary concretes incorporating a highly-reactive coarse aggregate, with and without NaOH addition, ground glass and one of the following SCMs: fly ash (FA), blast furnace slag (BFS), silica fume (SF) and metakaolin (MK), were made. The specimens were stored for two years at 38°C and R.H. 95%, over which their length change was monitored regularly. The expansion of given mixtures is significantly influenced by NaOH addition. In most cases, NaOH addition resulted in reduced expansion, but the latter reduction did not change the Pass/Fail outcome of the test.

***Keywords**: alkali-silica reaction (ASR); expansion; ground glass; glass powder; NaOH*

1. INTRODUCTION

Over the last few decades, global authorities worked thoroughly to inform and influence major greenhouse gas (GHG) emitters including the cement industry, which contributes to anthropogenic GHG emissions to a significant level (3.8-5%) [1]. As an example, the World Business Council for Sustainable Development (WBCSD) published reference material [1,2] suggesting that the use of supplementary cementitious materials (SCMs) decreases energy consumption per kilo of cementitious material produced [3] and leads to lower fuel consumption and gas emission per cubic meter of concrete.

Between 1990 and 2017, North American cement producers reduced their CO_2 emissions per ton of cementitious materials from 905 to 746 kg [4]. The above reductions in GHG emissions largely correlates with greater use of SCM and limestone fillers; indeed, the clinker-to-cement ratio went from 90% to 82% during that period.

Emerging SCMs, such as ground glass (GG), calcined clays or rice husk ash (RHA), are expected to gain in popularity and compensate for the declining or somewhat limited availability of more "conventional" SCMs, such as blast furnace slag (BFS), silica fume (SF), and fly ash (FA). For instance, FA scarcity is related to the declining use of thermal power as an energy supply in the USA (about 50% in 2005 and less than 38% in 2012) IEA [5]. The availability of BFS is limited since its production is already fully consumed in concrete [6] and the use of SF is often limited by its cost [7]. The next generation of SCMs shall target materials with great availability (although some "local/regional materials could be used on a specific-project basis), acceptable cost, and good performance regarding concrete durability.

Post-consumed GG is a pozzolanic material that is worth some attention since the material is worldwide available and municipalities are sometimes paying for disposal since there is no profitable market for recycled glass [8]. However, a closer look at its chemical composition can restrain the above enthusiasm because GG is an SCM with a high-alkali content (≈13% Na_2O_{eq}), which might be problematic regarding alkali-silica reaction (ASR). If alkalis from GG are indeed released in the concrete pore solution, this may increase the concentration of hydroxyl ions to balance the positive charges of alkalis, thus enhancing the attack of reactive phases within the concrete aggregates. The chemical environment is then favorable for the production of the swelling ASR gel, which is known to induce cracking into concrete and to jeopardize its durability. On the other hand, GG reacts as a pozzolanic material [9-12], which is known to generally lower the pH of concrete pore solution and mitigate ASR [13]. Scientists are still debating about the beneficial or detrimental contribution of GG to ASR in the presence of reactive aggregates in concrete.

The accelerated mortar bar test (AMBT) is generally the most popular method used in studies that aim to assess the beneficial effect of GG in preventing ASR. It is often used to characterize GG although the potential release of alkalis from GG is hard to evaluate under the AMBT conditions. Table 1.1 presents a collection of studies using the AMBT to evaluate the ASR potential of mixtures incorporating GG. The above studies suggest that at least 50% of GG ought to be used as a low-alkali cement replacement to reduce ASR expansion below the 0.10% limit when used with highly-reactive aggregates. For moderately reactive aggregates, 20 to 30% GG is considered enough/ necessary to prevent expansion.

Shayan and Xu [14] used the concrete prism test (CPT) with 20 to 30% mass replacement of a low-alkali cement (Na_2O_{eq} of 0.46%) by GG with particle size <10μm; after two years of monitoring, the expansion of the test specimens stored at 38°C and 100%RH was below 0.01% when non-reactive aggregates were used. Zidol [15] assessed the expansion of concrete prisms incorporating a highly reactive aggregate and 20/30% GG as replacement of a cement with Na_2O_{eq} content of 0.73%. As per the test requirement, the alkali content corresponding to the cement part in the system was raised to 1.25% with NaOH. After one-year of storage at 38°C and 100%RH, the expansions measured were all beyond the 0.040% limit of CSA Standard Practice A23.2-28A.

Since the beneficial effect of GG in preventing ASR expansion seems somewhat limited in a binary context, several authors documented the expansion of ternary mixtures incorporating reactive aggregates, GG and a second SCM, such as BFS, FA, SF, and MK when tested with the AMBT method. The results suggest that ternary systems are more efficient in reducing expansion due to ASR, as presented in Table 1.2.

The potential of ternary mixtures incorporating (high-alkali) GG in preventing deleterious expansion due to ASR in concrete is currently not documented by test methods that could be considered more reliable than those involving soaking of the test specimens in a NaOH solution. On the other hand, using the concrete prism testing for evaluating the beneficial effect of SCMs to prevent ASR involves raising the alkali content of the cement part in the system to 1.25% Na_2Oeq, as per CSA Standard Practice A23.2-28A and ASTM C1778. There is currently limited information about the impact that such an alkali addition may have on the expansion process in concretes incorporating an alkali-rich ground glass and whether this practice is appropriate or not.

Such a questioning appears important in view of the dual effect of alkali addition/contribution in concretes incorporating SCMs, i.e. 1) accelerating the “kinetics” of ASR to obtain faster results through laboratory testing; and 2) activating a “beneficial” reaction of SCMs for binder production. [16]. Other authors view that alkali addition is actually beneficial to the point that GG could be considered as an activator capable of stretching the activation window of FA, GGBS, and Metakaolin (MK) [17-20].

Table 1.1: Expansion of mortar bars according to ASTM C1260 when natural reactive aggregates are used in combination with GG with an Na2Oeq content ranging between 11.30 and 13.80% (mortar bars immersed 1 N NaOH at 80°C for 14 days); expansion < 0.10%: innocuous; expansion > 0.20%: deleterious.

	Expansion (%)		Aggregate	Cement and alkali addition	% of cement replacement	Size of glass particles	Source
	Specimens with GG	Control					
Highly reactive aggregate and 50% of GG	0.08*	≈0.50	Highly reactive (Spratt limestone)	0.63% of Na_2O_{eq} NaOH added to 0.90	50%	D_{50}≈50µm	[21]
Highly reactive aggregate and 10 to 40% of GG	<0.20 and >0.10	0.38	Natural sand	0.84% of Na_2O_{eq}	40%	45 to 75 µm	[22]
	0.41**, 0.30** and 0.30**	0.72	Highly reactive (Spratt limestone)	0.73% of Na_2O_{eq}	20, 30 and 40%	D_{50} ≈ 10µm	[15] **
	0.42* ,0.22* and 0.11*	0.5	Highly reactive (Spratt limestone)	0.63% of Na_2O_{eq} NaOH added to 0.90	10, 20, 30%	D_{50}≈50µm	[21]
	0.20*** and 0.12***	0.64	Highly reactive (Jobe sand)	1.22% of Na_2O_{eq}	30%	D_{50} ≈ 200µm and D_{50} ≈ 20µm	[23] ***
Moderately reactive aggregate and 20 to 30% of GG	0.07 and 0.07	0.20	Reactive sand	0.86% of Na_2O_{eq}	20% and 30%	<125µm	[24]
	0.09 and 0.06	0.27	Reactive Argillite	0.88% Na_2O_{eq}	20 and 30%	D_{50}≈70µm	[25]
	0.08*** and 0.05***	0.29	Reactive (Wright sand)	1.22% of Na_2O_{eq}	30%	D_{50} ≈ 200µm and D_{50} ≈ 20µm	[23] ***
	0.04	0.26	Not mentioned	0.46% of Na_2O_{eq}	20%	D_{50} ≈ 10µm	[26]
Moderately reactive and 5 to 10% of GG	0.20, 0.17 and 0.13	0.22	Reactive siliceous sand	0.73% of Na_2O_{eq}	5, 10, and 20%	D_{50}≈20µm	[27]
	0.18	0.27	Reactive Argillite	0.88% Na_2O_{eq}	10%	D_{50}≈70µm	[25]
	0.13 and 0.13	0.20	Alkali reactive sand	0.86% of Na_2O_{eq}	5 and 20% of aggregate	4.75 to 150µm	[24]
	0.12	0.26	Not mentioned	0.46% of Na_2O_{eq}	10 %	D_{50} ≈ 10µm	[26]

* Specimens with and without NaOH addition showed similar expansion

** CSA 23.2-25A,

*** ASTM C227, 38°C, immersed in 0.6 N NaOH for 6 month and expansion limit of 0.10% at 6 months

Table 1.2: Expansion of mortar bars (testing in accordance with ASTM C 1260 conditions) incorporating GG and another SCM as cement or aggregates replacement.

Expansion (%)		Aggregate	Cement and alkali addition	Type and % of glass replacement	Size of glass particles	Other SCM	Source
GG	CtrlCtrl						
<0.1	0.22	Reactive siliceous sand	0.73% of Na_2O_{eq}	5, 10, and 15% of cement	$D_{50} \approx 20 \mu m$	15, 10 and 5% FA (for total cement replacement of 20%)	[27]
< 0.05	0.25	Not mentioned	0.38% of Na_2O_{eq}	50% of aggregate	ASTM 1260 aggregate gradation	2.5 to 10% of MK or FA	[28]
<0.02*	0.02	River sand	Not mentioned	100% of aggregate	Sieved at 5, 2.36, 1.18 and 0.6-0mm	5 - 20% MK	[29]*
0.05 and 0.00	0.009	Quartz aggregate	K_2O of 0.66, Na_2O or Na_2O_{eq} not mentioned	7.5% of aggregate	4.75 to 2 mm	7.5 and 15% of MK	[30]
0.02 and 0,0					850 to 300μm		
< 0.04	0.02	River sand and granite	0.38% of Na_2O_{eq}	15, 30 and 45% of sand	80% > 0.6 mm	33% FA	[31]
< 0.05	0.9	100% crushed glass aggregate	0.9 of Na_2O_{eq}	10% of cement	Average size of 17μm	30% of BFS	[32]
						10% MK	
				20% of cement		20% of BFS	
0.04 and 0.02	-	Non-reactive sand	Cement: Na_2O of 0.3 and K_2O not mentioned Activator: SiO_2/Na_2O of 1.6 for BFS and 1.8 for FA	20% of alkali-activated BFS of FA	$D_{50} \approx 20 \mu m$	80% BFS or 80%FA	[33]

* ASTM and modified ASTM; just enough water for cohesion and slump of 0

2. OBJECTIVE AND SCOPE OF WORK

This project aimed at determining the effect of adding alkalis (NaOH) on the “severity” of the CPT used for evaluating the effectiveness in preventing ASR of ternary concrete mixtures incorporating a high-alkali GG. In this study, concrete prisms were made in accordance with Standard Practice CSA A23.2-28A (similar to ASTM C1778) to assess the expansive behaviour of ternary concrete mixtures, with and without the addition of NaOH, and incorporating a highly reactive aggregate, GG and ground granulated BFS / (FA) / SF / MK.

Ultimately, this work was aimed at determining whether expansion due to ASR can be efficiently prevented in concrete made with a high-alkali GG through the use of other SCMs, such as BFS, FA, SF or MK.

3. MATERIALS AND METHODS

3.1 Materials

Concrete specimens were made using a General Use (GU) Portland cement (C1) with an alkali content of 0.94%, Na_2O_{eq}; GG from a recycling facility located in Quebec (Canada); BFS of grade 80 from Ontario (Canada); Type F FA from Alberta (Canada); SF from a ferro-silicon plant located in Quebec

(Canada) and MK from Georgia (USA). The chemical composition and the specific gravity of the above materials are given in Table 3.1.

The fine aggregate used in the concrete mixtures consisted of manufactured high purity limestone (98% $CaCO_3$) from Newfoundland (Canada); it presents a density of 2.7 and an absorption capacity of 0.57%. The coarse aggregate was the highly-reactive Spratt limestone from Ontario (Canada) that presents a density of 2.7 and an absorption capacity of 0.43%. Both the non-reactive sand and the highly-reactive Spratt limestone have very low alkali contents and are not considered as potential alkali contributors to the concrete pore solution.

Table 3.1: Chemical composition and specific gravity of the GU cement and SCMs used in this study

Oxides	C1	GG	BFS	FA	SF	MK
SiO_2 (%)	18.7	70.53	37.74	56.72	94.27	51.6
CaO (%)	60.80	10.77	36.20	9.29	0.54	0.02
Al_2O_3 (%)	5.00	2.06	9.45	24.07	0.30	43.97
Fe_2O_3 (%)	3.70	0.35	0.36	3.14	0.10	0.49
Na_2O (%)	0.25	12.49	0.26	2.50	0.12	0.27
K_2O (%)	1.05	0.66	0.36	0.64	0.65	0.25
Na_2O_{eq} (%)	0.94	12.92	0.50	0.55	1.43	0.43
SO_3 (%)	3.80	0.11	2.45	-	0.02	-
MgO (%)	2.70	1.14	9.96	1.05	0.28	0.04
TiO_2 (%)	-	0.07	0.94	0.65	0.01	1.40
P_2O_5 (%)	-	0.03	0.08	0.09	0.12	0.09
MnO (%)	-	0.02	0.72	0.04	0.03	0.01
L.O.I (%)	1.90	1.71	1.84	1.05	3.20	1.84
Specific gravity	3.15	2.54	3.04	2.35	2.24	2.20

3.2 Concrete mix design

Table 3.2 presents the concrete mix designs used in this study. A constant W/B of 0.43 was used for all concrete mixtures, while superplasticizer was added when necessary to meet the slump requirement of 100 to 150 mm specified in CSA A23.2-28A. Considering the wide range in specific gravity of the cementitious materials and the specified binder content of 420 kg/m^3, the decision was made to maintain a constant proportion of reactive coarse aggregate throughout the experiment. The amount of non-reactive fine aggregate in the concrete was thus adapted to accommodate the binder volume variations, while maintaining a coarse-to-fine aggregate ratio of 1.50 ± 0.10 (specified mass ratio of 60:40 in CSA A23.2-28A). NaOH was added in selected mixtures to rise the alkali content corresponding to the cement part of the binder to 1.25% Na_2Oeq, as required by CSA A23.2-28A.

For comparison purposes, binary concrete mixtures incorporating GG as the only SCM were made, i.e. using cement replacement levels by GG ranging from 10 to 30%, with and without added alkalis.

3.3 Manufacture, storage, and testing of specimens

All concrete mixtures were made in a pan mixer of 30 liters capacity. As a precaution to reduce the deleterious impact of alkali leaching on expansion, test prisms, 100 x 100 x 300 mm in size (instead of 75 x 75 x 300 mm specified in CSA A23.2-28A), were made from each mixture. Four specimens were manufactured from each ternary concrete mixture, two in the case of binary mixtures. After 24 hours in their moulds, the prisms were demoulded and placed in sealed 25L plastic pails (lined with damp geotextile to maintain a relative humidity > 95%; 2 prisms per container), which were then stored at 38^{o}C.The length change monitoring of the test prisms was performed at regular intervals up to 104 weeks. Moreover, readings were made without pre-cooling of the test specimens prior to measuring, i.e. to prevent temperature cycles and the inherent condensation and runoff that result in excessive alkali leaching (Lindgård et al. 2013). Efforts were made to minimize thermic shock by keeping the test prisms in the hot room and remove them one by one for measurements. It is to be mentioned that the approach in the new RILEM methods AAR 10... will suggest to measure the prisms hot in order to minimize the deleterious effect of leaching on expansion.

Table 3.2: Proportioning of concrete mixtures made in this study.

	NaOH (kg/m^3)		Cement and SCMs (kg/m^3)						Aggregates (kg/m^3)	
Mixture	NaOH		C1	GG	BFS	FA	SF	MK	Coarse	Fine
	0.94	1.25								
Control	-	1.681	420	-	-	-	-	-	1054	732
10GG	-	1.513	378	42	-	-	-	-	1054	723
20GG	-	1.345	336	84	-	-	-	-	1054	714
30GG	-	1.177	294	126	-	-	-	-	1054	710
10GG-20BFS	-	1.177	294	42	84	-	-	-	1054	720
20GG-20BFS	-	1.009	252	84	84	-	-	-	1054	711
10GG-40BFS	-	0.840	210	42	168	-	-	-	1054	717
20GG-40BFS	-	0.672	168	84	168	-	-	-	1054	709
10GG-15FA	-	1.261	315	42	-	63	-	-	1054	704
20GG-15FA	-	1.093	273	84	-	63	-	-	1054	696
10GG-30FA	-	1.009	252	42	-	126	-	-	1054	686
20GG-30FA	-	0.840	210	84	-	126	-	-	1054	677
10GG-5SF	-	0.429	357	42	-	-	21	-	1054	716
30GG-5SF	-	1.093	273	126	-	-	21	-	1054	698
10GG-10SF	-	1.345	336	42	-	-	42	-	1054	708
30GG-10SF	-	1.009	252	126	-	-	42	-	1054	691
10GG-5MK	-	1.429	357	42	-	-	-	21	1054	715
30GG-5MK	-	1.093	273	126	-	-	-	21	1054	698
10GG-15MK	-	1.261	315	42	-	-	-	63	1054	700
30GG-15MK	-	0.924	231	126	-	-	-	63	1054	682

4. RESULTS

The expansion results obtained for the control with Spratt aggregates were 0.173% at two years.

Figure 4.1 presents the 104-week expansions of the test prisms cast from binary and ternary concretes, with and without added alkalis, incorporating 10 / 20% GG along with 0 / 20 / 40% BFS or 0 / 15 / 30% FA.

Expansions ranging from 0.11 to 0.15%, i.e. way beyond the 0.040% expansion limit, were obtained in the case of test prisms cast from binary mixtures incorporating 10 and 20%GG. The addition of NaOH enhanced slightly the expansion of the test specimens incorporating 10% GG, while having no significant impact on those incorporating 20%GG.

For ternary concrete mixtures incorporating 10%GG, the addition of NaOH had no significant impact when 20%BFS and 30%FA were used; however, significant reductions in expansion were noticed in the case of mixtures incorporating 40%BFS and 15%FA. All prisms cast from (ternary) “boosted” mixtures incorporating 20%GG showed significant expansion reduction compared to “unboosted” ones.

Regarding the 0.040% expansion limit proposed by CSA A23.2-28A, mixtures incorporating BFS required a 40% replacement level to reduce the expansion of the test prisms close to the limit regardless of the GG content; interestingly, the addition of NaOH resulted in expansions lower or equal to the limit in the case of the 40%BFS prisms, while the companion "unboosted" prisms expanded slightly above 0.040% (regardless of the GG content). Five out of the eight mixtures incorporating FA are clustered around the 0.040% limit; the concrete prism expansions corresponding to the two 15%FA mixtures without NaOH addition are well above the limit while that corresponding to mixture 20GG-30FA-1.25% is well below. The results suggest that GG concrete mixtures that are the most affected by NaOH addition incorporate 15%FA and/or 20%GG (BFS & FA); for the above combinations, NaOH addition indeed resulted in significant expansion reductions compared to the same combination without NaOH.

Figure 4.2 presents the expansion of test prisms cast from binary and ternary concretes, with and without NaOH, incorporating 10 / 30%GG along with 0 / 5 / 10%SF and 0 / 5 / 15%MK. When comparing the results obtained for binary mixtures incorporating GG, it is worth mentioning that 1) a 30%GG content resulted in slightly lower expansions than that of a 20%GG mix (Figure 4.1); however, values are still above the 0.040% limit, and 2) the NaOH addition slightly reduced concrete prism expansion when 30%GG was used, while it slightly enhanced expansion in the case of the 10%GG mix.

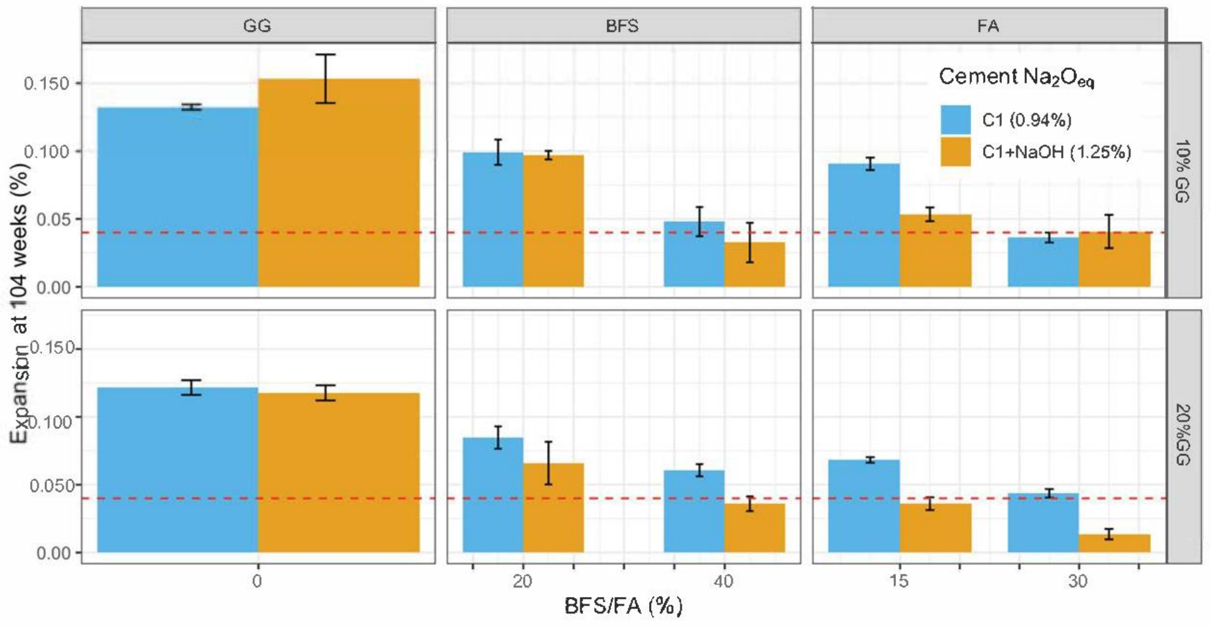

Figure 4.1: Expansion at 104 weeks of test prisms cast from concrete mixtures, with and without the addition of NaOH, incorporating various amounts of GG and BFS/FA. The error bars correspond to the SD calculated from the two or four test prisms from the same mix, while the red dotted line is the 0.040% expansion limit.

Actually, alkali addition enhanced the expansion of concrete prisms cast from ternary concrete mixtures incorporating 10%GG combined with 5/10%SF and 15%MK. For ternary mixtures incorporating 30%GG, such an increase in alkali content significantly reduced concrete prism expansion when GG was combined with SF, but it had no significant impact when GG was combined with MK.

The only ternary concrete mixture incorporating 10%GG that clearly resulted in concrete prism expansion below the 0.040% level was the "unboosted" mix incorporating 15%MK. In the case of ternary mixtures incorporating 30%GG, those meeting the expansion requirement incorporated 10%SF, without NaOH addition, and 15%MK, regardless of the NaOH addition.

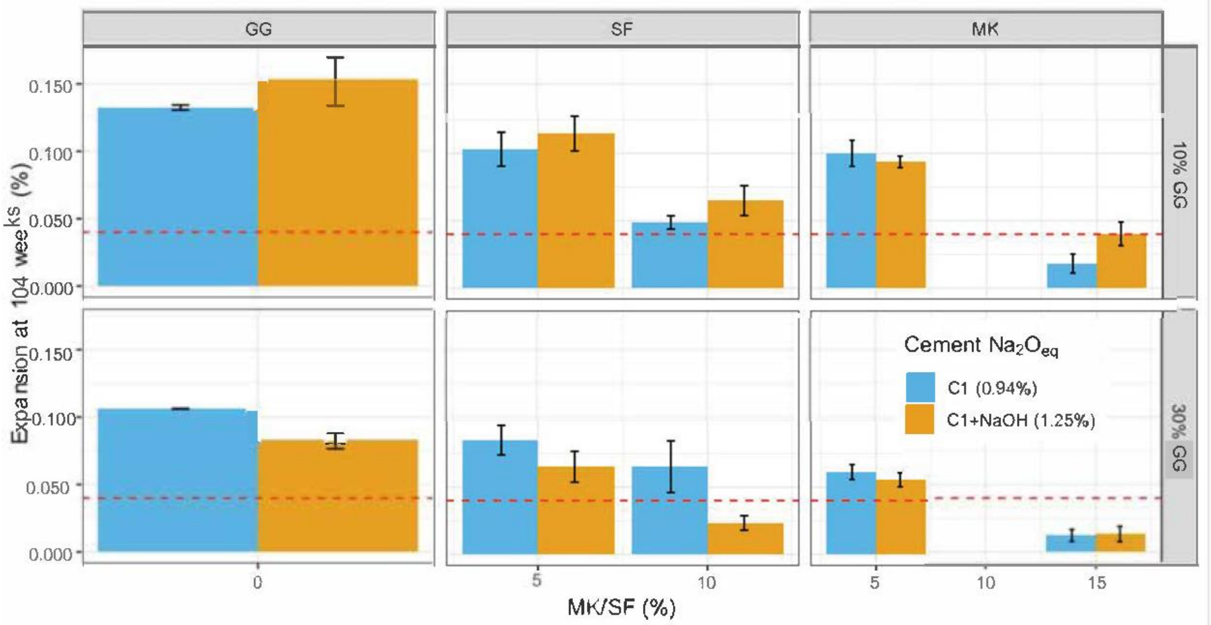

Figure 4.2: Expansion at 104 weeks of test prisms cast from concrete mixtures, with and without the addition of NaOH, incorporating various amounts of GG and MK/FA. The error bars correspond to the SD calculated from the four test prisms from the same mix, while the red dotted line is the 0.040% expansion limit.

5. DISCUSSION

The CPT is generally considered to provide a reliable assessment of the long-term potential alkali-reactivity of aggregates, perhaps with the exception of some slowly reactive granitic/gneiss aggregates. In order to do so, the "sensitivity" of the aggregate to deleterious alkali reactions is assessed through accelerated test conditions consisting of a storage at high temperature (38°C) and RH>95%, and NaOH addition (1.25% Na_2Oeq, by cement mass; total concrete alkali content of 5.25 kg/m^3, Na_2Oeq). For the large number/majority of reactive aggregates tested in the CPT, an increase in the concrete alkali content results in higher concrete prism expansion, at least within a certain range of concrete alkali contents. A "threshold" alkali content beyond which "deleterious" expansion is observed can thus be established, provided precautions are taken to avoid/reduce the deleterious effect of alkali leaching on expansion. Such an alkali threshold, which varies from one aggregate to another, can thus be used to establish acceptable concrete compositions as a function of their total alkali content.

For the majority of ternary concrete mixtures tested in this study, which incorporate 10 to 30% of a high-alkali GG, the NaOH addition actually resulted in lower concrete prism expansions compared to unboosted companion mixtures. Considering that precautions were taken to reduce the impact of alkali leaching from test prisms, the above data suggest that NaOH addition did not necessarily play its role of aggregate's reactivity accelerator but rather some sort of enhancer of the ASR preventive capacity of the binder systems. It thus appear appropriate to question whether the addition of alkalis is affecting the reliability of the CPT in assessing the long-term effectiveness of the various mixtures investigated in preventing expansion due to ASR.

Other phenomena, such as pessimum effect, alkali dilution, etc., were considered during the analysis of the result and were not found to be consistent in all systems with all binders. The scope of the study being wide, with binary/ternary mixtures and several SCMs, different dosages and different alkali additions, many phenomena are thought to be observed; however, no single phenomenon seemed to similarly control all systems.

Figure 5.1 illustrates graphically the impact of NaOH addition on the expansion of concrete prisms and the standard deviation between the results obtained for the four prisms of a set. As also observed in Table 5, for most mixtures, the addition of NaOH results in lower expansions compared to the companion mixture without NaOH. It is especially the case for mixture incorporating FA, BFS with an average reduction of 41.6% and 21.4% associated to NaOH addition. Concrete mixtures incorporating MK are mostly non-NaOH sensitive. For SF-bearing mixtures, the addition of NaOH increases the expansion by an average of 18.3%% when only 10% GG is used, while it reduces concrete prism expansions by an average of 39.6 % when 30% GG is used.

In the case of binary concrete mixtures, expansion is enhanced (+15.8%) by NaOH addition when 10%GG is used; it has no impact on the expansion when 20%GG (-3.3%) is used and it reduces the expansion when 30%GG is used (-21.6%). The latter suggest a synergetic effect between GG and NaOH addition that is beneficial in reducing the expansion. This effect is also noticeable in ternary mixtures since the average reduction in the expansion values of the test prisms due to NaOH addition is 0.026% for specimens incorporating FA/BFS and 20%GG, while it is 0.015% for the mixtures with the same amount of FA/BFS but with only 10%GG. Similarly, for specimens incorporating SF/MK and 30%GG, the average reduction in concrete prism expansion is 0.017% and for the same mixture with only 10%GG, the average concrete prism expansion enhancement due to NaOH addition is 0.011%.

The average concrete prism expansion reductions associated to NaOH addition in the case of ternary mixtures incorporating BFS, FA, SF and MK are respectively 0.015, 0.024, 0.009 and -0.003%; this suggests that the “beneficial” effect of NaOH addition in ternary mixtures incorporating GG is more pronounced when GG is mixed with FA or BFS. Actually, in several mixtures incorporating SF and MK, the NaOH addition leads to an increased expansion of the test specimens. MK-bearing mixtures are somewhat insensitive to NaOH addition and the SCM that is most responsive to NaOH addition when coupled with GG is FA.

Table 5.1 presents the 104-week expansions of the various binary and ternary mixtures, with and without NaOH addition, as well as the outcome of the test (i.e. pass or fail), its reliability being based on the p-value of a t-test for the hypothesis that the expansion is truly different (i.e. above or below) than the 0.040% limit. The results in Table 5.1 indicate that 26 out of the 38 mixtures tested, showed a similar outcome (i.e. Pass/Pass or Fail/Fail), regardless of the NaOH addition. Indeed, in most cases, the NaOH addition was found to reduce expansion but did not change the outcome of the test. Twelve mixtures (highlighted in Table 5.1) showed opposite outcomes when considering the effect of NaOH addition. However, for five of those twelve mixtures, the expansion results are either too close to the 0.040% limit or the variability between test specimens is too high to conclude with confidence on the Pass/Fail outcome of the mixture. Higher variability are most of the time associated to lower expansions, since the absolute value of the variability of the experimental set-up is more noticeable for mixture with minor expansion results. The lack of confidence on the conclusion of the test is indeed indicated by a p-value below 0.90. Finally, only two SCM combinations (i.e. four mixtures) showed statistically different outcomes for the test specimens, i.e. mixtures 20GG-30FA and 30GG-10SF.

Figure 5.1 illustrates graphically the impact of NaOH addition on the expansion of concrete prisms and the standard deviation between the results obtained for the four prisms of a set. As also observed in Table 5.1, for most mixtures, the addition of NaOH results in lower expansions compared to the companion mixture without NaOH. It is especially the case for mixture incorporating FA, BFS with an average reduction of 41.6% and 21.4% associated to NaOH addition. Concrete mixtures incorporating MK are mostly non-NaOH sensitive. For SF-bearing mixtures, the addition of NaOH increases the expansion by an average of 18.3%% when only 10% GG is used, while it reduces concrete prism expansions by an average of 39.6 % when 30% GG is used.

In the case of binary concrete mixtures, expansion is enhanced (+15.8%) by NaOH addition when 10%GG is used; it has no impact on the expansion when 20%GG (-3.3%) is used and it reduces the expansion when 30%GG is used (-21.6%). The latter suggest a synergetic effect between GG and NaOH addition that is beneficial in reducing the expansion. This effect is also noticeable in ternary mixtures since the average reduction in the expansion values of the test prisms due to NaOH addition is 0.026% for specimens incorporating FA/BFS and 20%GG, while it is 0.015% for the mixtures with the same amount of FA/BFS but with only 10%GG. Similarly, for specimens incorporating SF/MK and 30%GG, the average reduction in concrete prism expansion is 0.017% and for the same mixture with only 10%GG, the average concrete prism expansion enhancement due to NaOH addition is 0.011%.

The average concrete prism expansion reductions associated to NaOH addition in the case of ternary mixtures incorporating BFS, FA, SF and MK are respectively 0.015, 0.024, 0.009 and -0.003%; this suggests that the “beneficial” effect of NaOH addition in ternary mixtures incorporating GG is more pronounced when GG is mixed with FA or BFS. Actually, in several mixtures incorporating SF and MK, the NaOH addition leads to an increased expansion of the test specimens. MK-bearing mixtures are

somewhat insensitive to NaOH addition and the SCM that is most responsive to NaOH addition when coupled with GG is FA.

Table 5.1: Expansion of the concrete mixtures, with and without NaOH, as well as the outcome of CPT (i.e. Pass / Fail) based on the 0.040% expansion limit and the reliability of the outcome. The latter considers the standard deviation between the prisms of a set and its significance is expressed as the probability that the expansion is above or below 0.040% (p-value). The Δ indicates opposite outcomes between companion mixtures, with and without added alkalis (the significance of the p-value is based on Ramsey, Schafer [34]). N is the number of test prisms in a set (i.e. 2 in the case of binary mixes and 4 in the case of ternary mixes).

		C1 (0.94%)				C1 +NaOH (1.25%)			
Mixture	n	Expansion (%)	Out come	COV (%)	p-value	Expansion (%)	Out come	COV (%)	p-value
10GG	2	0.153	Fail	12	0.9935	0.132	Fail	1	0.9935
20GG	2	0.118	Fail	5	0.9772	0.122	Fail	4	0.9789
10GG-15FA	4	0.53	Fail	9	0.9903	0.091	Fail	5	0.9998
10GG-30FA	4	0.041	Pass	30	0.5420	0.036	Pass	10	0.9102
20GG-15FA	4	0.036	Pass	13	0.8798	0.068	Fail	3	0.9999
20GG-30FA	4	0.014	Pass	28	0.9994	0.044	Fail	7	0.9307
10GG-20BFS	4	0.097	Fail	3	0.9999	0.099	Fail	9	0.9992
10GG-40BFS	4	0.033	Pass	45	0.7770	0.048	Fail	22	0.8578
20GG-20BFS	4	0.066	Fail	24	0.9678	0.085	Fail	10	0.9987
20GG-40BFS	4	0.036	Pass	15	0.8563	0.061	Fail	7	0.9980
10GG	2	0.153	Fail	12	0.9935	0.132	Fail	1	0.9935
30GG	2	0.083	Fail	8	0.9510	0.106	Fail	0	0.9987
10GG-5SF	4	0.105	Fail	11	0.9989	0.103	Fail	12	0.9984
10GG-10SF	4	0.065	Fail	17	0.9850	0.049	Fail	10	0.9725
30GG-5SF	4	0.065	Fail	18	0.9840	0.085	Fail	13	0.9971
30GG-10SF	4	0.023	Pass	23	0.9937	0.065	Fail	29	0.9461
10GG-5MK	4	0.094	Fail	5	0.9999	0.100	Fail	10	0.9991
10GG-15MK	4	0.040	Fail	22	0.5200	0.018	Pass	39	0.9936
30GG-5MK	4	0.055	Fail	9	0.9928	0.061	Fail	9	0.9965
30GG-15MK	4	0.013	Pass	43	0.9980	0.012	Pass	36	0.9992

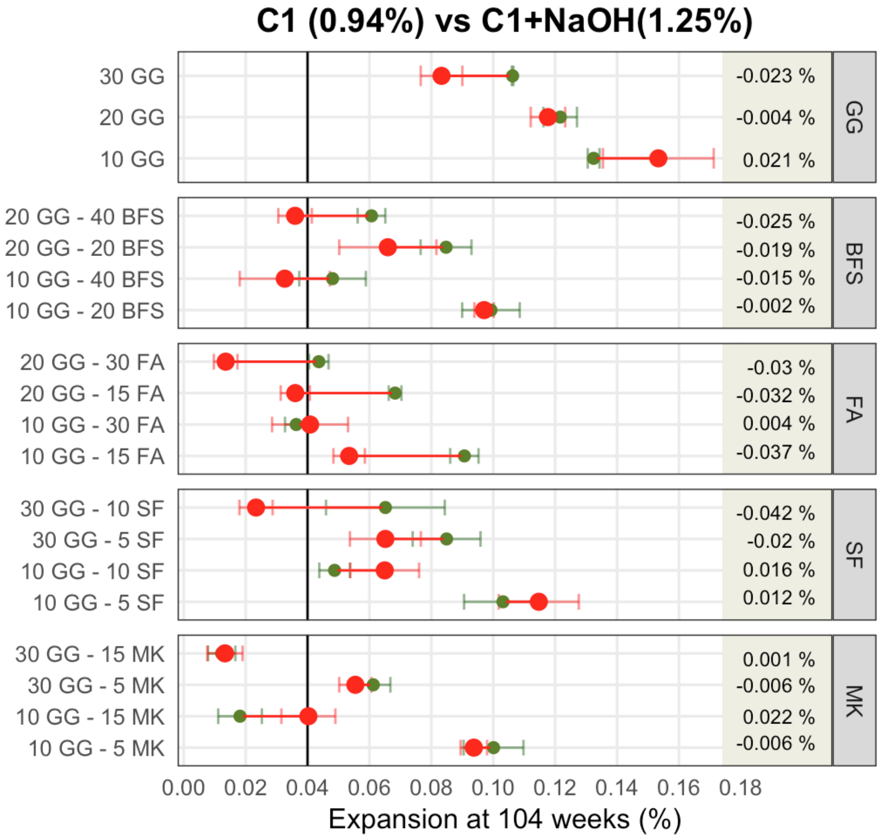

Figure 5.1: Difference in expansion at 104 weeks of the different concrete mixtures with (red) and without (green) NaOH addition.

6. CONCLUSION

In this study, the impact of the NaOH addition in concrete prism testing was assessed by comparing the average expansion of binary/ternary concrete specimens, with and without added alkalis, incorporating 10 to 30% of high-alkali ground glass (GG), a highly-reactive coarse aggregate (Spratt limestone) and various proportions of blast-furnace slag (BFS), fly ash (FA), silica fume (SF) or metakaolin (MK). The concrete prisms were manufactured from the above concrete mixtures and their length-change was monitored up to 104 weeks (stored at 38°C and R.H. > 95%). Special attention was put in reducing the deleterious impact of alkali leaching, i.e. by using larger prisms (100mm instead of 75 mm section, as normally specified in Standard Practice CSA 23.2-28A) and by avoiding the 24-hr pre-cooling period prior to measurements (i.e. prisms were measured “hot”). .

The conclusions that can be drawn from this experiment are the following:

1) For most of the tested mixture, the NaOH addition decreases the expansion compared to the same mixture without NaOH, but not enough to change the outcome of the test (i.e. Pass or Fail).
2) The “severity” of the test is reduced by the addition of NaOH for 13/19 SCM combinations and increased for 6/19. More precisely:
    - For binary mixtures incorporating 10% GG, NaOH addition enhanced the expansion while it has the opposite effect for binary mixtures incorporating 30%GG;
    - NaOH addition lead to lower expansion for all ternary mixtures incorporating 20 or 30% GG coupled with BFS, FA and SF;
    - NaOH addition lead to lower expansion for all mixtures incorporating BFS and FA, regardless of the GG content;
    - NaOH addition lead to mixed results for SF and MK bearing specimens.

3) None of the binary concrete mixtures incorporating 10 to 30%GG and the highly-reactive Spratt limestone met the 0.040% expansion limit used for concrete prism testing. The only ternary concrete mixtures incorporating 10%GG that clearly resulted in concrete prism expansion below the 0.040% level were the “unboosted” mix incorporating 15%MK and the 30%FA mix (just at the limit). In the case of ternary mixtures incorporating 30%GG, those meeting the expansion requirement incorporated 10%SF and 10%MK, without NaOH addition, and 15%MK, regardless of the NaOH addition.

NaOH addition used for concrete prism testing in the laboratory was initially meant to accelerate aggregate’s reactivity and combat the deleterious effect of alkali leaching. However, the results obtained in this study strongly suggest that it can also interact to enhance the beneficial effect of SCMs for preventing ASR expansion. Although, in most of the cases presented in this study, the expansion reduction associated to NaOH addition did not change the outcome of the test, it should be considered that NaOH addition may decrease its severity at least in the combinations evaluated through this study. This was especially the case for ternary mixtures with high content of SCM and/or high alkali content like in the case of GG.

7. FURTHER WORK

This study covered complexes mixt design with various parameter. It provided some sort of data base in which many phenomena were observed at different amplitude. For example, in some system it seemed that high quantity of alkali would overwhelm the preventives capacities of the binders while in other systems the pessimum effect could be hypothesized to relate rationally low expansion and high dosage of alkali. Further work would be required to answer specific questions on single phenomenon.

8. REFERENCE

[1] CSI (2009) Cement Industry Energy and CO2 Performance,“Getting the Numbers Right”. World Business Council for Sustainable Development

[2] IEA/WBCSD (2009) Cement Technology Roadmap 2009. In: Publication I (ed) Carbon emission reduction up to 2050

[3] (OECD) OfEC-oaD, (IEA) IEA (2007) Tracking Industrial Energy Efficiency and CO2 Emissions. International Energy Agency 34 (2):1-12

[4] (GCCA) GCCA (2017) Get Numbers Right (GNR). https://gccassociation.org/gnr/. 2020

[5] IEA I, Energy Agency) (2014) Energy Policies of IEA Countries: The United States.

[6] Scrivener K, Martirena F, Bishnoi S, Maity S (2018) Calcined clay limestone cements (LC3). Cement and Concrete Research 114:49-56. doi:10.1016/j.cemconres.2017.08.017

[7] Huang W, Kazemi-Kamyab H, Sun W, Scrivener K (2017) Effect of replacement of silica fume with calcined clay on the hydration and microstructural development of eco-UHPFRC. Materials & Design 121:36-46. doi:10.1016/j.matdes.2017.02.052

[8] Willona S (2019) 2019 Brings New Changes for Municipal Glass Recycling. https://www.waste360.com/glass/2019-brings-new-changes-municipal-glass-recycling.

[9] Idir R, Cyr M, Tagnit-Hamou A (2011) Pozzolanic properties of fine and coarse color-mixed glass cullet. Cement and Concrete Composites 33 (1):19-29

[10] Taha B, Nounu G (2008) Using lithium nitrate and pozzolanic glass powder in concrete as ASR suppressors. Cement and Concrete Composites 30 (6):497-505. doi:http://dx.doi.org/10.1016/j.cemconcomp.2007.08.010

[11] Shi C, Wu Y, Riefler C, Wang H (2005) Characteristics and pozzolanic reactivity of glass powders. Cement and Concrete Research 35 (5):987-993. doi:http://dx.doi.org/10.1016/j.cemconres.2004.05.015

[12] Shi C, Zheng K (2007) A review on the use of waste glasses in the production of cement and concrete. Resources, Conservation and Recycling 52 (2):234-247. doi:http://dx.doi.org/10.1016/j.resconrec.2007.01.013

[13] Thomas MDA, Fournier B, Folliard KJ (2013) Alkali-Aggregate Reactivity (AAR) Facts Book. U.S. Dept of Transportation edn.,

[14] Shayan A, Xu A (2006) Performance of glass powder as a pozzolanic material in concrete: A field trial on concrete slabs. Cement and Concrete Research 36 (3):457-468. doi:http://dx.doi.org/10.1016/j.cemconres.2005.12.012

[15] Zidol A (2009) Optimisation de la finesse de la poudre de verre dans les systèmes cimentaires binaires. Université de Sherbrooke,

[16] Li Z, Thomas RJ, Peethamparan S (2019) Alkali-silica reactivity of alkali-activated concrete subjected to ASTM C 1293 and 1567 alkali-silica reactivity tests. Cement and Concrete Research 123. doi:10.1016/j.cemconres.2019.105796

[17] Redden R, Neithalath N (2014) Microstructure, strength, and moisture stability of alkali activated glass powder-based binders. Cement and Concrete Composites 45:46-56. doi:http://dx.doi.org/10.1016/j.cemconcomp.2013.09.011

[18] Zhang S, Keulen A, Arbi K, Ye G (2017) Waste glass as partial mineral precursor in alkali-activated slag/fly ash system. Cement and Concrete Research 102:29-40. doi:https://doi.org/10.1016/j.cemconres.2017.08.012

[19] Maraghechi H, Maraghechi M, Rajabipour F, Pantano CG (2014) Pozzolanic reactivity of recycled glass powder at elevated temperatures: Reaction stoichiometry, reaction products and effect of alkali activation. Cement and Concrete Composites 53 (0):105-114. doi:http://dx.doi.org/10.1016/j.cemconcomp.2014.06.015

[20] Zhang L, Yue Y (2018) Influence of waste glass powder usage on the properties of alkali-activated slag mortars based on response surface methodology. Construction and Building Materials 181:527-534. doi:10.1016/j.conbuildmat.2018.06.040

[21] Shi C, Wu Y, Shaob Y, RieflerC C (2004) Alkali-Aggregate Reaction Expansion of Mortar Bars Containing Ground Glass Powder. Paper presented at the age, Pekin,

[22] Pereira-de-Oliveira LA, Castro-Gomes JP, Santos P (2012) The potential pozzolanic activity of glass and red-clay ceramic waste as cement mortars components. Construction and Building Materials 31:197-203

[23] Zheng K (2016) Pozzolanic reaction of glass powder and its role in controlling alkali–silica reaction. Cement and Concrete Composites 67:30-38. doi:http://dx.doi.org/10.1016/j.cemconcomp.2015.12.008

[24] Serpa D, Santos Silva A, de Brito J, Pontes J, Soares D (2013) ASR of mortars containing glass. Construction and Building Materials 47 (0):489-495. doi:http://dx.doi.org/10.1016/j.conbuildmat.2013.05.058

[25] Afshinnia K, Rangaraju PR (2015) Mitigating alkali-silica reaction in concrete: Effectiveness of ground glass powder from recycled glass. Transportation Research Record 2508:65-72. doi:10.3141/2508-08

[26] Chen Z, Poon CS (2017) Comparing the use of sewage sludge ash and glass powder in cement mortars. Environmental Technology 38 (11):1390-1398. doi:10.1080/09593330.2016.1230652

[27] Schwarz N, Cam H, Neithalath N (2008) Influence of a fine glass powder on the durability characteristics of concrete and its comparison to fly ash. Cement and Concrete Composites 30 (6):486-496

[28] Lam CS, Poon CS, Chan D (2007) Enhancing the performance of pre-cast concrete blocks by incorporating waste glass – ASR consideration. Cement and Concrete Composites 29 (8):616-625. doi:http://dx.doi.org/10.1016/j.cemconcomp.2007.03.008

[29] Lee G, Ling T-C, Wong Y-L, Poon C-S (2011) Effects of crushed glass cullet sizes, casting methods and pozzolanic materials on ASR of concrete blocks. Construction and Building Materials 25 (5):2611-2618. doi:http://dx.doi.org/10.1016/j.conbuildmat.2010.12.008

[30] Cota FP, Melo CCD, Panzera TH, Araújo AG, Borges PHR, Scarpa F (2015) Mechanical properties and ASR evaluation of concrete tiles with waste glass aggregate. Sustainable Cities and Society 16:49-56. doi:http://dx.doi.org/10.1016/j.scs.2015.02.005

[31] Kou SC, Poon CS (2009) Properties of self-compacting concrete prepared with recycled glass aggregate. Cement and Concrete Composites 31 (2):107-113. doi:http://dx.doi.org/10.1016/j.cemconcomp.2008.12.002

[32] Afshinnia K, Rangaraju PR (2015) Efficiency of ternary blends containing fine glass powder in mitigatingalkali–silica reaction. Construction and Building Materials 100 (15):234–245

[33] Maraghechi H, Salwocki S, Rajabipour F (2017) Utilisation of alkali activated glass powder in binary mixtures with Portland cement, slag, fly ash and hydrated lime. Materials and Structures 50 (1):16

[34] Ramsey F, Schafer D (2002) Inference using t distribution. In: Brooks/Cole CL (ed) The statistical sleuth.