

## Alkali boosting in ASR performance testing – Will extra addition of alkalis to the mix design candidate reflect expansion behaviour of cement clinker alkali variation?

Terje F. Rønning <sup>(1)</sup>, Jan Lindgård <sup>(2)</sup>, Sigrun K. Bremseth <sup>(3)</sup>

(1) Heidelberg Cement NE, Brevik, Norway, [terje.ronning@heidelbergcement.com](mailto:terje.ronning@heidelbergcement.com)

(2) SINTEF, Trondheim, Norway, [jan.lindgard@sintef.no](mailto:jan.lindgard@sintef.no)

(3) NORCEM AS, Brevik, Norway, [sigrun.bremseth@norcem.no](mailto:sigrun.bremseth@norcem.no)

### Abstract

Concrete constituents are subject to short and long-term variation in properties, during the period of a construction project, a certification period or even during day-to-day operation. Quality assessment of a construction material must take this into account. Measures applied comprise statistical assessment by auto-control and audit testing. Within a context of performance assessment however, combining several concrete constituents, the potential effect of their co-variation must be considered. This may be typically done by applying a safety margin, conservative “safe side” testing conditions etc.

One parameter that will vary is the alkali level of cement and additions. The addition of limited amount of extra alkalis to the mix design candidate has become a usual measure to compensate for such alkali variations. This is a key measure in the new RILEM AAR-10, AAR-11 and AAR-12 test methods.

Of the different cement/binder constituents, variation in the cement clinker alkali content is the property with the expected major sensitivity on the concrete pore water alkali content. In the present study, quality variations of a specific cement product were monitored over a period of almost two years to detect “extremes” for sampling. This resulted in cement samples that differed by 0.2 % in alkali content, i.e. within the typical band width of (high alkali) cement due to variations mainly in the fuel and raw meal. Other properties like fineness, chemical composition and content of gypsum were identical. Combined with a well-documented ref. alkali-reactive aggregate, the “low-natural-alkali-mix” with added alkali (amount corresponding to the gap in cement alkali content) was compared to the “high-natural-alkali-mix”. This was repeated with addition of fly ash. Concrete expansion testing was conducted at 38°C and 60°C. The test results exhibited satisfactory relation between the boosted and natural mixes. This is of great significance for the applicability and user value of performance testing.

**Keywords:** alkali boosting; alkali-silica reactions (ASR); performance testing method

## 1. INTRODUCTION

Performance testing may be performed as one of several steps in the assessment of concrete constituents or pre-qualification of a concrete mix design. The target subject may be a single construction project, product development or a framework of establishing guidelines for durable concrete when using potentially ASR susceptible aggregates.

Whether for a single construction project or for establishing general guidelines, it is essential for the value of the investigations that the test results have validity beyond the exact properties of the concrete constituents subjected to testing, taking future properties variation into account. The essential value of performance testing lies in its adequate prediction of a safe material combination, given actual/maximum alkali content. For aggregates, general validity may be endeavoured by selecting a worst case composition or grading. For cement and/or binder, the approach may be amongst other precautions to increase the alkali content by adding extra alkali to the mix subject to accelerated laboratory testing. Other alternative ways of deliberately changing alkali level during testing (changing the type or content of cement or additions) will imply other artefacts.

The reasons for the varying alkali content of cement and SCMs are several. Modern cement plants attempt to replace fuel based on coal with alternative fuels. The types, composition and ratio of such fuel may vary over time. Also coal sources and properties at a single plant may change over time, depending on market conditions. With the introduction of residual domestic waste based fuels or fuels containing liquid waste, vehicle tyres, bio-based components etc., but also due to alternative raw

materials, the burning conditions have been challenged. A cement plant may also apply different lime stone qualities at the same time. The production process is subject to advanced monitoring and control, including secondary air feed and kiln gas by-pass operation in order to maintain a stable kiln atmosphere (avoiding collapse/blocking in the pre-calciner), inducing or caused by e.g. variations in content of volatile compounds in the fuel, like sulphates and alkalis. Some of these factors also apply in SCM production. The point here is that the level of alkalis must be expected to vary over time, on shorter or longer terms.

The alkali content in performance testing context may principally be modified in various manners. Changing the alkali level “naturally” by increasing the cement (clinker) content of the mix design will have secondary effects like changing the w/b-ratio, having adverse effects on the test specimen internal humidity and, hence, the expansion potential. Extensive discussion of such and other parameters influencing laboratory testing is provided by Lindgård et al [1]. Minor adjustments of the cement content without significantly influencing consistency and compaction (air void content) or segregation may be achieved by modifying the aggregate grading curve, but the options are limited. One may also replace the cement with another product with higher alkali content (if the aggregate is the main variable of the test series), but a cement with different alkali content normally is developed for a different application (or produced at a different plant or kiln line) and implies other differences as well, like different fineness, SO<sub>3</sub> content, fresh and hardened concrete properties. These are all parameters potentially influencing chemical or physical properties, e.g. the pH level or shrinkage potential. Since the alternative ways of deliberately changing the alkali level for testing may affect the expansion level or rate, the addition of limited amounts of extra alkalis to the trial mix has become a common approach to ensure a sufficient range for potential variations of the constituents. In the present context, such extra addition of alkalis is denoted alkali boosting.

Alkali boosting may also be done in order to directly change/accelerate exposure conditions (aggregate testing) or to compensate for alkali leaching during concrete prism testing (depending on a set of parameters), but this will not be discussed within the present context.

The principal of boosting has been questioned since the addition of extra alkalis to the concrete is expected to accelerate the hydration processes, may increase the heat evolution and/or affect the pore size distribution of the concrete. The latter may influence moisture distribution and the shrinkage potential. Hence, the question becomes whether artificial addition of alkalis leads to test results differing from those where the alkali origin is the cement itself.

## 2. SCOPE

The research subject of the present study is whether and in what manner moderate alkali boosting affects the ASR expansion behaviour during concrete prism performance testing at 38 °C or 60 °C, using the RILEM AAR-10 or AAR-11 testing methods [2,3]. The objective is to validate that limited alkali boosting by adding of NaOH to the concrete is an adequate measure with respect to performance testing, i.e. that the expansion of a boosted concrete mix is similar to or higher than the expansion of the corresponding non-boosted mix with equal alkali content of “natural origin”.

## 3. TESTING PROGRAMME

### 3.1 Potential change in properties caused by alkali boosting, implications

Several effects may be expected when increasing the alkali level, although difficult to assess with respect to relevance for the expansion properties. Some of the effects may also counteract each other and include for example the following:

- Reduction of the solubility of Ca(OH)<sub>2</sub> will influence the pH level and the concentration of Ca<sup>2+</sup>
- Application of alkali acetates/formates may enhance the solubility of Ca(OH)<sub>2</sub> and, again, the pH level and the Ca<sup>2+</sup> concentration
- Change in the pH level may affect the reaction rate of pozzolanic constituents
- Change in the Ca<sup>2+</sup> concentration as well as the additional alkalis may affect the composition of the ASR-gel and its swelling properties
- Change in the pH level may affect the aggregate solubility rate

- Change in the pH level may influence the amount and type of compounds (incl. alkalis) released from the aggregates
- Addition of alkalis (e.g. by boosting with NaOH) may influence the pore size distribution, moisture distribution (if not completely saturated) and shrinkage potential

In addition to prism expansion testing, pH and moisture properties should be considered. Since the objectives include performance testing, the effects should be investigated with at least one type of SCM.

## 3.2 Materials

### 3.2.1 Cement

The cement quality of one specific product (single kiln production line, label and target application/segment/properties) at the Norcem cement plant Brevik was monitored for a period of almost two years during 2014-15 and the following two CEM I [EN 197-1] cement samples extracted:

- I: CEM I, alkali content 0.97 % Na<sub>2</sub>O<sub>eq.</sub> (labelled "BP4-14") (producer's batch reference)
- II: CEM I, alkali content 1.16 % Na<sub>2</sub>O<sub>eq.</sub> (labelled "BP6-15") (producer's batch reference)

They are based on the same clinker type, produced from the same raw materials sources and with close to identical chemical composition and fineness as displayed in Table 3.1. The alkali content differs with 0.2 % Na<sub>2</sub>O<sub>eq.</sub>, mainly due to differences in the fuel mix used during the cement production.

Table 3.1: Composition (weight-%) of the two CEM I cement samples (source = cement producer)

Type	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	SO <sub>3</sub>	K <sub>2</sub> O	Na <sub>2</sub> O	Na <sub>2</sub> O <sub>e</sub>	P <sub>2</sub> O <sub>5</sub>	LOI
I	20.42	4.77	4.05	62.32	2.15	2.93	0.85	0.41	0.97	0.16	1.25
II	20.41	5.14	2.98	62.34	2.13	2.94	1.03	0.48	1.16	0.19	2.71

Presenting these type of data with the displayed accuracy automatically should set off questioning the accuracy of the laboratory measurements. The actual cement plant laboratory is included in an extensive proficiency testing programme with internal and external materials standards and rating. Its standard coefficient of variation for alkali content (at this alkali level) is 0.01% (!).

### 3.2.2 Fly ash

The fly ash (Table 3.2) is a low calcium one (EN 450-1:2012). It is identical with the fly ash used in other studies reported at ICAAR 2020, e.g. referred to as the "LNEC cube study" [4] (a co-operation between the Norwegian so-called "KPN-ASR" project and WP2 in RILEM TC 258-AAA) and the "kinetics study" [5] (part of the "KPN-ASR" project).

Table 3.2: The oxide composition of the fly ash (FA) in wt.% determined by XRF (by the cement plant)

	CaO	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	SO <sub>3</sub>	K <sub>2</sub> O	Na <sub>2</sub> O	LOI
Fly ash	3.24	57.56	23.12	5.86	1.84	0.35	2.01	1.08	1.97

### 3.2.3 Aggregates

The aggregate composition is carefully selected, with three main focus points; 1) fine and coarse aggregates of known alkali level, 2) resulting expansion level in the sensitive and target range and, 3) not releasing alkalis to the concrete pore water. The sand (0/5 mm) is a Norwegian crushed, pure (i.e. non alkali-bearing) non-reactive limestone. The reactive (4/22 mm) coarse aggregate is a Canadian highly reactive "Spratt" silicified limestone. For the CEM I test series, Spratt is mixed with the 4/16 mm fraction of the Norwegian non-reactive limestone (see later).

### 3.2.4 Concrete mix design

The concrete mixtures that were carefully designed are displayed in Table 3.3, with characteristics summarized as:

- Aggregate composition (see below)

- Fine aggregate: Crushed limestone 0/5 mm (non-reactive, non-alkali-releaser)
- Coarse aggregate: Crushed spratt 4/22 mm (non alkali-releaser) and crushed limestone 4/16 (non-reactive, non-alkali-releaser)
- w/b 0.50 (deviation from the prescribed ratio 0.48 in the draft RILEM AAR-10 38°C concrete performance test [2])
- No air entrainment
- Boosting by adding NaOH chemical grade "Reag. Ph. Eur., max 0.02 % K" (NaOH is chosen since it is used in the RILEM AAR-10 [2]. An option could have been using a mix of NaOH and KOH resulting in a Na/K-ratio corresponding to that of the cement, but this is less practical for standard application.)
- Use of minor amounts of a low alkali plasticizer (i.e. preferably far less than 3 kg/m<sup>3</sup>)

Six binder compositions were prepared (Table 3.3), three with CEM I and three with CEM I added fly ash (i.e. the boosted/non-boosted comparison was done with and without SCM as suggested in Ch. 3.1). The following considerations were taken into account during the design of the six mixtures:

- The target expansion level of the three CEM I concretes (mix no. 1-3) should not be too high. The expansion should lie in a realistic range for performance testing, for example in the range 0.10-0.15 % after one year of exposure. However, with the relative high alkali level of the CEM I concretes (even after reducing the cement content from 440±10 kg/m<sup>3</sup> (RILEM AAR-10) to about 400 kg/m<sup>3</sup> – see next bullet point), it is not possible to obtain a moderate expansion if Spratt is used as the only coarse reactive aggregate. The selected option was to mix the reactive Spratt (4/22) with the non-reactive limestone (4/16) (ratio 35/65) for the three CEM I mixtures (no. 1-3). The selected "dilution-factor" for Spratt (i.e. blending ratio with limestone) is based on input from previous testing at CANMET/Canada [6].
- Furthermore, if too much alkali is used, far above the alkali threshold, the effect of boosting the alkali level will be lower compared to an alkali level in the ascending part of the "alkali vs. expansion curve". This called for limiting the cement content in the mix to about 400 kg/m<sup>3</sup>, and consequently also the water content down to about 200 l/m<sup>3</sup>. To be able to obtain a sufficient workable concrete, the limestone sand should preferably be washed because it contained much fines, thus having a high water demand. However, this is very time demanding and costly. Another solution, that was the chosen option, was to add some more superplasticizer (SP) to the mixtures. The amount of SP added varied from 1.5-1.9 kg/m<sup>3</sup> (vs. 0 in the fly ash mixtures).

Table 3.3: Nominal binder composition of the six mix designs (Note: The alkali content of the fly ash is not included in the calculated total alkali content, as its influence is constant within its sub-series. This is in accordance with the procedure in the new RILEM performance tests [2,3]).

Mix no.	Cement				Fly ash		Binder Total	NaOH	Total alkali content
	Type	% Na <sub>2</sub> O <sub>eq</sub>	kg/m <sup>3</sup>	kg/m <sup>3</sup> Na <sub>2</sub> O <sub>eq</sub>	kg/m <sup>3</sup>	% of binder	kg/m <sup>3</sup>	kg/m <sup>3</sup> Na <sub>2</sub> O <sub>eq</sub>	kg/m <sup>3</sup> Na <sub>2</sub> O <sub>eq</sub>
1	I	0.97	400	3.88	0	0	400	0	3.88
2	II	1.16	400	4.64	0	0	400	0	4.64
3	I	0.97	400	3.88	0	0	400	0.76	4.64
4	I	0.97	405	3.93	45	10	450	0	3.93
5	II	1.16	405	4.70	45	10	450	0	4.70
6	I	0.97	405	3.93	45	10	450	0.77	4.70

- The objective of including fly ash in three of the mixtures (no. 4-6) was to obtain a more realistic binder combination with respect to performance testing (i.e. not only testing a CEM I). The target expansion level of the three mixes incorporating fly ash should not be too low: Statistically, it is problematic to compare two test series with hardly any expansion at all. A relevant range of expansion could e.g. be 0.04-0.10 %. Expectedly, this expansion level could be obtained by the

use of Spratt as the coarse aggregate and a moderate content of fly ash. Thus, 10 % fly ash was added to the binder.

- For both binder systems (i.e. CEM I and CEM I plus fly ash), two control mixtures (no. 1 and 4) were included with the objective of directly exhibiting the effect of alkali boosting on ASR expansion and pore water composition. To limit the laboratory costs, neither porosity - nor moisture state measurements were performed for these two reference / control mixtures.

### 3.3 Testing methods

#### 3.3.1 ASR Performance testing / Concrete prism testing

The following two draft performance testing methods were conducted (determination of longitudinal expansion, dynamic E-modulus and weight development):

- Draft version of RILEM AAR-10 38°C concrete performance test [2] (100 x 100 x 450 mm<sup>3</sup> prisms, similar to the Norwegian CPT, measured without pre-cooling of the prisms)
- Draft version of RILEM AAR-11 60°C concrete performance test [3] (70 x 70 x 280 mm<sup>3</sup> prisms, measured without pre-cooling of the prisms)
- The only deviation of relevance from the final versions of [2] and [3] is the applied w/b of 0.50, compared to the final version ratio of 0.48.

For both testing methods, rate and extent of alkali leaching from the concrete prisms was determined in accordance with the procedure provided in appendix of [2].

#### 3.3.2 Supplementary investigations

Attempting to explore any additional effect of alkali boosting, the following supplementary measurements were performed after four weeks of exposure at 38°C or 60°C:

- Measurement of alkali content, Na and K, and pH in the concrete pore water: After mixing, the fresh concrete was sieved on an 8 mm sieve, before being put on 125 ml plastic bottles. After 28 days of exposure at 38°C and 60°C, respectively, pore water was pressed from the "mortar". The analysis of Na and K was measured by Flame atomic absorption spectroscopy (FS). The FS instrument used is a SpectrAA-400. The pH of the expressed solution was determined using a 6.0255.100 Profitrode from Metrohm. The procedures are described in [5].
- Measurement of various porosities ("PF-method", [7]), Degree of Capillary Saturation (DCS) and Relative Humidity (RH) (only performed for mixture no. 2, 3, 5 and 6):

- PF and DCS; One extra prism of each of the eight test series were cast and exposed similarly as the other expansion test specimens (see 3.3.1). After 28 days of exposure, each extra prism was consecutively removed from its container, wiped off and immediately sealed in plastic (to avoid loss of moisture), before being cooled down overnight. The following day, 2-3 parallel slices were split from each of these prisms. The procedures are described in [7, 8].

- RH; Measured on a parallel slice from the extra prism used for testing PF/DCS by crushing the slice with a hammer, collecting smaller pieces of cement paste (of size approx. 4-8 mm) and put them on a glass tube, before installing a pre-calibrated Vaisala sensor, properly seal the top of the glass tube that subsequently was placed into pre-drilled holes in an insulating board that was stored in a temperature controlled room at 20°C. The RH was measured every morning during a 5-days period. More details about the procedure can be found in [8].

- Measurement of 28-days compressive strength on 100 mm cubes (cured in water at 20°C).

## 4. TEST RESULTS AND DISCUSSION

The binder content of the mixes 1-3 differed from the binder content of the mixes 4-6, and therefore the results from each set of three mixes are considered separately.

### 4.1 Longitudinal expansion, Dynamic E-Modulus and Mass change

The expansion is displayed in Figure 4.1. Each set of three mixes contains one reference and two with higher alkali level, one of which is boosted. Mix no. 1 is the reference and should exhibit the lowest expansion level, which is confirmed. The interesting relations are between the mixes 2 and 3, which should be close. This is also the case, i.e. the boosted mixes ("NaOH") exhibit slightly higher expansion, which is on the conservative side.

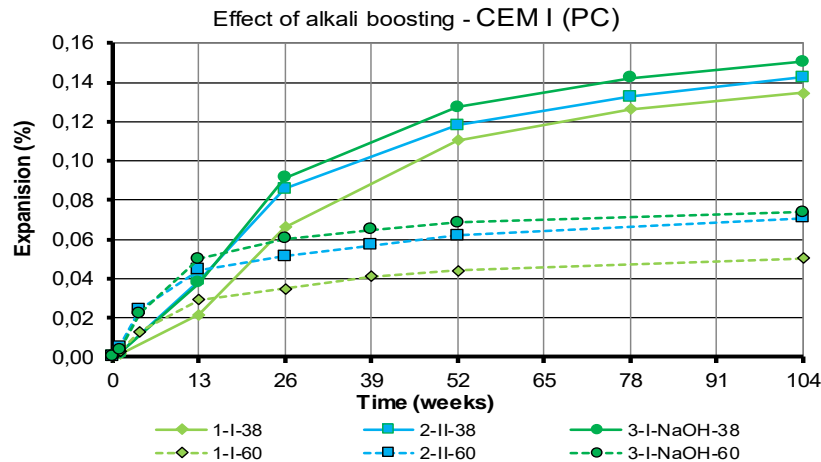


Figure 4.1: Expansion of the six CEM I (EN 197-1) / OPC test series. 38/60 denotes temperature level during exposure [°C], I/II cement sample no., NAOH = boosted, ref Ch. 3.

Figures 4.2 and 4.3 display the dynamic Young's Modulus of elasticity ( $E_{dyn}$ ) and the mass change, respectively. Both correlates well with the expansion and correspond with previous experiences [8]. The typical damage indicator is seen as a drop in  $E_{dyn}$  caused by internal cracking. Since the 60°C prisms start to expand immediately, the drop in  $E_{dyn}$  is pronounced already after four weeks. The subsequent increase of  $E_{dyn}$  with time is probably due to an "ASR-gel strengthening".

The test results from the fly ash containing mixes are displayed in Figures 4.4 – 4.6. Again, mix no. 4 form as a reference only and should exhibit the lowest expansion level within each set-of-three mixtures (i.e. 4-6), and again, this is confirmed.

The interesting relations are between the mixes 5 and 6, which should be close. Again, this is true, however, there is a very slight difference in the pattern between the 38°C and the 60°C sets of data: In the former case (38°C), the difference is still on the conservative side, since the boosted mix exhibits slightly higher expansion than the "natural" one. At 60 °C, the natural alkali mix (mix 5) expanded very slightly more than the boosted mix if indeed the difference is significant.

The general experience from performance testing at SINTEF with the Norwegian CPT (that is very similar to the draft RILEM AAR-10 CPT used in this study) is that the repeatability is very good. This is mainly due to a good quality control in SINTEF laboratory, combined with long term experience (trained technicians) in performing expansion tests. A review revealed that for test series with expansion higher than approximately 0.025 %, the coefficient of variation (c.o.v.) for the expansion was lower than 10 % for most test series, with an average in the range 6 to 8 % [9]. In a follow-up study at SINTEF [10], a corresponding good repeatability was found; the average multi-specimen c.o.v. was in the range of 6–7% for the concrete prism testing at 38°C. In the same study [10], a corresponding low c.o.v. for the RILEM AAR-4.1 60°C CPT (that is very similar to the draft RILEM AAR-11 CPT used in this study) was found; mean c.o.v. in the range 7-10 %. The additional statistical analyses (t-test, ANOVA and f-test) performed in the study [10] showed that the mean of all parallel test series cast was found to be equal to each other at all ages. Thus, even though the expansion results presented in the following figures do not differ too much between the various concrete mixtures, the general trends found are regarded to be significant.

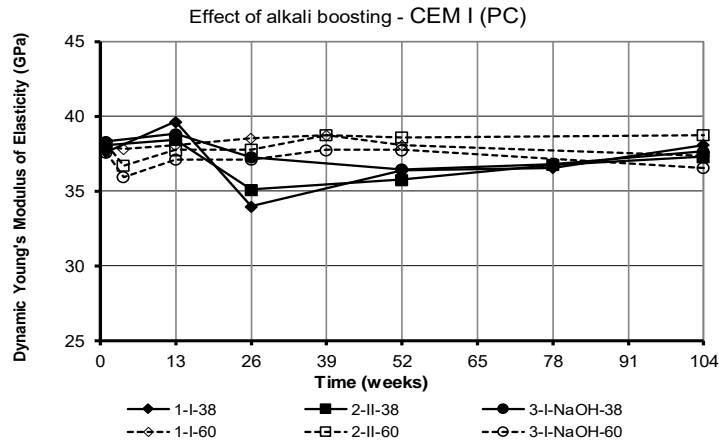


Figure 4.2: Dynamic E-Modulus of the six CEM I (EN 197-1) / OPC test series. Labelling: See Fig. 4.1.

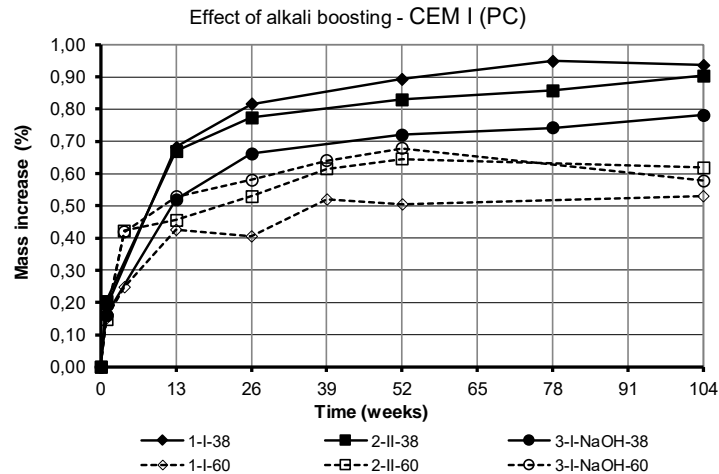


Figure 4.3: Mass increase of the six CEM I (EN 197-1) / OPC - test series. Labelling: See Fig. 4.1.

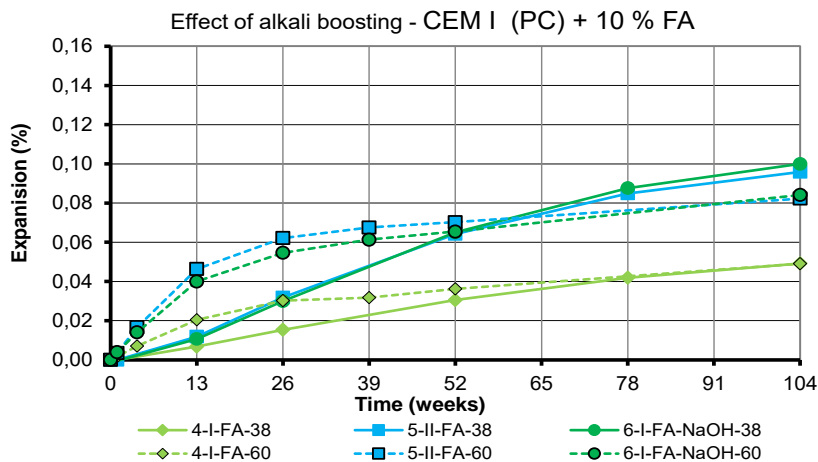


Figure 4.4: Expansion of the six CEM I (EN 197-1) plus fly ash test series. 38/60 denotes temperature level during exposure [°C], I/II cement sample no., NaOH = boosted, ref Ch. 3.

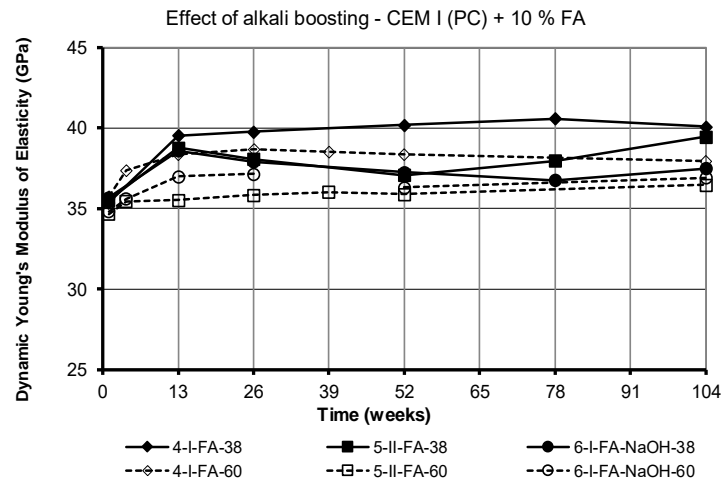


Figure 4.5: Dynamic E-Modulus of the six CEM I plus fly ash test series. Labelling: See Fig. 4.4.

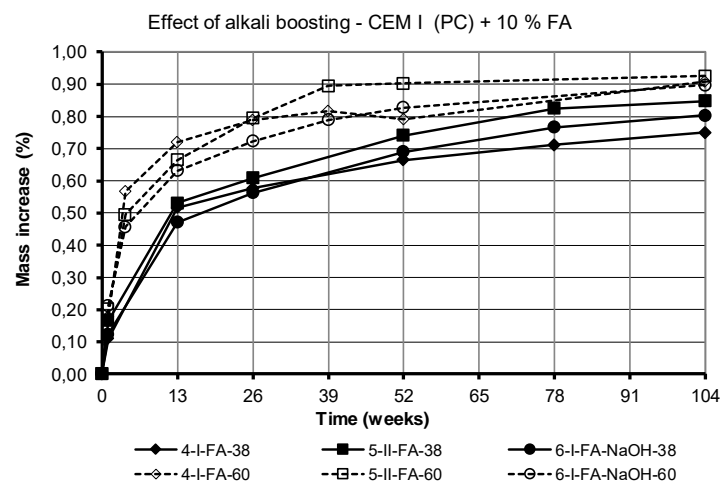


Figure 4.6: Mass increase of the six CEM I plus fly ash test series. Labelling: See Fig. 4.4.

Figures 4.5 and 4.6 display dynamic E-Modulus and mass change, respectively. As for the CEM I test series, these correspond well with the expansion curves and previous experiences [8].

Hence, the observation at this stage confirms the assumption of conservatism when boosting, with or without the addition of fly ash. The assumption is slightly better at 38 °C than at 60 °C.

## 4.2 pH level and alkali content

The alkali content of the six CEM I (EN 197-1) mixes after four weeks of exposure is displayed in Figure 4.7. Corresponding results for the six CEM I plus fly ash mixes are shown in Figure 4.9. At both temperature levels, there is as expected a clear tendency that boosting with NaOH enhances the sodium level. However, the potassium level remains constant (mix 3 and 6) and is, not surprisingly, lower than in the “natural high alkali” mixes (2&5), since both cement samples (type I and II; see Table 3.1) and the fly ash (see Table 3.2) have a potassium/sodium ratio close to 2. This pattern may be recognised without - (Figure 4.7) and with fly ash (Figure 4.9) and at both temperature levels.

Figure 4.8 and 4.10 display the corresponding pH levels after four weeks. There appear to be little effect of the boosting on the four weeks old pore water pH level: pH of the boosted “low alkali” mixes (3&6) is very similar to the pH of the non-boosted reference mixes (1&4), while pH of the “natural high alkali” mixes (2&5) are considerably higher. Isolated, this is not consistent with the alkali content measurements, indicating that some of the increased alkali content of the boosted mixes is perhaps



balanced by something else than OH<sup>-</sup>: The ionic-stoichiometric relations are notable. In all cases, boosting results in an intermediate cation level (mix3&6) if only Na and K are summarized, in between the reference “low-alkali” mixes (1&4) and the “natural high-alkali” mixes (2&5).

Considering these properties, it should be kept in mind that the fly ash is added on top of constant cement content and not on replacement basis (see Table 3.3). Figures 4.7-4.10 clearly document that the alkali content and the pH in the concrete pore water are significantly lower in the fly ash concretes (4-6) compared to the pure CEM I concretes (1-3). This indicates that some of the alkalis have been bound into the fly ash or the fly ash reaction products. The alkali content and the pH are also in general considerably lower at 60°C compared with 38°C.

More research is needed on the pore water composition and time dependency to fully explain all chemical effects of alkali boosting (changing binding equilibria). Still, the “lack” of increased pH level when boosting appears not to have adversely affected the ASR reaction potential (with that aggregate).

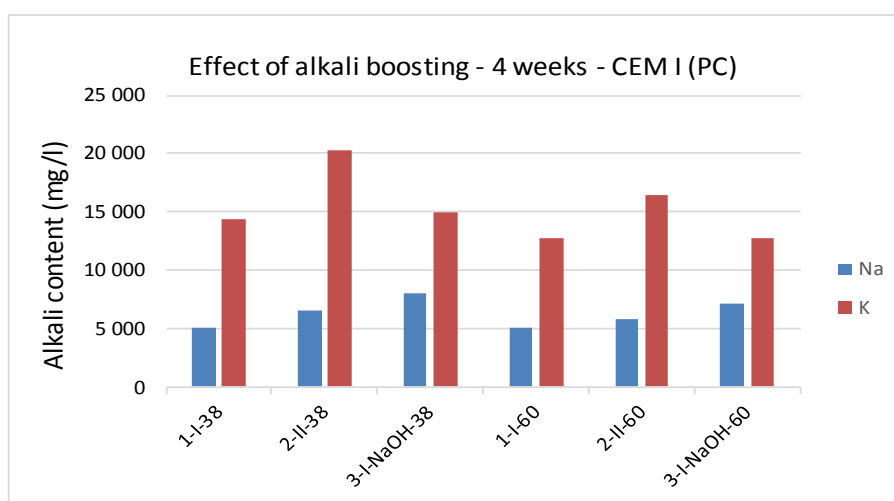


Figure 4.7: Measured alkali content of the six CEM I (EN 197-1) / OPC test series. 38/60 denotes temperature level during exposure [°C], I/II cement sample no, NaOH = boosted, ref Ch. 3.

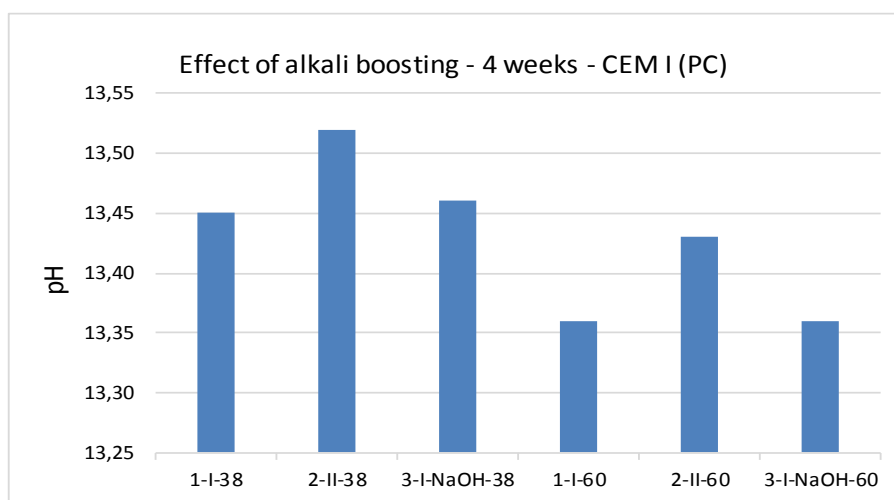


Figure 4.8: Measured pH level of the six CEM I (EN 197-1) / OPC test series. 38/60 denotes temperature level during exposure [°C], I/II cement sample no, NaOH = boosted, ref Ch. 3.

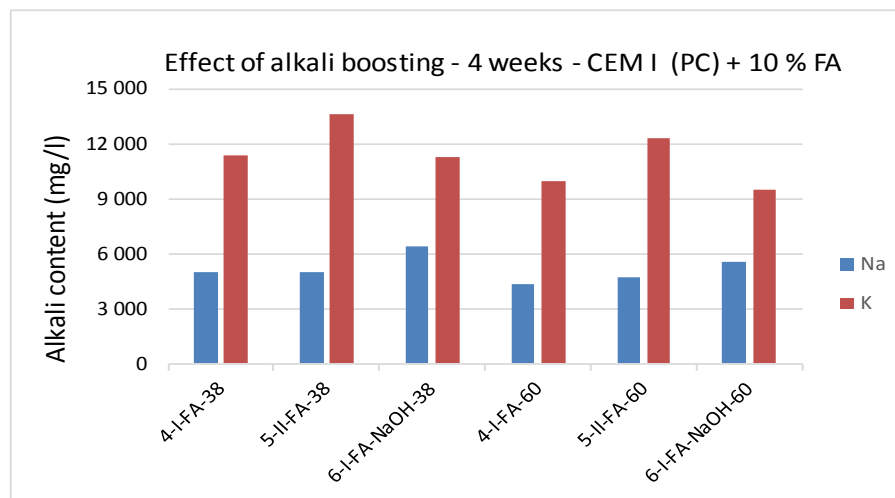


Figure 4.9: Measured alkali content of the six CEM I plus fly ash test series. 38/60 denotes temperature level during exposure [°C], I/II cement sample no, NaOH = boosted, ref Ch. 3.

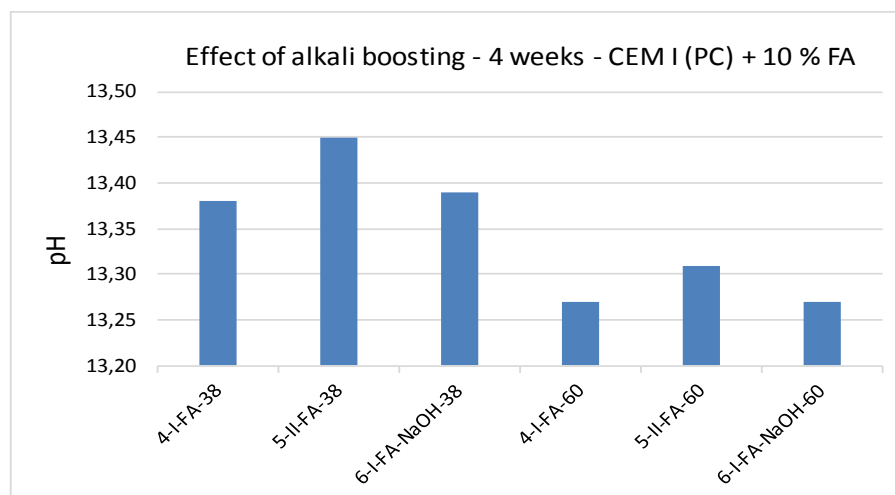


Figure 4.10: Measured pH level of the six CEM I plus fly ash test series. 38/60 denotes temperature level during exposure [°C], I/II cement sample no, NaOH = boosted, ref Ch. 3.

### 4.3 Porosity and moisture content

The suction porosity after four weeks of exposure is slightly higher for the boosted mixes compared with the “natural high alkali” mixes. This is valid both with or without fly ash and at both temperature levels, see Figure 4.11. This is a general picture and relatively pronounced. Isolated, this may imply a larger potential for attracting moisture and reducing the shrinkage potential in the beginning of the exposure period. Reduced shrinkage potential in the present context may imply less susceptibility to counteract the ASR expansion mechanisms. The slightly higher suction porosity in the boosted mixtures was also reflected in a corresponding 5-6 % lower compressive strength than for the “natural high alkali” mixes.

Another general observation is that for the same concrete mixture, the suction porosity is lower for the 60°C test series compared with the 38°C test series. This is due to a higher degree of hydration at higher exposure (curing) temperature.

A third, and more pronounced, general observation is that the suction porosity is considerably higher for the fly ash test series compared with the CEM I test series. This is not surprising. After four weeks, only a part of the fly ash has reacted. Because the water-to-binder-ratio (w/b) was kept constant for all mixtures, the fly ash mixtures will consequently behave as mixtures with apparently higher water-to-cement-ratio (w/c). This is in accordance with previous experiences, that also documented that the suction porosity of fly ash mixtures will decrease with time and end up as lower than corresponding pure CEM I mixtures [8]. The higher suction porosity for the fly ash mixtures was also reflected in a

corresponding 8-11 % lower compressive strength than measured for the pure CEM I mixtures (be aware that the 100 mm cubes used for the compressive strength testing were cured at 20°C, meaning that the fly ash in these cubes has reacted far less than in the prisms used for measuring the suction porosity).

The macro porosity (air content) was rather constant for all test series, varying from 0.9 to 1.4 %.

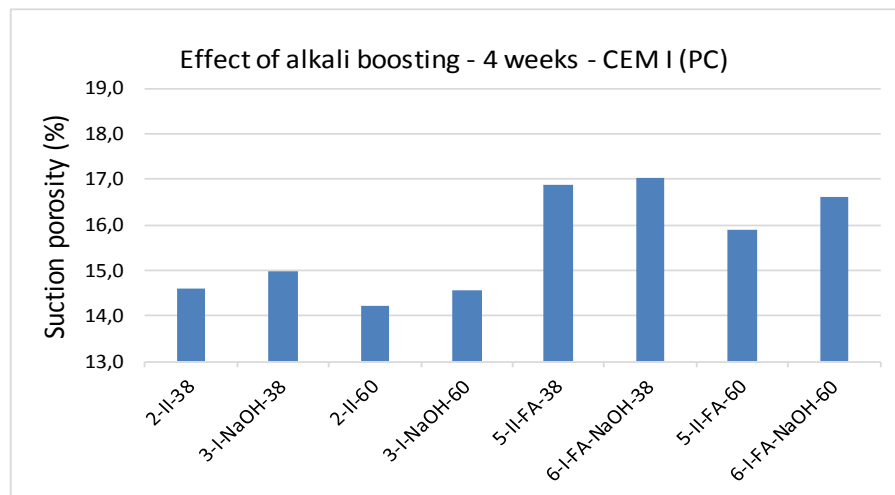


Figure 4.11: Suction porosity of all test series except the four reference ones. 38/60 denotes temperature level during exposure [°C], I/II cement sample no, NaOH = boosted, ref Ch. 3.

However, the larger potential for attracting moisture for the boosted mixtures (due to the slightly higher suction porosity) was not in general reflected in a higher water content (expressed as weight-% water of dry concrete); For the four CEM I test series (2&3), the water content after four weeks of exposure was identical (6.3-6.4 weight%). This was also the case for the two fly ash test series at 38°C (5&6) that both had water content 7.3 weight-%. But, when comparing the four fly ash test series (5&6) with the four pure CEM I test series (2&3), the general higher suction porosity for the fly ash mixtures (Figure 4.11) resulted in a general higher water content, varying from 6.5-7.3 weight-%. Moreover, the relatively low suction porosity for the test series "5-II-FA-60" also resulted in the lowest water content (6.5 weight-%) of the four fly ash test series.

The degree of capillary saturation (DCS) and relative humidity (RH) were also determined after four weeks of exposure, see Figures 4.12 and Figure 4.13. Only at 60°C and for the fly ash binder, DCS increased when boosting the concrete (mix 5 vs. mix 6). In all other cases, DCS was slightly reduced when boosting. This is in accordance with the results presented above; because boosting leads to a slightly increased suction porosity and the water content expressed as weight-% is rather constant, the result will be a slightly lower DCS.

The same picture is valid when exploring the RH values (Figure 4.13). Except for 60°C and incorporating fly ash (mix 5 vs. mix 6), boosting led to slightly lower RH. Continued, long-term hydration (during RH stabilisation) of the cement or fly ash might account for the slightly lower RH, but the pattern would expectedly look different. Boosting may cause a more open structure, facilitating moisture exchange and emphasizing the significance of reducing moisture loss.

Two general observations were made regarding the RH results; 1) RH was slightly higher for the 60°C test series compared with the 38°C test series, and 2) RH was in general lower for the fly ash test series compared with the pure CEM I test series. Both observations are in accordance with previous experiences [8].

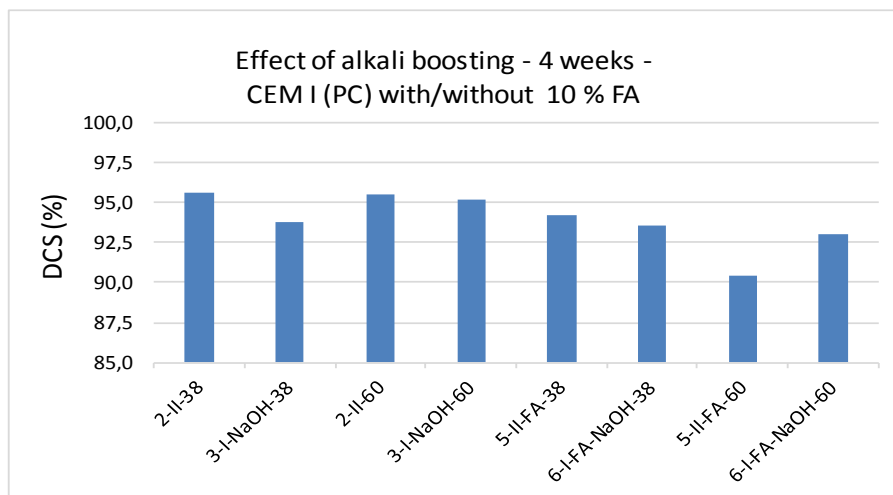


Figure 4.12: Degree of capillary saturation (DCS) of all test series except the four reference ones. 38/60 denotes temp. level during exposure [°C], I/II cement sample no, NaOH = boosted, ref Ch. 3.

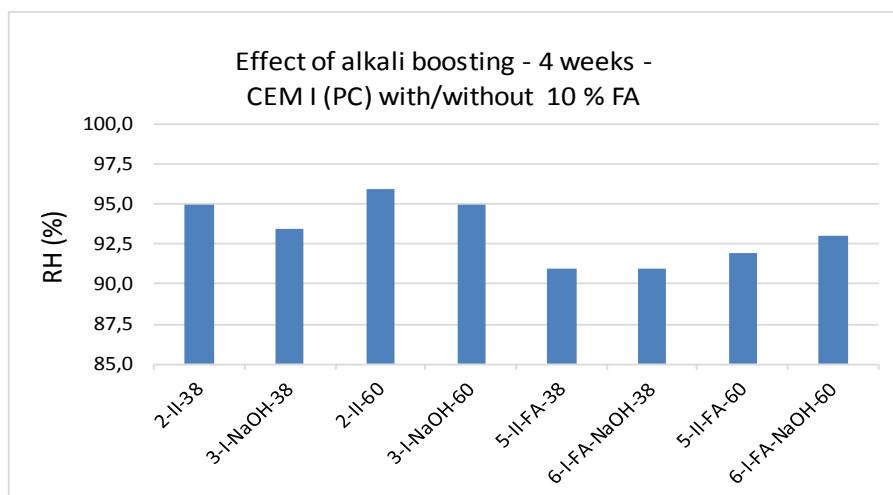


Figure 4.13: Relative humidity (RH) of all test series except the four reference ones. 38/60 denotes temperature level during exposure [°C], I/II cement sample no, NaOH = boosted, ref Ch. 3.

## 5. CONCLUSIONS

Moderate alkali boosting leads to the similar ASR expansion level as if the alkali origin is the cement clinker. This was found with and without fly ash. The degree of conservatism (“safe side”) is slightly more pronounced at 38 °C than at 60 °C.

The alkali content after four weeks of exposure is increased when boosting with NaOH, but the pH level is hardly influenced, compared to the original, non-boosted reference, indicating a higher complexity than what could be explained in the present study. Additional determination at later ages might have proved useful.

Moderate alkali boosting only marginally influences the porosity and internal moisture state. The suction porosity is marginally increased, whereas the degree of capillary saturation (DCS) and relative humidity (RH) are in general slightly reduced. However, all concretes at both exposure temperatures had high enough internal moisture state to sustain the alkali-silica reaction.

The results of the performance test are time dependent but suggest that moderate alkali boosting with NaOH is a practical and acceptable method of increasing the alkali content of the concrete, particularly at 38 °C.

## 6. REFERENCES

- [1] Lindgård J, Özge AC, Fernandes I, Rønning TF, Thomas MDA (2012) Alkali-silica reactions (ASR): Literature review on parameters influencing laboratory performance testing. *Cement and Concrete Research*, 42:223-243. <https://doi.org/10.1016/j.cemconres.2011.10.004>
- [2] RILEM Recommended Test Method: AAR-10 Determination of binder combinations for non-reactive mix design using concrete prisms – 38°C test method, Draft recommendation by RILEM TC 258-AAA, publication expected 2020
- [3] RILEM Recommended Test Method: AAR-11 Determination of binder combinations for non-reactive mix design or the resistance to alkali-silica reaction of concrete mixes using concrete prisms – 60°C test method, Draft recommendation by RILEM TC 258-AAA, publication expected 2020
- [4] Custódio I et al. (2022) Correlating field and laboratory investigations for preventing ASR in concrete – the LNEC cube study, Proceedings of the 16<sup>th</sup> ICAAR, Lisbon, Portugal
- [5] De Weerd K, Hemstad P, Justnes H, Østnor T, Rønning TF, Lindgård (2020) Fundamental study on ASR kinetics – effect of temperature on aggregate reactivity and pore water composition, Proceedings of the 16<sup>th</sup> ICAAR, Lisbon, Portugal
- [6] Personal communication with Benoit Fournier, Laval University, Canada (2018) (CANMET data on Spratt from 1993).
- [7] Sellevold EJ, Farstad T (2005) The PF-method – A Simple Way to Estimate the w/c-ratio and Air content of Hardened Concrete, Mindness Symposium, ConMat Conference, Vancouver, Canada
- [8] Lindgård J (2013) Alkali-silica reaction (ASR) – Performance testing, Doctoral theses at NTNU, 2013-269 (<https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/249422>)
- [9] Lindgård J, Pedersen B, Bremseth SK, Dahl PA and Rønning TF (2010) Experience Using the Norwegian 38°C Concrete Prism Test to Evaluate the Alkali Reactivity of Aggregates, Concrete Mixes and Binder Combinations, *Nordic Concrete Research*, publication no. 42, 2/2010, pp. 31-50.
- [10] Lindgård J, Thomas MDA, Sellevold EJ, Pedersen B, Andiç-Çakır Ö, Justnes H, Rønning TF (2013) Alkali-silica reaction (ASR) - Performance testing: Influence of specimen pre-treatment, exposure conditions and prism size on alkali leaching and prism expansion, *Cement and Concrete Research* 53 (2013) 68-90.

