ALKALI AGGREGATE REACTION IN ICELAND RESULTS FROM LABORATORY TESTING COMPARED TO FIELD EXPOSURE SITE

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Abstract

In total 10 concrete mixes with the same type of a reactive- and a non-reactive aggregate, with different types of cements and amount of silica fume, were tested both by the concrete prism tests; RILEM AAR-3 and AAR-4 and by concrete cubes exposed outdoor at an exposure site for close to 8 years. In addition a concrete mix with the well-known reactive Spratt 3 aggregate was used for comparison. The main objective of this project was to provide inputs regarding some of the uncertainties still remaining regarding Alkali Aggregate Reaction and reliable performance based testing of concrete by accelerated concrete prism tests in laboratory. The effect of different types of cement, alkali level, silica fume and reactive aggregate particle sizes were investigated. For some concrete mixes, e.g. with very high- or low alkali-level, expansion results from the concrete prism tests correspond very well with expansion results from cubes at the outdoor exposure site. However, for other concrete mixes with types of cement containing inter-milled silica fume, or boosted alkali-level, it seems that these types of mixes are showing relatively high expansion in cubes at the outdoor exposure site, while most of these mixes are showing expansion below critical limits in the concrete prism tests. Contradictory results are also observed for the effect of the reactive particle size of aggregates (sand vs. gravel), where high amounts of reactive sand appears to be the governing factor for high expansion in the concrete prism tests, whereas the opposite seems to be the case for cubes at the outdoor exposure site, where the amount of reactive gravel is the governing factor.

Keywords: Alkali Aggregate Reaction, Concrete Prism Testing, RILEM Test Methods, Field Exposure Site

1 INTRODUCTION

Uncertainties in mix design and production of non-alkali reactive concrete are still of great concern in most parts of the world. A large number of vital concrete structures suffer from the effects of deleterious Alkali Aggregate Reaction (AAR). The problem is both associated with the mix design of new concrete, and as a durability problem in existing structures. In the laboratory, it is possible to determine the potential reactivity of aggregates, either by petrographical examination, or by testing aggregates in accelerated conditions using mortar- or concrete prism methods. The reaction might be accelerated by elevated temperature (38°C, 60°C or 80°C), by enhanced alkali content in the solution surrounding mortar prisms, or by boosted alkali content in concrete prisms.

To be able to utilize potentially alkali-silica reactive aggregates for production of durable concretes, there is a need for reliable performance tests to evaluate the alkali reactivity of concrete mixes and/or binders resistant to AAR. Several such performance tests have been used worldwide for the last 15-20 years. In principle two groups of accelerated laboratory performance test methods exist, one using mortar bars and the other using concrete prisms. Thomas et al. (2006) [1] provided a critical evaluation of different test methods. The authors conclude that none of the currently available or commonly used test methods meet all the criteria for an ideal performance test. However, research is processing towards improving current test methods and developing alternative tests, for instance within the recent established RILEM Technical Committee "TC 258-AAA", which is scheduled to work on a performance testing concept until 2019. In order to verify the reliability of results from accelerated performance tests in the laboratory, there is a need to compare the expansion test results to expansion results of concrete specimens (cubes) of the same concrete composition, exposed outdoor at exposure sites.

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1.1 Previous research in Iceland

Research regarding AAR in Iceland started in the nineteen seventies and eighties. The results and regulations gained by the research decreased the possibility of deleterious AAR in Icelandic concrete structures. This included the inter-milling of 7.5% silica fume in the cement, and washing of sea-dredged aggregates. However, the situation today is still challenging, as the production of the domestic types of cements with silica fume has been terminated, and there are new types of imported cements on the market. Icelandic research and regulations have previously depended to a great extent on ASTM C227 [2], mortar bar expansion test, which gives results after one year. This method has been criticised internationally and has been abandoned in most countries. In order to maintain the safety against deleterious AAR in new Icelandic concrete structures, it was considered necessary to carry on with research in Iceland, and assess the suitability of new test methods developed internationally for Icelandic aggregates. As a consequence, and in cooperation with RILEM, the laboratory of the consultant company; Mannvit, in 2004 initiated an Icelandic research project where four different test methods for AAR were examined (Wigum et al., 2007 [3] and Einarsdóttir, & Wigum, 2008 [4]). As part of this project, two BSc. projects were also accomplished, Ásgeirsdóttir (2004) [5] and Sveinbjörnsdóttir (2005) [6]. The methods examined were; the accelerated mortar bar method (RILEM AAR-2) [7], mortar bar method (ASTM C227) [2], concrete prism method (RILEM AAR-3) [8] and accelerated concrete prism method (RILEM AAR-4) [9]. The results of these studies showed that the accelerated mortar bar test, RILEM AAR–2, exhibited significantly higher expansion than the other test methods examined. It was proposed that results from RILEM AAR-2, for Icelandic aggregates, should only be used for assessing the reactivity of the aggregates, and not as an assessment of the effects of the additives and types of cement, i.e. not to be used as a performance test. The two new concrete prism tests from RILEM (AAR-3 and AAR-4) appeared to reflect well the effects of various types of aggregates, cements and pozzolanic additives. The mortar bar test ASTM C227 also seemed to reflect well the effect of pozzolanas. However, it appeared to exhibit less expansion for mixes with cements with low alkali content compared to the concrete prism tests. This is assumed to be due to the effect of leaching of alkalis, which will be higher in the long and thin mortar bars. Justifications were made of the need of a subsequent project with the aim of further assessment of concrete prism tests along with field examination of Icelandic concrete structures.

The research on AAR at Mannvit since 2007, for some selected concrete mixes, is presented in this paper, and includes testing by the RILEM AAR-3 (wrapped version) and AAR-4 methods, compared with the same concrete mixes cast in concrete cubes (30x30x30 cm) stored at an outdoor exposure site, established in Reykjavik, Iceland in 2007.

The current Building Regulations have been in force in Iceland since 2012, and they include the RILEM AAR-2 method for assessing aggregate reactivity, and using RILEM AAR-3 (unwrapped prism version) for assessing aggregate/binder combinations. The regulations still also include the method ASTM C 227 as an alternative method.

1.2 Objectives of the project

The main objective of this project was to provide answers of some of the uncertainties still remaining in order to enable fast and reliable performance based testing of concrete in order to avoid deleterious AAR. More precisely the aim was to evaluate how various reactive aggregates sizes and cement types, along with silica fume, may influence important AAR related parameters. This was done by comparing results from accelerated concrete prisms testing in laboratory to results from concrete cubes stored at an outdoor exposure site. Some theoretically assessment of these parameters has been considered earlier, e.g. Wigum et al. (2006) [10], along with previous presentation and discussion of the results from the concrete prism tests (Wigum, 2012) [11].

2 MATERIALS AND METHODS

2.1 Materials; Same reactive aggregate with variable alkali-level and silica fume in the cements

In order to investigate the effects of different types of Icelandic and Danish cements, and the effect of silica fume, a total of 10 concrete mixes were cast and investigated in this study. The same reactive aggregate was used in all mixes, which was a highly reactive Icelandic aggregate, labelled; "H" (H-coarse & h-fine). The H aggregate was also mixed with various proportions of a Norwegian non-reactive aggregate labelled; "N" (N-coarse & n-fine). The aggregate H is from the east coast of Iceland, and exhibits very high expansion in the AAR-2 method, showing result of expansion of 0.71 % after 14 days of exposure and reaches 1.17 % after 28 days. For comparison a concrete mix with the Canadian Spratt 3 aggregate (both coarse and fine) was tested with a high alkali Norwegian ordinary Portland cement.

The test methods; RILEM AAR-3 (wrapped) and AAR-4 (unwrapped), were applied. An overview of the 10+1 different mixes is presented in Table 1. The cements used were:

- HP; Icelandic high alkali cement (1.5% Na_2O_{eq}) with no silica fume.
- Aa; Danish low alkali cement (0.55% Na_2O_{eq}) with no silica fume.
- VP; Icelandic high alkali cement (1.5% Na_2O_{eq}) with 6% silica fume and 3% grounded rhyolite pozzolanas.
- KS; Icelandic high alkali cement (1.5% Na_2O_{eq}) with 4% silica fume and 4% lime filler.

Alkali boosting

In this study, only one mix (H3), containing the low alkali Danish cement was boosted with alkalis.

Amount of reactive fine- or coarse aggregates

The issue of varying amount of reactive fine or coarse amount of reactive aggregate in concrete mixes was investigated in this study. This was carrying out by mixing proportion of the amount of reactive aggregates in the coarse (H> 8mm) or fine (h< 8mm) aggregate size fractions, combined with the non-reactive Norwegian coarse (N) and fine (n) aggregate as following:

- H1 (100% H + 100% h)
- H7 (0% H + 50% h)
- H8 (0% H + 75% h)
- H10 (0% H + 100% h)
- H9 (100% H + 0% h)

2.2 Methods for assessment and analysis

Concrete prism tests

The two different concrete prism tests used in this study is further described by Wigum (2012) [11]. The two methods applied were:

- RILEM AAR-3 Concrete prism method (storage at 38°C for 56 weeks) – wrapped concrete prisms.
- RILEM AAR-4 Accelerated concrete prism method (storage at 60°C for 20 weeks) – unwrapped concrete prisms.

Outdoor exposure site

In 2007 Mannvit established an outdoor exposure site at the roof of the laboratory building in central Reykjavik. For all the 10+1 concrete mixes tested by the concrete prism tests, concrete cubes (30 x 30 x 30 cm) were cast in end of 2007 – beginning of 2008 and placed outdoor. The concrete mixes used for concrete cubes for outdoor exposure, was exactly the same, without adding any entrained air for the exposure cubes. The outdoor results are from a period of close to 8 years. Continuing testing since 2007, both research and commercial testing, have developed the site today to contain a total of 40 concrete cubes with different concrete mixes, with both international and Icelandic aggregates and binders used. However, results from these additional cubes are not included in this study.

Measuring studs were glued into drilled holes on 3 sides of the cubes, enabling monitoring of expansion over time. Standard procedures for measurement were developed during the PARTNER project (Lindgård et al. (2010) [12]. All cubes were stored in the same direction in relation to the compass rose. The edge of the cubes limiting both adjacent side faces prepared for measuring dimension changes are oriented to the west, see figure 1.

The measurements between the studs on the concrete cube are taken diagonally on top of the cubes and horizontally and vertically on two sides. Each set of these three measurements are in themselves an average of two measurements. Looking at the results for all the 40 cubes in the exposure site, most having been measured over ten times each already, there is no apparent trend in whether diagonal, vertical or horizontal results show the maximum or minimum expansion. Consequently it was chosen to use the average of the three as a representative expansion for each cube in this study.

3 RESULTS & DISCUSSION

3.1 Concrete prism tests

As presented by Wigum (2012) [11], a reasonable good correlation was shown between the results of expansion by the AAR-3 method after 56 weeks compared to the results of expansion by the AAR-4 method after 20 weeks. It was however observed a general trend of relatively higher expansion by the AAR-4 method compare to the AAR-3 method. A possible explanation for the lower expansion in the AAR-3 method could be the use of cotton wrapping of the prisms. It has been proved that cotton wrapping increase the level of alkali leaching from the concrete prism, reducing the total expansion. Hence, the cotton wrapping have now been removed from the new AAR-3 test procedure. Two outliers, H5 and H3 exhibited relative high expansion in the AAR-4 method compare to low expansion (below 0.05%) in the AAR-3 method. The reason for this is not known. Expansion results from concrete prism tests, both AAR-3 and AAR-4, can be seen in table 2, along with average exposure from the outdoor exposure site in figure 2 and figure 3. A reference mix containing Spratt 3 aggregate with Norwegian high alkali cement is included.

3.2 Comparison of results from concrete prism tests and outdoor exposure site

Effect of types of cement – alkali level and silica fume

Good correlations, i.e. similar expansion values, are observed for expansion results from concrete prism tests (AAR-3 and AAR-4) and expansion of cubes at the outdoor exposure site after almost 8 years, for concrete mix H2, with low alkali cement (2.4 kg Na_2O_{eq} kg/m^3), which exhibits almost no expansion, and for concrete mix H1, with high alkali cement (6.6 kg Na_2O_{eq} kg/m^3), which exhibits a very high expansion. Also concrete mix with Spratt 3 aggregate and high alkali cement show similar expansion values measured both in the concrete prism tests and the outdoor exposure site. Based upon these very few concrete mixes it seems that the accelerated testing period in the laboratory (56 weeks for AAR-3 and 20 weeks for AAR-4), correspond well with the 8 years of outdoor exposure in the Icelandic climate. However, this is not at all the case for all concrete mixes, and this study includes too few different concrete mixes to draw an overall conclusion. Continued study is needed to try to answer what expansion measured at the outdoor exposure site is the critical limit value to classify the concrete mixes as deleterious reactive or not. It is also important to bring into consideration that when cracks are starting to open at the cubes outdoor, water will ingress into these cracks enabling further expansion when the water is freezing.

Three of the concrete cubes (H4, H5 & H6) contained concrete mixes with types of cement containing inter-milled silica fume. All of the three mixes contained the same aggregate, H, and same alkali-level (6.6 kg $NaOH_{eq}$ kg/m^3). The concrete cubes H4 and H6 contained the cement type VP, containing 6% silica fume + 3% inter-milled rhyolite. The only difference between H4 and H6 was the initial curing and humidity regime, which are not considered further in this study. The concrete cube H5 contained the cement type KS, with 4% silica fume. Expansion results from the AAR-3 method show that all the three concrete mixes with silica fume show expansion below the critical expansion limit after 56 weeks, while expansion results from the AAR-4 method show that H4 and H6 were below the critical limit after 20 weeks. The concrete cube H5 showed however relatively high expansion in the AAR-4 method. Results from the outdoor exposure site showed that all three concrete cubes were showing expansion results over 0.10%, i.e. relatively high expansion. The use of inter-milled silica fume has previously been used in Iceland to mitigate deleterious AAR. The Icelandic cements with inter-milled silica are not anymore on the marked, however, silica fume is added to imported high alkali cements. The results from the outdoor exposure site, with a very highly reactive aggregate, indicate that 4% or 6% silica fume is not sufficient to hinder deleterious expansion in the longterm. The Icelandic building industry needs to take this into consideration.

Alkali boosting

The cube H3 contained the same concrete mix as the cube H2, with low alkali cement (2.4 kg Na_2O_{eq} kg/m^3), except that cube H3 is boosted with alkali to reach; 4.0 kg Na_2O_{eq} kg/m^3. The boosting of alkali in the concrete prism tests is often common practice, in order to compensate for the alkali leached out of the concrete prisms during the testing period. The effect of enhance alkali-level in cube H3 is not observed in the expansion results from the AAR-3 method. It is however a question if the effect of alkali boosting would have been observed in the AAR-3 method if the testing period had been extended to two year, which is common procedure in many countries when using this method as a performance test. The effect of boosting is however observed both in the results from the AAR-4 method and the outdoor exposure site which showed significant higher expansion for H3 compare to H2. It is however interesting to observe that both in the AAR-4 method and in the cube at the outdoor exposure site, the expansion is postponed, i.e. a certain incubation time is needed before the boosted concrete mix is starting to expand.

Amount of reactive fines- and coarse aggregates

Results from both of the concrete prism tests (AAR-3 and AAR-4), in the laboratory, exhibited very clear that the concrete mix, H10, with 100% reactive fine aggregate and 0% reactive coarse aggregates obtained the highest expansion. Consequently it was concluded by Wigum (2012) [11] that the reactive fine contributed most to the overall expansion, at least for this kind of reactive aggregate. The high expansion by H10 was in the laboratory followed by H8 with 75% reactive fine and 0% reactive coarse, and H7 with 50% reactive fine and 0% reactive coarse. The concrete mix, H9, with 0% reactive fine and 100% reactive coarse showed a relatively low expansion. However, contradictory results are observed when examining the expansion results from the outdoor exposure site, where it is clear that the amount of reactive coarse aggregate governing the expansion. The expansion of H9 exhibits higher expansion than both H10 and H8, where H7 does not show any expansion at all. The reason why H7 does not expand at all at the outdoor exposure site is unknown. The cube H1 is showing the highest expansion both in the laboratory and in the outdoor exposure site. International studies have also shown a discrepancy regarding the effect on the AAR expansion of the grain size of reactive aggregate particles. It is for instance documented in Norway (Lindgård & Wigum, 2003) [13] that coarse aggregates (>8mm) are twice more expansive than fine aggregates (<8mm), and this is accounted for in the Norwegian regulations. This is important to examine further, to see if this effect is global, or if it varies for different types of reactive aggregates, different types of binders etc.

Total expansion at outdoor exposure site vs. starting point of the expansion

As evident in figure 4, shrinkage is measured in most of the concrete cubes at the outdoor exposure site, in the period of 10 – 30 months of exposure. After that period some of the cubes start immediate expansion, e.g. cubes H1, H9 and Spratt 3.

The cube H2 (low alkali cement) and H3 (low alkali cement + boosted alkali) exhibit the same non-expansive trend until almost 70 months. After that the cube H2 continues without any expansion, however, cube H3 suddenly starts to expand after that period. Also others cubes appear to need incubation time of 60 – 80 months before the expansion start, e.g. cubes H8, H5, H6 & H4.

4 CONCLUSIONS

Based upon examination of expansion results of a rather limited number (10+1) of concrete mixes, both measured in laboratory by the concrete prism tests; AAR-3 and AAR-4, along with measurements of concrete cubes exposed on an outdoor exposure site for almost 8 years, this study shows the following conclusions:

- The concrete prism methods in laboratory mirror well the high expansion results, after about 7 years of exposure, measured at the outdoor exposure site for concrete cube made with highly reactive aggregate and high alkali cement (H1), and almost non expansion for concrete cube made with highly reactive aggregate and low alkali cement (H2).
- Inter-milled amount of 4% & 6% silica fume appears to hinder the expansion of concrete prism in the AAR-3 method and 6% appear sufficient to hinder expansion in the AAR-4 method. However, concrete cubes with cement containing both 4% and 6% are showing expansion more than 0.10% after almost 8 years at the outdoor exposure site.
- The effect of boosting of alkalis is not observed in the expansion results from the AAR-3 test, where results from the concrete mix with boosted alkali is showing almost non-expansion as the parallel un-boosted mix. However, both the results from the AAR-4 method and expansion results from the outdoor exposure site showing significant higher expansion for the boosted mix. However, results from both the AAR-4 method and the outdoor exposure site show relatively long incubation time before the boosted concrete cube started to expand.
- Contradictory results are observed for the effect of the reactive particle size of aggregates, where expansion results from concrete prism methods evidently show that concrete mixes with 100% reactive fines and 0% reactive coarse exhibit the highest expansion. The opposite is observed for concrete cubes at the outdoor exposure site

It is the ambition that considerations and limited conclusions in this study will bring input to the ongoing work of developing adequate performance test procedures for the future.

ACKNOWLEDGEMENT

This study has been sponsored by internal contribution by the laboratory of Mannvit, along with funding by the "Ludvig Storr Foundation" at the University of Iceland. These contributions are highly appreciated and made this study possible.

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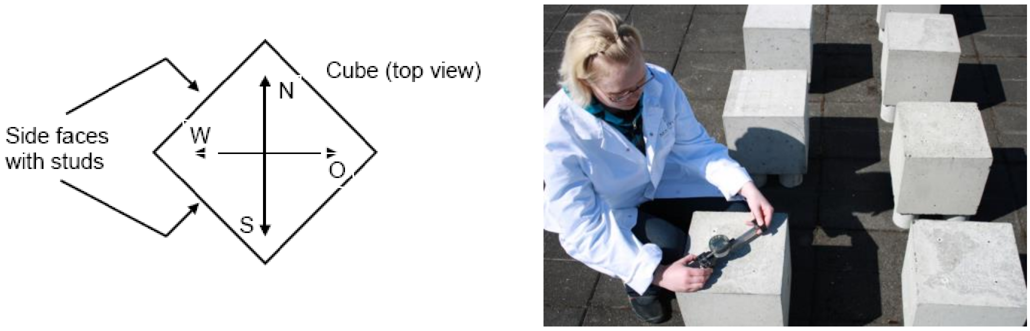

FIGURE 1: Orientation of cubes (left), and measurement of cubes (right).

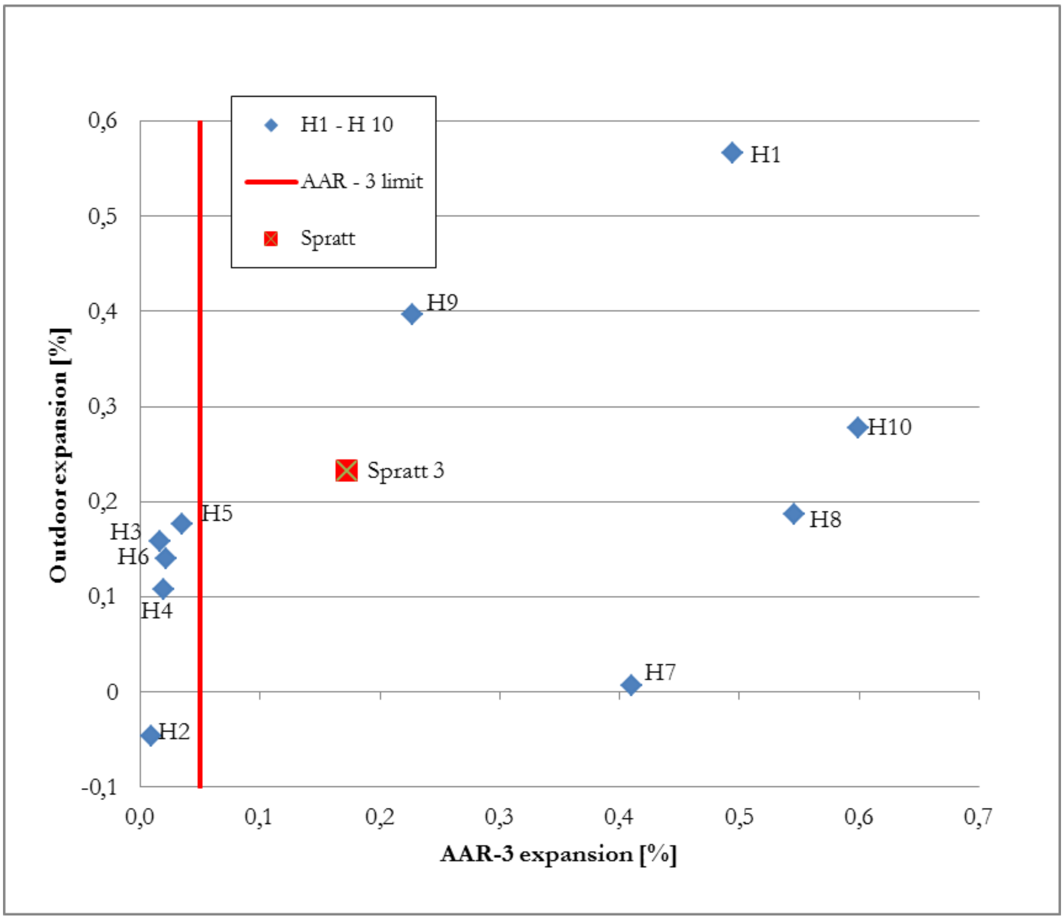

FIGURE 2: Results of expansion from the AAR-3 method compare to results of expansion from cubes at outdoor exposure site after close to 8 years of outdoor exposure.

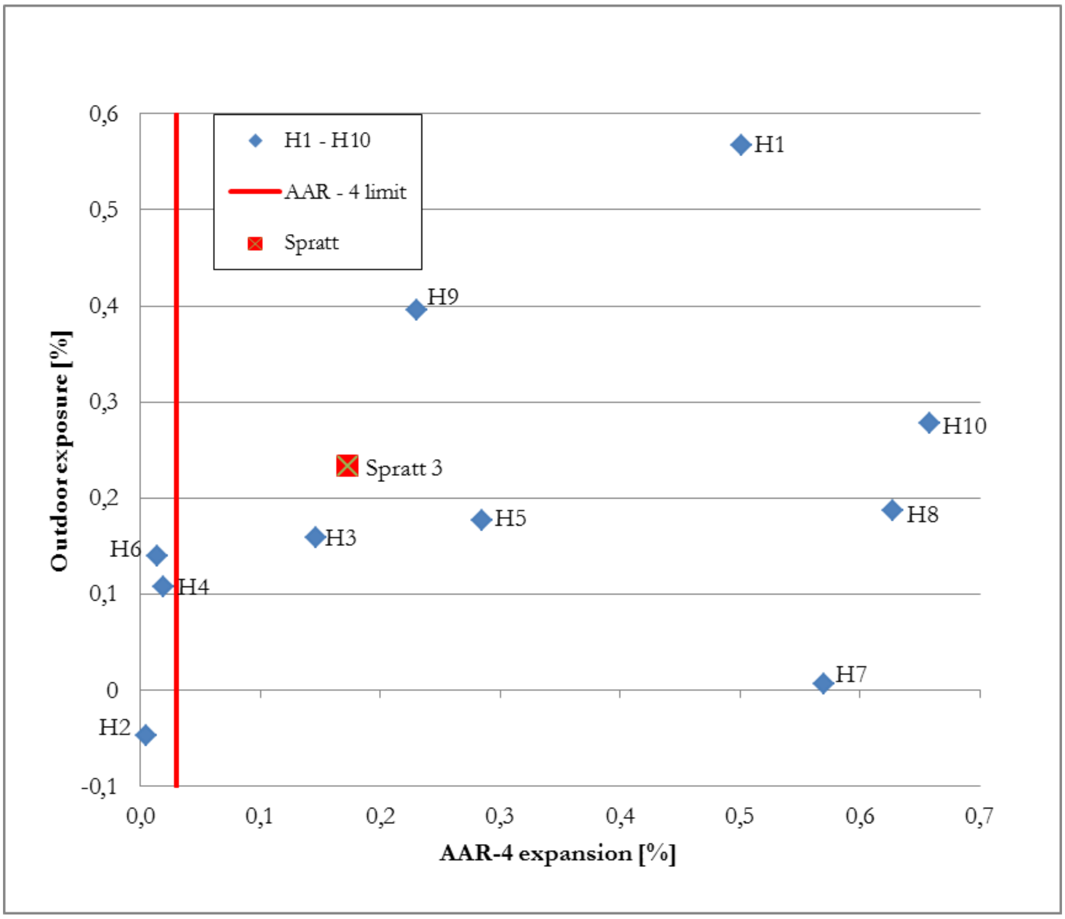

FIGURE 3. Results of expansion from the AAR-4 method compare to results of expansion from cubes at outdoor exposure site after close to 8 years of outdoor exposure.

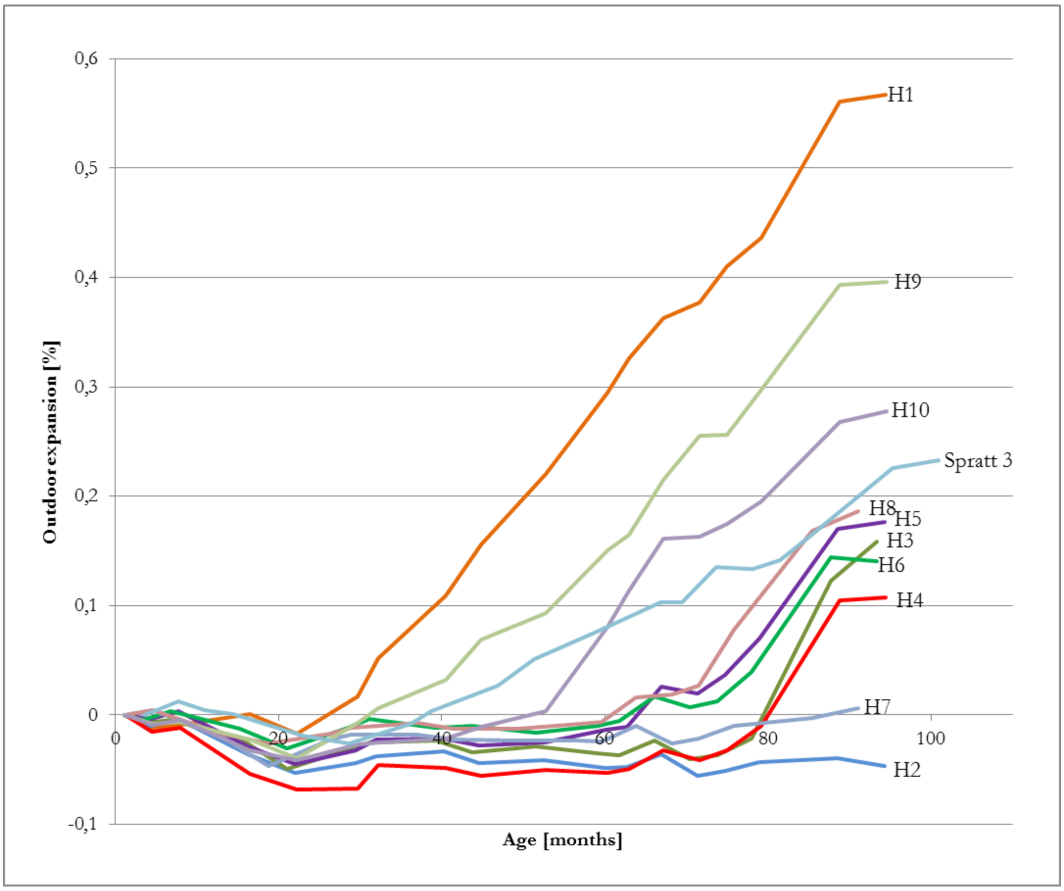

FIGURE 4. Development of the expansion of 10+1 concrete cubes at the outdoor exposure site in central Reykjavik, Iceland.

TABLE 1: Overview of sample tested.

Samples	Alkali content (Na_2O Eq%)	Alkali content (Na_2O Eq kg/m^3)	Silica-fume (%)	Comments
H1: H+h+HP	1.50%	6.6	0	Reference test - **High alkali content**
H2: H+h+Aa	0.55%	2.4	0	**Low alkali content**
H3: H+h+Aa+Alkali	0.90%	4.0	0	**Medium alkali content**
H4: H+h+VP	1.50%	6.6	6	**High alkali content** with **6% silica fume** + **3% Rhyolit**
H5: H+h+KS	1.50%	6.6	4	**High alkali content** with 4**% silica fume**
H6: H+h+VP	1.50%	6.6	6	Changed **curing** & **humidity** regime
H7: N+h50/n50+HP	1.50%	6.6	0	Coarse 100% NR - Fine 50%R + 50%NR
H8: N+h75/n25+HP	1.50%	6.6	0	Coarse 100% NR - Fine 75%R + 25%NR
H9: H+n+HP	1.50%	6.6	0	**Grading;** Non-reactive fines
H10: N+h+HP	1.50%	6.6	0	**Grading;** Non-reactive coarse
Spratt 3	1.20%	5.3	**0**	**Reference aggregate and high alkali cement**

TABLE 2: Overview of the results of expansion for the 10+1 concrete mixes, both by the concrete prism test (AAR-3 and AAR-4) and concrete cubes at the exposure site exposed outdoor for about 7 years.

Mix	AAR-3	AAR-4	Outdoor
	Expansion [%]		
H1	0,494	0,502	0,567
H2	0,009	0,005	-0,047
H3	0,016	0,147	0,159
H4	0,019	0,019	0,107
H5	0,035	0,285	0,176
H6	0,022	0,014	0,140
H7	0,410	0,570	0,006
H8	0,546	0,628	0,187
H9	0,227	0,231	0,396
H10	0,599	0,658	0,278
Spratt	0,173	0,344	0,233