ASSESSMENT AND DEVELOPMENT OF PERFORMANCE TESTS FOR ALKALI AGGREGATE REACTION IN ICELAND

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Børge Johannes Wigum [1, 2*]

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[1]Norwegian University of Science and Technology, Trondheim, NORWAY
[2]Mannvit, Reykjavik, ICELAND

Abstract

The main objective of this project was to provide inputs regarding some of the uncertainties still remaining regarding AAR and reliable performance based testing of concrete. The effect of different types of cements, silica fume and aggregate particle sizes were investigated in two concrete prism methods. In the RILEM AAR-3 test it is observed that low alkali cement mitigates the expansion even more than high alkali cements with silica fume. The effect of alkali boosting was only investigated in the RILEM AAR-4 test. For the type of Icelandic reactive aggregates examined it was evident that reactive fine particles contribute more to the expansion. In most cases the expansions observed in the RILEM AAR-4 test are higher than corresponding results in the RILEM AAR-3 test after the regular testing periods. Extent of alkali leaching from prisms in the RILEM AAR-4 test is less than observed in some other countries.

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Keywords: Alkali Aggregate Reactions, Laboratory Testing, RILEM Test Methods, Performance testing

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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 Reactions (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 world wide for at least 15 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 RILEM technical committee TC 219-ACS.

* Correspondence to: wigum@mannvit.is

State-of-the-art 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. However, the situation today is more complicated, as some new concrete structures in Iceland are now designed for specified working lifetime of 100 years, as opposed to 50 years working lifetime specified previously. There are also more cement types on the market. The original 7.5% addition of silica fume in Icelandic cements to mitigate AAR, has now been reduced to 4-6% depending on the type of cement. A special cement with 10% silica fume and 25% ground rhyolite is no longer available on the market. In addition, cement, aggregates and various admixtures for concrete are now being imported. 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 is thus 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 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].These methods were; 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 relatively 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. 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 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.

AAR research at Mannvit since 2007 is presented in this paper, and includes additional testing by the RILEM AAR-3 and AAR-4 methods focusing on parameters affecting the tests when used as performance tests. As it is realized the need to calibrate the test results with what happens in field, an outdoor exposure site was established at Mannvit in 2007. From all concrete mixes tested in the laboratory (23 so far), cubes (30x30x30cm) are cast and stored outdoor. Examination of a limited number of real concrete structures, by sampling of concrete cores with subsequent examination of thin-sections in petrographic microscope has also been carried out.

A draft for new Building Regulations is now being proposed in Iceland, including the RILEM AAR-2 method for assessing aggregate reactivity, and using RILEM AAR-3 (unwrapped prism version) for assessing aggregate/binder combinations. The method ASTM C 227 will be allowed for a period of time, but then possible phased out.

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 aggregates sizes and cement types may influence important AAR related parameters. Some theoretically assessment of these parameters has been considered earlier, e.g. Wigum et al. (2006) [10].

2 MATERIALS AND METHODS

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2.1 Materials and mixture proportions

Effects of various cements types and content of silica fume

In order to investigate the effects of different types of Icelandic and Danish cements, and the effect of silica fume, a variety of concrete mixes were cast. The same reactive aggregate was used in all mixes, which was a highly reactive Icelandic aggregate (H-coarse & h-fine). The H aggregate was also tested with Norwegian non reactive (N-coarse & n-fine).

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

- HP; Icelandic high alkali cement (1.6% Na_2Oeq) with no silica fume.
- Aa; Danish low alkali cement (0.55% Na_2Oeq) with no silica fume.
- VP; Icelandic high alkali cement (1.6% Na_2Oeq) with 6% silica fume and 3% grounded rhyolite pozzolanas.
- KS; Icelandic high alkali cement (1.6% Na_2Oeq) with 4% silica fume.

Critical alkali level in concrete and leaching of alkali from prisms

The critical alkali level (kg/m^3) in concrete is a key issue for the deleterious alkali expansion. Icelandic cements have very high alkali content. However, it has been mixed with various amounts of silica fume, which have been documented to mitigate deleterious AAR expansion to a certain degree. Imported Danish cements have however an intermediate to low content of alkali. In this study cements with different alkali content were applied. In order to document the critical alkali level, it is also necessary to examine the degree of leaching of alkalis from the prisms during the testing periods. Internationally it has been documented that up to 35% of the original alkali level may leach out during the testing period (Bérubé & Fournier, 2004) [11]. Alkali boosting of the original concrete mix has been used to compensate for the leaching, but whether that mirrors the true situation has been questioned. In this study, one mix (H3) was boosted, using the low alkali Danish cement.

Aggregate grain sizes and grading curves

International studies have 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) [12] that coarse aggregates (>8mm) are twice more expansive than fine aggregates (<8mm). In some countries the opposite has been found. This issue is investigated further in this study.

Pessimum behaviour of aggregates

The so-called "pessimum effect" is a phenomena where a concrete mix reaches its maximum expansion with a certain pessimum amount of reactive aggregates. Larger or less amounts of reactive aggregates will however lead to less expansion. This effect is well known and quantified for various types of aggregates internationally. Earlier results in Iceland (Helgason, 1982) [13], based on the mortar bar method, ASTM C 227, have shown that the pessimum effect may be observed for some types of Icelandic rocks. However, this is tested further in this study by testing various concrete mixes (RILEM AAR-3 and AAR-4) with various amounts of reactive aggregates.

Verification of test methods by outdoor exposure site

For each of the 10 various concrete mixes tested by the concrete prism tests, one cube with 300 mm lateral length was cast for outdoor storage at the established outdoor exposure site of Mannvit in Reykjavik, Iceland. Measuring studs were glued 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) [14]. Similar field exposure sites have been established in eight locations in Europe, in addition to several locations in North America. 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.¶

2.2 Methods for assessment and analysis

In this project, two different concrete prism tests were evaluated:

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

The details of the methods are given in the references [8,9]. In general, both the methods monitor the expansion and the weight change of concrete specimens containing the test aggregate and fixed cement content, which are stored in conditions of high humidity and elevated temperatures. For RILEM AAR-3, the storage period is 52 weeks, but for the RILEM AAR-4 method the exposure period is reduced to 20 weeks (or even 15 weeks) by use of the higher temperature of storage (60°C). RILEM has recently renamed the AAR-4 method, and named it "AAR-4.1" when applied for testing aggregates. However, in this report, the method is consequently called "AAR-4".

As presented in RILEM AAR-0 [15], the RILEM acceptance criteria for the interpretation of the results of AAR-3 and AAR-4 have not yet been finally agreed. However, on the basis of trials carried out by RILEM on aggregate combinations of known field performance from various parts of the world, it seems that results in the AAR-3 test (usually after 52 weeks) of less than 0.05% are likely to indicate non-expansive materials, whilst results exceeding 0.10% indicate expansive materials. These suggested criteria apply only to results using the preferred prism size in AAR-3. The use of larger prism sizes, which is permitted as an alternative, is thought likely to produce different values. Currently it is not possible to provide interpretative guidance for results in the intermediate range 0.05% to 0.10% and, for all practical purposes in the absence of additional local experience, aggregates yielding AAR-3 results in this range will need to be regarded as being potentially alkali-reactive. On the basis of an initial assessment of the AAR-4 trials carried out by RILEM TC 191-ARP on aggregate combinations of known field performance from various parts of the world, it seems that a maximum expansion in the RILEM AAR-4 test of 0.03% at 15 weeks indicates a non-reactive aggregate combination. It follows that, in the case of aggregate combinations producing AAR-4 results greater than 0.03% at 15 weeks, in the absence of local experience to the contrary, precautions should be taken to minimize the risk of ASR damage to any concrete in which the material is used.¶

3 RESULTS & DISCUSSION

Concrete prism test – RILEM AAR-3

The expansion results of the AAR-3 method, after 52 weeks of exposure, from all the 10 concrete mixes are presented in Figure 1. It is evident that the effect of various cements types and amount of silica fume is significant. The concrete mixes H1, H4, H5 and H6 all have the same reactive aggregate, both in the coarse and the fine part. They all have the same Icelandic cement; however the types of cements have different content of pozzolanas, i.e. silica fume and rhyolite. A high expansion is observed for H1, with the HP cement. The mixes H4 and H6 are the same mixes – with VP cement – and exhibit both a low expansion under the critical limit. The only difference between H4 and H6, is that H6 was stored one week longer prior to testing, and more water (10ml) was added to the plastic bag during the AAR-3 testing, which seems not to affect the results. The concrete mix H5 – with KS cement – also exhibit a low expansion, however higher than the H4 and H6 mixes. The concrete mixes H2 and H3 have the same aggregate combinations as H1, H4, H5 and H6, however the cement is the Danish Aa. It is evident that the Aa cement mitigates the expansion even more than the VP and KS cements. No additional expansion is observed for the concrete mix H3 with boosted alkali content.

Considering the effect of aggregate grain sizes and grading curves, it is evident that the concrete mix H10 – with 100% of the reactive aggregate "h" in the fines, and 0% reactive in the coarse ("N") – exhibits the highest expansion. It is also evident that when decreasing the amount of reactive aggregate in the fine fraction; the expansion decreases. The lowest expansion is observed for H9 with reactive coarse aggregate and no reactive aggregates in the fine fraction. More tests are required in order to know more about if this effect is only due to the aggregate grain sizes or in a combination with a pessimum behaviour of aggregates.

Accelerated concrete prism test – RILEM AAR-4

The expansion results of the AAR-4 method, after 20 weeks of exposure, from all the 10 concrete mixes are presented in Figure 2. Regarding the effect of various cements types and amount of silica fume, it is evident that for the concrete mixes H1, H4, and H6, the results are very similar to the trends observed in the AAR-3 test. However, the concrete mix H5 – with the KS cement – exhibit an expansion significantly higher than in the AAR-3 test. The concrete mix H2 exhibit a low expansion as in the AAR-3 test. However, for the concrete mix H3 – with Aa cement and boosted alkali content – the expansion is significantly higher in the AAR-4 test. It is observed that the expansion of H3 is delayed, and starts after 10 weeks. Considering the aggregate grain sizes and grading curves, the different mixes are in most cases ranked as in the AAR-3 test, i.e. indicating that the worst case is with 100% of the reactive aggregate "h" in the fines, and 0% reactive ("N") in the coarse fraction.

Comparison of expansion between RILEM AAR-3 and AAR-4

Comparison of the expansion results after 52 weeks in the AAR-3 test, and after 20 weeks in the AAR-4 test, is presented in Figure 3. It is evident that in most cases the expansion results observed in the AAR-4 test are higher than corresponding results in the AAR-3 test. According to the critical limits for the tests (provided in the PARTNER project([14], the concrete mixes H3 and H5 would have been classified as nonreactive in the AAR-3 test but reactive in the AAR-4 test. The reason for this discrepancy is not fully understood, but might be connected to a higher degree of alkali leaching in the wrapped AAR-3 test. Consequently, the effect of boosting alkalis in the H3 mix and the effect of low silica fume content in the H5 mix, require further research.

Leaching of alkalis

Results of the measured amount of leaching of alkalis in samples H1-H6 in the AAR-4 test are presented in Table 2. The percentage range of leached alkali content ($Na_2Oeq.$) is from 4.5% - 9.7%. These results are significantly lower than what have been previously reported from similar measurements, e.g. in Canada, where up to 35% leaching has been observed (Bérubé & Fournier, 2004) [11] and (Thomas et. al 2006) [1]. Unpublished results from Norway indicate leaching in the range of 12-15%. Alkali leaching may particularly be a problem during performance testing, where on of the aims is to document the concrete prism expansion using various alkali levels in concrete mixes containing alkali reactive aggregates. Hence this topic needs to be studied further.

Outdoor exposure site

The cubes from the concrete mixes in this study have now been exposed for up to approximately 40 months at the outdoor exposure site at Mannvit in Reykjavik. The results from vertical expansion are presented in Figure 4. This is not sufficiently long enough time period to make any correlation with the results from the laboratory testing. It is however evident that all cubes exhibit various degree of shrinkage during the first 20-25 months. The concrete mixes H1, H9 and H8 all started to expand after 30 months, and micro-cracks were observed in H1 and H9 after 35 months. Mannvit will continue to measure the expansions at the outdoor exposed cubes in the years to come.

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4 CONCLUSIONS

Some important results are observed in this project:

- In both concrete prism tests it is evident that both low alkali cement and cements with various amount of silica fume reduce the expansion significantly. It is evident in the AAR-3 test that the Danish AA cement mitigates the expansion even more than the Icelandic VP and KS cements.
- In the AAR-3 a slightly higher expansion was observed with a reduced level of silica fume (KS cement), however the same mix in the AAR-4 test showed a significant higher expansion. The effect of using KS cement to mitigate highly reactive Icelandic aggregates needs to be studied further.
- In the AAR-3 test no higher expansion was observed when boosting the low alkali Danish cement, however the same mix in the AAR-4 test showed a significant higher expansion starting after 10 weeks. The effect of boosting in the AAR-3 test vs. the AAR-4 test needs to be studied further.
- It is clear that the aggregate grain size for this particular type of aggregate influence the extent of expansion. Reactive fine particles contribute more to the expansion.
- The potential pessimum effect of various types of aggregate needs to be studied further.
- A fairly good correlation is observed between the results from the AAR-3 test and the AAR-4 test, except for two concrete mixes. It is however evident that in most cases the expansion results observed in the AAR-4 test were higher than corresponding results in the AAR-3 test.
- Degree of alkali leaching from prisms in the AAR-4 test is less than observed in other countries. The reason for this is not known.
- It is premature to use the results from the outdoor exposure site to make comparison between results from the laboratory vs. results from the field. Further measurements are needed.

Based upon this limited project, it is not possible to provide any overall conclusion regarding the development of performance tests in order to document non Alkali Aggregate Reactive concrete. However, the results from this project are an important input to the continuing work ongoing in RILEM towards performance based testing concepts.

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TABLE 1: Overview of concrete mixes tested.					
Concrete mixes*	Alkali content (Na_2O Eq%)	Alkali content (Na_2O Eq kg/m^3)	Silica-fume (%)	Test procedure	Comments
H1: H+h+HP	1.50%	6.6	0	Standard according to RILEM method	Reference test - **High alkali content**
H2: H+h+Aa	0.55%	2.4	0	Standard according to RILEM method	**Low alkali content**
H3: H+h+Aa+Alkali	0.90%	4.0	0	Standard according to RILEM method	**Medium alkali content**
H4: H+h+VP	1.50%	6.6	6	Standard according to RILEM method	**High alkali content** with **6% silica fume** + **3% Rhyolit**
H5: H+h+KS	1.50%	6.6	4	Standard according to RILEM method	**High alkali content** with 4**% silica fume**
H6: H+h+VP	1.50%	6.6	6	Pre-stored 1 week longer in water **(AAR-4)** Added 10ml water **(AAR-3)**	Changed **curing** & **humidity** regime (compared to H4)
H7: N+h50/n50+HP	1.50%	6.6	0	Standard according to RILEM method	Coarse; 100% Non Reactive – Fine; 50%Reactive + 50%Non Reactive
H8: N+h75/n25+HP	1.50%	6.6	0	Standard according to RILEM method	Coarse; 100% Non Reactive – Fine; 75%Reactive + 25%Non Reactive
H9: H+n+HP	1.50%	6.6	0	Standard according to RILEM method	**Grading;** Non reactive fines
H10: N+h+HP	1.50%	6.6	0	Standard according to RILEM method	**Grading;** Non reactive coarse

* ***H***= *Reactive coarse,* ***h***= *Reactive fine,* ***N***= *Non reactive coarse,* ***n***= *Non reactive fine*
HP, ***Aa***, ***VP*** *&* ***KS*** = *various cement types*

TABLE 1: Results of leaching of alkalis in the RILEM AAR-4 test.			
Concrete mixes	Original alkali-content in the concrete prisms (kg/m^3)	Leached alkali-content $Na_2Oeq.$ (kg/m^3) after 20 weeks of exposure	Leached alkali-content $Na_2Oeq.$ (%)
H1	6.6	0.41	5.8
H2	2.4	0.23	9.7
H3	4.0	0.24	6.0
H4	6.6	0.31	4.8
H5	6.6	0.30	4.9
H6	6.6	0.29	4.5

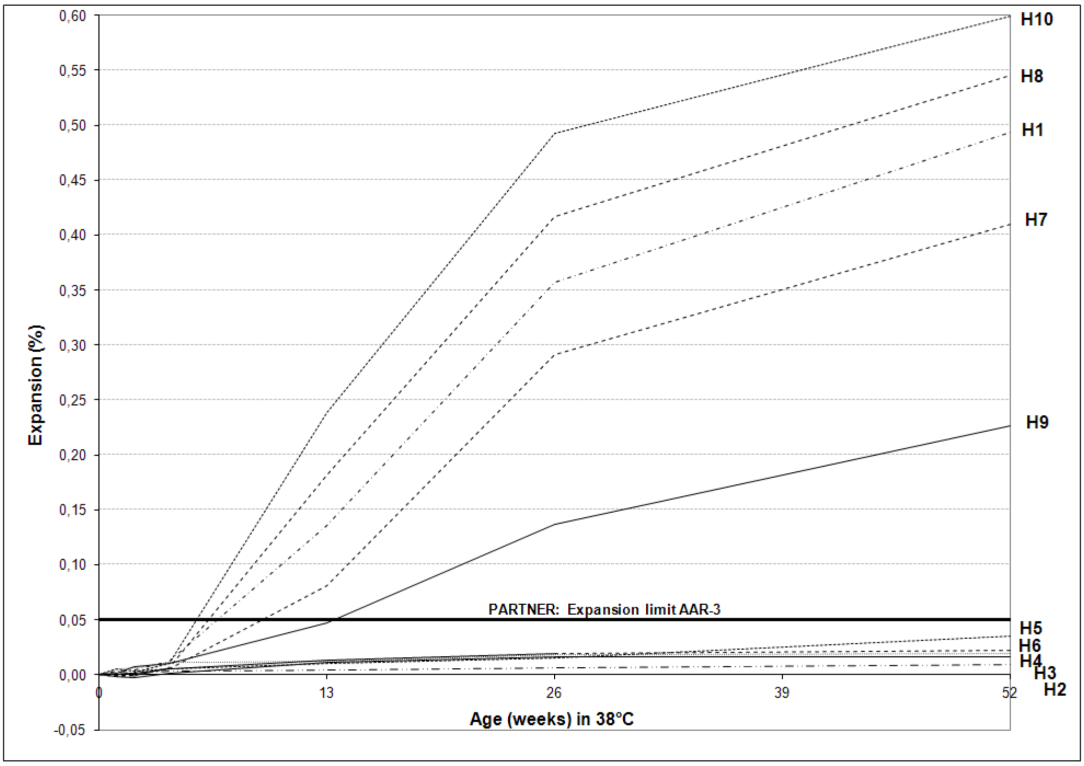

FIGURE 1: RILEM AAR-3 – Expansion results after 52 weeks of exposure in 38°C.

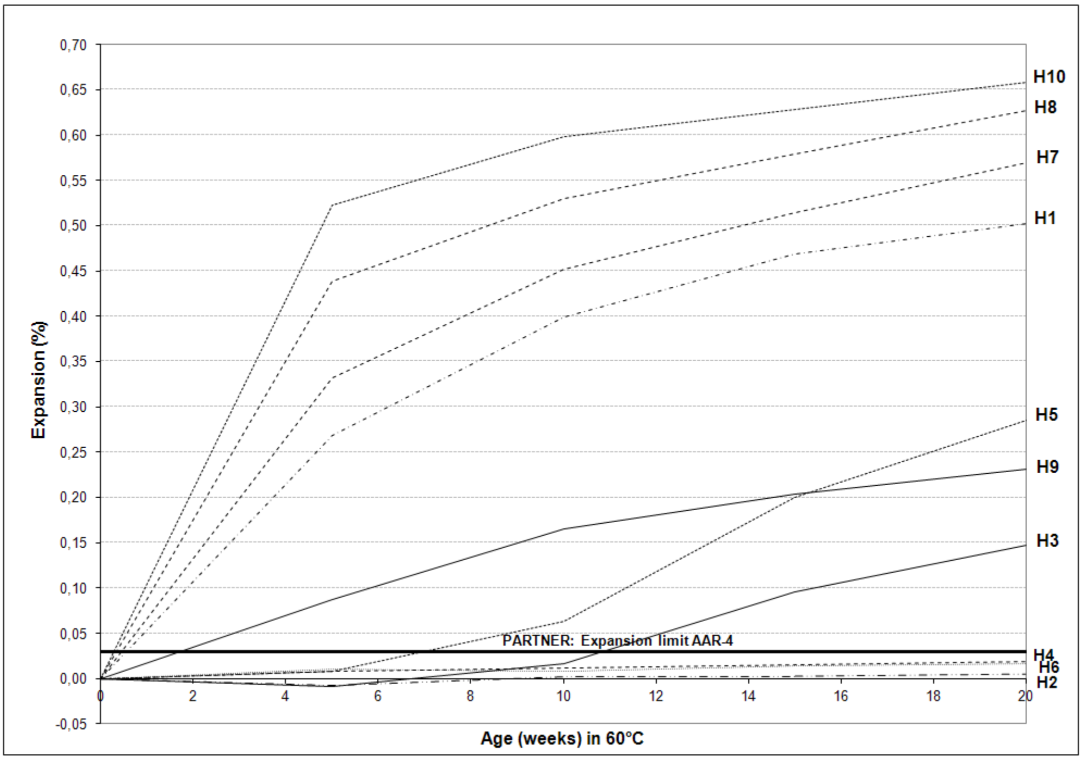

FIGURE 2: RILEM AAR-4 – Expansion results after 20 weeks of exposure in 60°C.

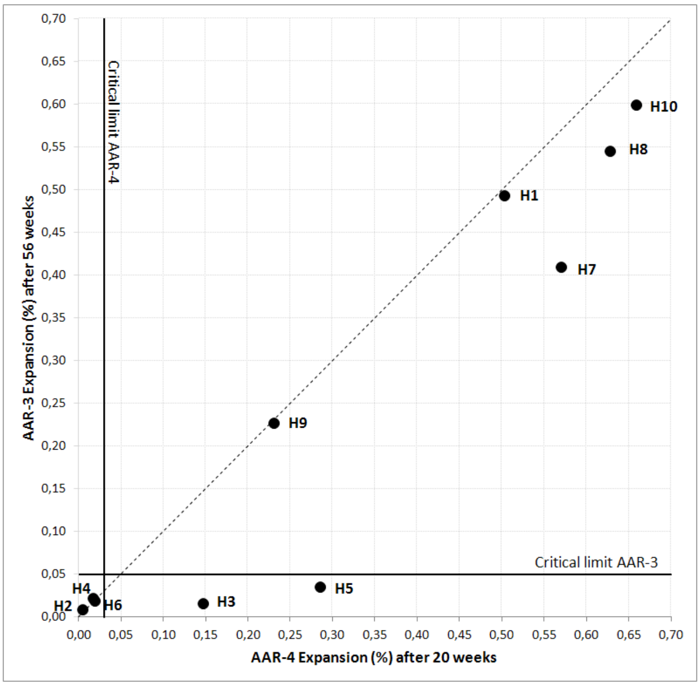

FIGURE 3: Comparison of expansion between RILEM AAR-3 and AAR-4.

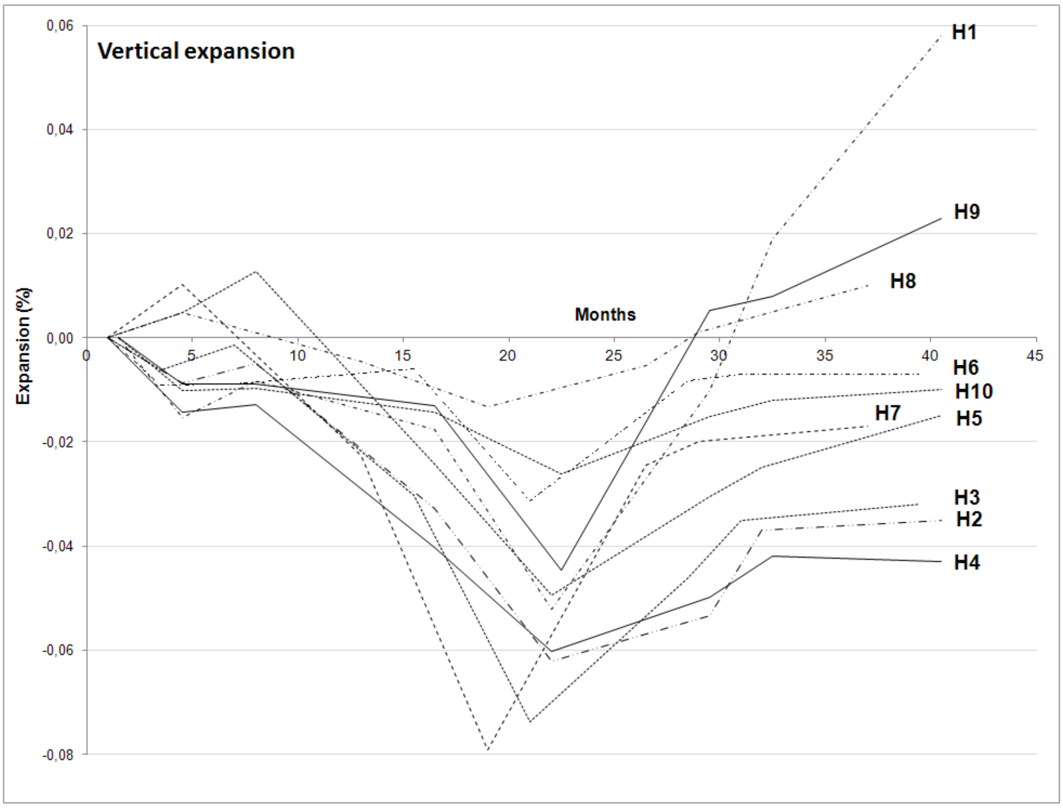

FIGURE 4: Outdoor exposure site - Vertical expansion results.