Testing of Icelandic aggregates and various binders – laboratory vs. field; A decade of results and experiences

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Abstract

As part of durability concrete testing of alkali aggregate reactivity, the laboratory at the consulting company; Mannvit started early in 2007, in Iceland, to cast additionally concrete cubes of the same concrete batches as tested in accelerated testing by concrete prisms in the previous versions of the RILEM AAR-3 and AAR-4 methods. 40 cubes (30x30x30 cm) are stored outside at the field exposure site. Since then, measurements of expansions have been carried out 2-3 times a year. This paper describes the results so far regarding laboratory testing vs. expansion results from this site. This includes both assessment of reactivity of different types of aggregates, i.e. effect of rock types and grading etc., along with the mitigating effect of various binders, i.e. low alkali cement, and effect of SCM's such as silica-fume and fly-ash.

A good relationship is not observed between results from laboratory vs. field, where outdoor cubes exhibit higher expansion. It seems promising to use low alkali cements to mitigate the expansion of medium reactive aggregates. However, it is not sufficient to neither limit the alkali-content, nor use cements with silica-fume, in order to mitigate the expansion of a highly reactive aggregate, which probably release alkalis over time. It is of great global research interest to measure this potential alkali-release in laboratory, by the RILEM AAR-8 method, and compare with alkali-levels measured in the cubes. It is clear that for the highly reactive aggregate, the highest expansion in cubes stored outside, is when using 100% of reactive aggregate as coarse aggregates. This contrasts with what is found in laboratory. No indication of pessimum behaviour is found for this type of aggregate.

***Keywords**: AAR; concrete prism testing; Iceland; outdoor exposure site*

1. INTRODUCTION

As part of durability concrete testing of Alkali Aggregate Reactivity (AAR) in concrete, the laboratory of the consulting company; Mannvit in Reykjavik, Iceland, started early in 2007 to cast additionally concrete cubes when casting concrete for accelerated laboratory testing by concrete prisms in the RILEM AAR-3 (wrapped – old version) and AAR-4 methods. These cubes; 30x30x30cm, were stored outside at the roof of the laboratory at Mannvit in Reykjavik. During 2019, the cubes were moved to a new outdoor exposure site, south of Reykjavik. – see Figure 2.1. Responsibilities of this new outdoor exposure site is a collaboration between Mannvit and Norcem/HeidelbergCement Northern Europe.

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. 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. Consequently, and in cooperation with RILEM, the laboratory of Mannvit, initiated in 2004 an Icelandic research project where four different test methods for AAR were examined [1] & [2]). As part of this project, two BSc. projects were also accomplished [3] & [4]. The methods examined were; the Accelerated Mortar Bar Test (AMBT) method (RILEM AAR-2) [5], the mortar bar method (ASTM C227) [6], Concrete Prism Test (CPT) method (RILEM AAR-3) [7] (old version), and accelerated concrete prism method (RILEM AAR-4) [8]. The results of these studies showed that 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 CPTs 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 (old 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; however, ASTM now formally has withdrawn this method. The regulations will be revised during 2021.

1.2 Objectives of the project

The main objective of this project was to provide answers to some of the uncertainties 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, 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 theoretical assessment of these parameters has been considered earlier, e.g. [9], along with previous presentation and discussion of the results from these concrete prism tests [10] & [11].

2. MATERIALS

Table 2.1 provides the overview of the main types of aggregates used, and Table 2.2 presents the various types of cements and binder combinations used. The mix design was according to the RILEM AAR-3 and AAR-4 methods. No air entrainment agents were used. In addition to CPT, AMBT-results are available for all the Icelandic types of the aggregates used. No cores have been extracted from the cubes and neither have any other tests been performed on them.

The test-series of the first 10 mixes (cubes 1-3 and 5-11) are testing the local commercial aggregates in the Reykjavik region with different types of cement. This is the reactive coarse materials from Hvalfjörður combined with the non-reactive coarse materials from Kollafjörður and fine Björgunarsandur. In addition 1 mix (cube 4) was cast with the Canadian reactive Spratt aggregate, as part of a Round Robin test. However, these results are not included in this paper.

The subsequent test-series of the next 10 mixes (cubes 12-21) are testing of the “worst case“ reactive Icelandic aggregate (Stokksnes: both coarse and fine) with different types of binders, in order to see the mitigating effect of the various binders. In additions some of the reactive Icelandic aggregates were partly replaced by Norwegian non-reactive coarse and fine materials, in order to examine the effect of coarse vs. fine reactive materials.

The third test-series (cubes 24&25 and 29 – 31) are testing in order to examine the mitigating effect of the various types of cement.

he field exposure site contains a total of 40 cubes, including some extra commercial mixes, two cubes sent from Turkey, and 6 cubes from LNEC, Portugal, as part of a research program associated to the RILEM; TC 258-AAA. However, results from these cubes are not presented in this paper.

Table 2.1: The main types of aggregates used

Hvalfjarðarperla A, B & C – medium reactive natural gravel from Hvalfjörður – Iceland (Batches A, B & C)
Perla C (GBS) - medium reactive natural sand from Hvalfjörður – Iceland (Batch C)
Kollafjarðarmöl - non reactive natural gravel from Kollafjörður – Iceland
Björgunarsandur - non reactive natural sand from Kollafjörður – Iceland
Stokksnesmöl – highly reactive natural gravel from Stokksnes - Iceland
Stokksnessandur – highly reactive natural sand from Stokksnes - Iceland
Norwegian coarse – non reactive Norwegian coarse crushed aggregate - Norway
Årdal sand – non reactive Norwegian fine natural aggregate - Norway

Table 2.2: The main types of cements and binder-combinations used

HP	Icelandic high alkali cement (1.5% 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.
KS	Icelandic high alkali cement (1.5% Na_2O_{eq}) with 4% silica fume and 4% lime filler (milled shells)
AaR	Danish Aalborg Rapid cement CEM I 52,5 N. (0.55% Na_2O_{eq}) without any SCMs
No-Ind	Norwegian Norcem Industri CEM I 52,5 R. (1.3% Na_2O_{eq}) without any SCMs
No-Anl	Norwegian Norcem Anlegg CEM I 52,5 N.(0.6% Na_2O_{eq}) without any SCMs
No-FA	Norwegian Norcem StFA CEM II/B-M 42,5 R.(1.4% Na_2O_{eq}) with 18% fly-ash

Figure 2.1: The new location of the field exposure site, south of Reykjavik, Iceland.

Table 2.3: Overview of concrete mixes for all concrete cubes at the outdoor exposure site in Reykjavik

No. cubes	Sample	Aggregates		Type of cement	Year Cast
		Coarse	Fine		
1	A+HP	Hvalfjarðarperla A	Björgunarsandur	HP	2007
2	A+Aa	Hvalfjarðarperla A	Björgunarsandur	AaR	2007
3	B+Aa	Hvalfjarðarperla B	Björgunarsandur	AaR	2007
4	S+S+NC	Spratt 3	Spratt control sand	No-Ind	2007
5	1-AAR	Hvalfjarðarperla A	Björgunarsandur	KS	2007
6	2-AAR	Hvalfjarðarperla A (50%) and Kollafjarðarmöl (50%)	Björgunarsandur	KS	2007
7	3-AAR	Hvalfjarðarperla A (50% and Kollafjarðarmöl (50%)	Björgunarsandur	VP	2007
8	4-AAR	Kollafjarðarmöl	Björgunarsandur	HP	2007
9	5-AAR	Hvalfjarðarperla A (20%) and Kollafjarðarmöl (40%)	Björgunarsandur	KS	2007
10	6-AAR	Hvalfjarðarperla A (20%) and Kollafjarðarmöl (40%)	Björgunarsandur and Rauðamelssandur	KS	2007
11	A+Aa+alkali	Hvalfjarðarperla A	Björgunarsandur	AaR + NaOH	2008
12	H1-AAR	Stokksnesmöl	Stokksnessandur	HP	2007
13	H2-AAR	Stokksnesmöl	Stokksnessandur	AaR	2007
14	H3-AAR	Stokksnesmöl	Stokksnessandur	AaR + NaOH	2008
15	H4-AAR	Stokksnesmöl	Stokksnessandur	VP	2007
16	H5-AAR	Stokksnesmöl	Stokksnessandur	KS	2007
17	H6-AAR	Stokksnesmöl	Stokksnessandur	VP	2008
18	H7-AAR	Norwegian coarse	Stokksnessandur 50% + Årdal sand 50%	HP	2008
19	H8-AAR	Norwegian coarse	Stokksnessandur 75% Årdal sand 25%	HP	2008
20	H9-AAR	Stokksnesmöl	Årdal sand	HP	2007
21	H10-AAR	Norwegian coarse	Stokksnessandur	HP	2007
24	Norc+Stokk	Stokksnesmöl	Stokksnessandur	No-FA	2011
25	Norc+PerlaA	Perla A möl	Perla A sandur	No-FA	2011
26	Kraft+PerlaA	Perla A möl	Perla A sandur	KS	2011
27	ÍsPort+PerlaA	Perla A möl	Perla A sandur	HP	2011
29	Perla C+Anl	Hvalfjarðarperla C	Perla C (GBS)	Norcem Anlegg	2012
30	Perla C+Ind sf	Hvalfjarðarperla C	Perla C (GBS)	No-Ind + 6% silica-fume bwt	2012
31	Stokk + Anl.	Stokksnesmöl	Stokksnessandur	Norcem Anlegg	2013

3. METHODS FOR ASSESSMENT AND ANALYSIS

The two methods applied were: RILEM AAR-3 Concrete prism method (storage at 38°C for 56 weeks) – wrapped concrete prisms (old version) and RILEM AAR-4 Accelerated concrete prism method (storage at 60°C for 20 weeks) – unwrapped concrete prisms. The aggregate fractions were combined in mass proportions on a dry basis of 30% fine aggregate (0/4mm), 30% (4/10mm) and 40% (10/20mm). 440 kgm^3 of cement and 180 litres of water (w/c = 0.40) were used in each mix. It should be noted that the RILEM AAR-3 method procedures was changed in 2016, and unwrapped concrete prisms were introduced, which give lower level of alkali-leaching from the prisms, and hence higher ultimate expansion.

3.1 Measurement of outdoor exposure cubes

The concrete used to cast the cubes, were of the same concrete batch as used for the concrete prisms, and no air entrainment was added. For each cube (30x30x30cm), measuring studs were installed on two side face and on the top side of each cube, see Figure 3.1. Measurements of expansions were originally carried out 2-3 times a year for all cubes, however, less frequent during the last years. The cubes are each placed on 4 concrete cylinders approximately 10 cm above the floor of concrete tiles.

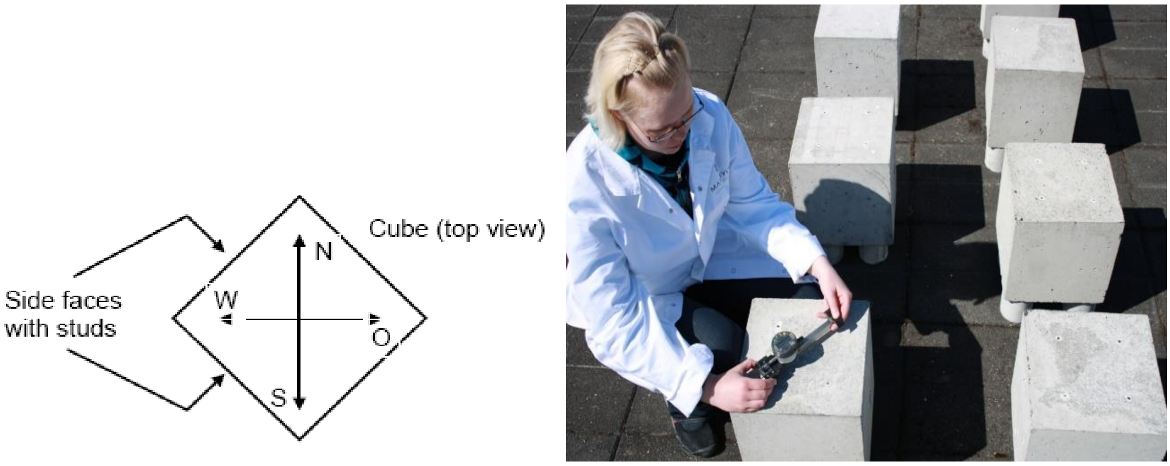

Figure 3.1: Location of measuring studs and measurement of expansion between studs

4. RESULTS AND DISCUSSION

4.1 Medium reactive aggregates from Hvalfjörður

The first test-series of the first 10 mixes (cubes 1-3 and 5-11) are testing the local commercial aggregates in the Reykjavik region with different types of cement. This is a medium reactive coarse material from Hvalfjörður combined with the non-reactive concrete coarse material from Kollafjörður and fine Björgunarsandur from Kollafjörður. In addition, a second test series (cubes 25, 26, 27, 29 & 30) are tested with the both the coarse- and fine medium reactive aggregate from Hvalfjörður. One mix (cube 4) was cast with the well-known Canadian reactive Spratt aggregate, as part of a Round Robin test. However, these results are not included in this paper. The first 10 mixes + the Spratt mix have been stored outside for more than 13 years, while the second test series have been stored outside for around 9 years.

This is very important testing and results for future utilisation of aggregates from Hvalfjörður as concrete aggregates. The coarse aggregate from Hvalfjörður has during the previous year's not been used as concrete aggregates because of local regulations and limitations by the building authorities due to AAR. However, these limitations are not in force anymore.

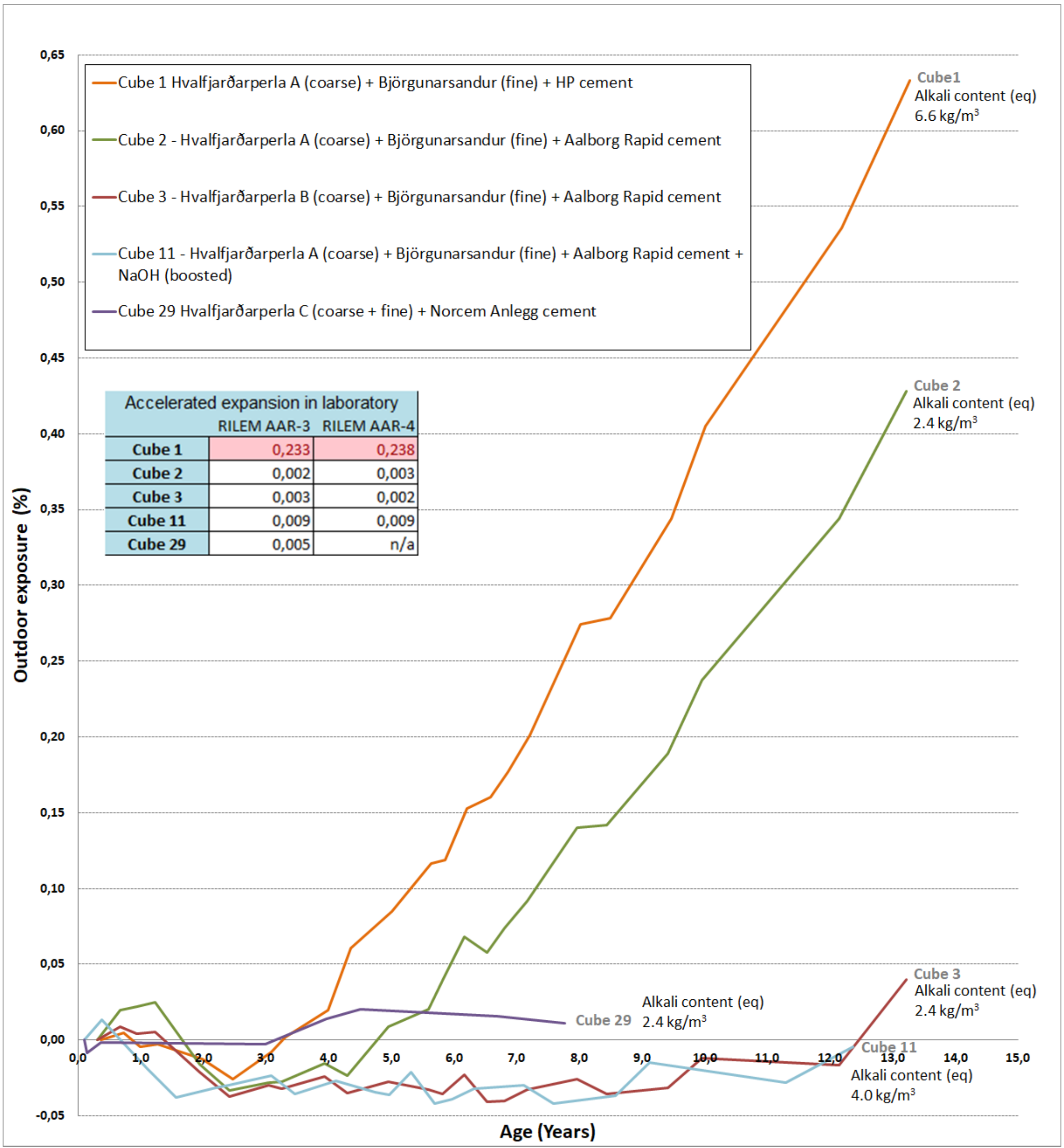

Figure 4.1: Effect of various alkali-content in concrete mixes with similar medium alkali-reactive aggregates studs

4.1.1 Effect of various alkali-content

Figure 4.1 presents the results of the effect of the various alkali-content in the concrete mixes on expansion in the outdoor exposure site. As expected, reference cube 1, with the HP cement, with a high alkali-content (Na_2O_{eq}) of 6.6 kg/m^3, is exhibiting high expansion. The cube 3, with the low alkali-content of 2.4 kg/m^3 exhibiting no expansion up to 12 year, along with cube 11, which was boosted to a medium alkali-content of 4.0 kg/m^3. However, cube 3 starts to expand after 12 years. There is however no explanation for the high expansion of cube 2, which is identical to cube 3, i.e. with a low alkali-content of 2.4 kg/m^3. Both cube 2 and 3 are exhibiting very low expansion in both the RILEM AAR-3 and AAR-4 method. It could be reason to believe that by some unfortunate circumstances, the labelling of cube 11 and cube 2 have been shifted by mistake. However, there are no possibilities to check that without “sacrifice” these two cubes and measure the alkali-content in a laboratory. Cube 29 contains the Hvalfjörður aggregates (both coarse and fine) and low alkali-content of 2.4 kg/m^3. After almost 8 years of outdoor exposure, very little expansion is measured, which is promising and an argument that it seems possible to mitigate the expansion of this aggregate by using cement with low alkali content, e.g. the Norcem Anlegg cement.

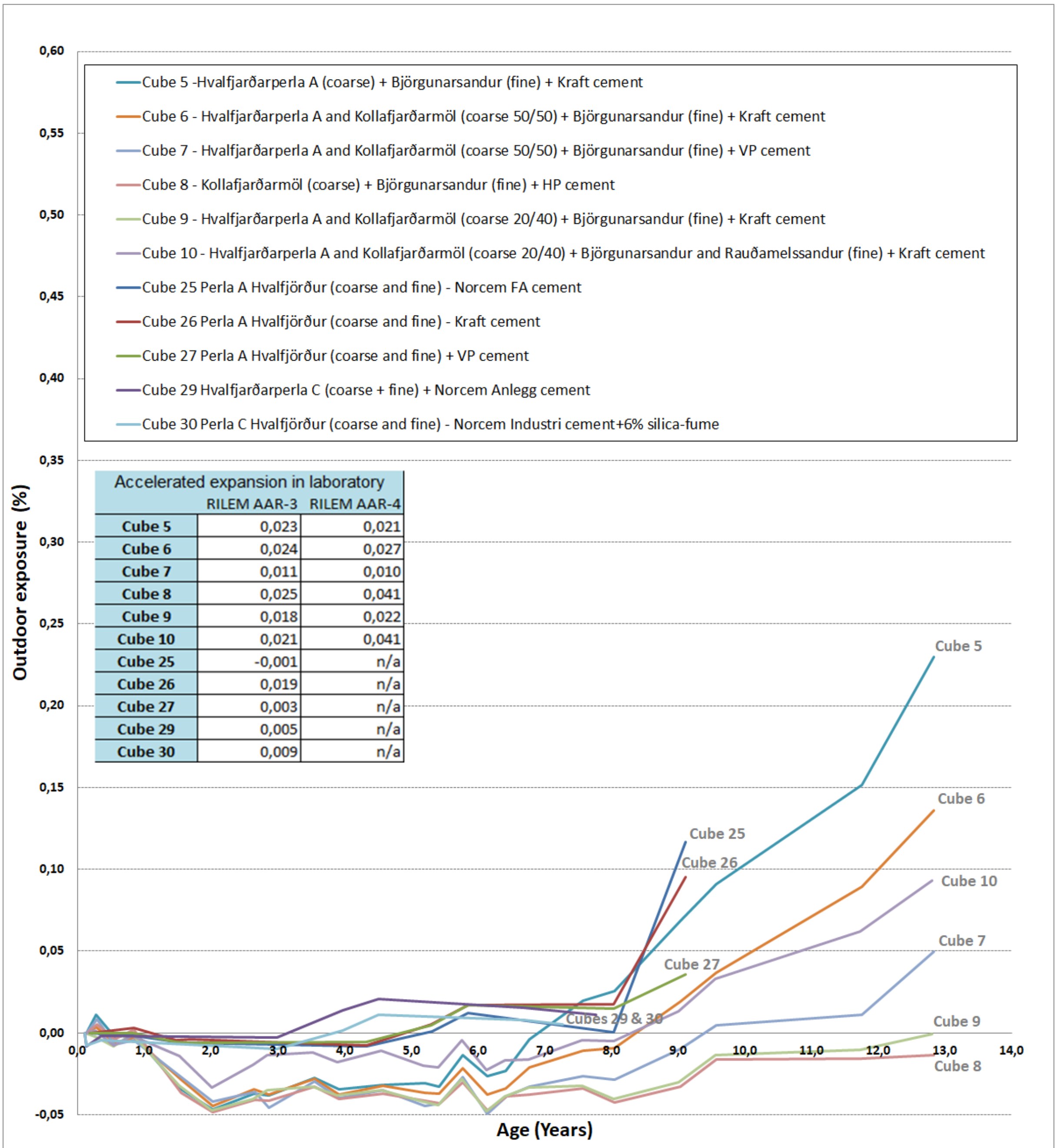

Figure 4.2: Effect of different types of cement and aggregate combination.

4.1.2 Effect of different types of cement and aggregate combination

Figure 4.2 presents the results of the effect of the Hvalfjörður aggregates in combination with other types of aggregates and the effect of different types of cement. It is evident that after approximately 6 years, cubes 5, 6 & 10 start to expand. All of them contain Kraft cement, and it is evident that this type of cement, with only 4% silica-fume, is not efficient in mitigating expansion. However, when coarse aggregates from Kollafjörður is added to the Hvalfjörður course in cube 9, the Kraft cement is sufficient to mitigate the expansion. This is also the case for cube 7 with the VP cement, however, it starts to expand after 13 years. Cube 8, which contains both non-reactive coarse and fines from Kollafjörður, exhibits non expansion after 13 year, even when using the HP cement, with a high alkali-content. This confirms the non-reactivity of the aggregates from Kollafjörður. All of these concrete mixes exhibited low expansion in the concrete prism tests.

The cubes 25, 26, 27, 29 & 30 are all made with Hvalfjörður aggregates (both coarse and fine), and various types of cements. Unexpectedly, cube 25, with fly-ash cement, starts suddenly to expand after 8 years, along with cube 26, with Kraft cement. The future measurements of these cubes are important, and will be followed closely. Cubes 29 and 30 show no expansion after 8 years.

4.2 Highly reactive aggregates from Stokksnes

The test-series of 10 mixes (cubes 12-21) are testing of the "worst case" alkali reactive Icelandic aggregate (both coarse and fine), from Stokksnes, with different types of cement, in order to see the mitigating effect of the various binders. In additions some of the Stokksnes aggregates were partly replaced by Norwegian non-reactive coarse and fine materials, in order to examine the effect of coarse vs. fine reactive materials.

4.2.1 Effect of types of cement

Figure 4.3 presents the results of the effect of the various types of cement. Cube 12, with the HP-cement, with a high alkali-content (Na_2Oeq) of 6.6 kg/m^3, starts to expand after 2 years, and exhibiting a very high expansion of more than 1.1% after around 13 years of outdoor exposure. It is interesting to note that both cube 16, with Kraft cement, and cubes 15 & 17, with VP cement, all start to expand after around 6 years of outdoor exposure, and exhibit then a rate of expansion, similar to cube 12. Hence, both Kraft cement and VP cement are not efficient of mitigating expansion for this "worst type" of Icelandic alkali-reactive aggregates.

It is however interesting to note that the expansion is postponed for 6 years. This could be due to the potential effect of alkali release from aggregates, which is discussed in the next sub-chapter.

Only cube 12 exhibited expansion above the critical limit in the RILEM AAR-3 method, while cube 12 and 16 are above the critical limit in the RILEM AAR-4 method.

4.2.2 Effect of alkali content – alkali release from aggregates?

Figure 4.4 presents the results of effect of various alkali-content in the concrete mixes. The reference cube 12, with high alkali-content of 6.6 kg/m^3, starts to expand after 2 years of outdoor exposure. Cube 14, with a boosted medium alkali content of 4.0 kg/m^3, starts to expand after about 6 years, while cube 13, with a low alkali content of 2.4 kg/m^3, starts to expand after about 8 years. All cubes are showing a similar rate of expansion, once the expansion is started. One explanation for this postponed initiation of the expansion could be the release of alkalis from the aggregate, leading to successive increase in the alkali-level in the concrete, until it reach a threshold level, and the expansion is initiated.

The cube 31, contains a low alkali-content of 2.4 kg/m^3, and has been exposed outdoor for little less than 8 years. It will be very interesting to observe if this cube also will start expansion soon, which happened to cube 13, as these two cubes have a very similar composition. Unexpectedly, cube 24, with fly-ash cement, starts suddenly to expand after 8 years. This needs to be followed up closely, and could also be the effect of alkali-release reaching a threshold value, not enabling the fly-ash cement to mitigate AAR anymore. This issue of potential alkali-release from aggregates is a very relevant research issue, which has been discussed and studied within the newly finished RILEM Technical Committee (TC) 258-AAA.Recent measurement of the potential alkali-release of the Stokksnes aggregates, by the RILEM AAR-8 method, have exhibited significant high values. It is important to follow this up and measure the alkali-content in the cubes 12, 13, 14, 24 and 31. This could be an important contribution to the verification of amount of alkali-release under accelerated conditions, compare to what is occurring in real outdoor concrete.

RILEM TC 258-AAA is now developing a new performance based concrete prism test (RILEM AAR-10), where prisms are stored unwrapped at 38^{o}C, and where the prism size is increased, which will mirror the outdoor exposure situation better. Maybe it will be necessary to run the test for 2 years to obtain sufficient results. The test-procedure will be published during 2021.

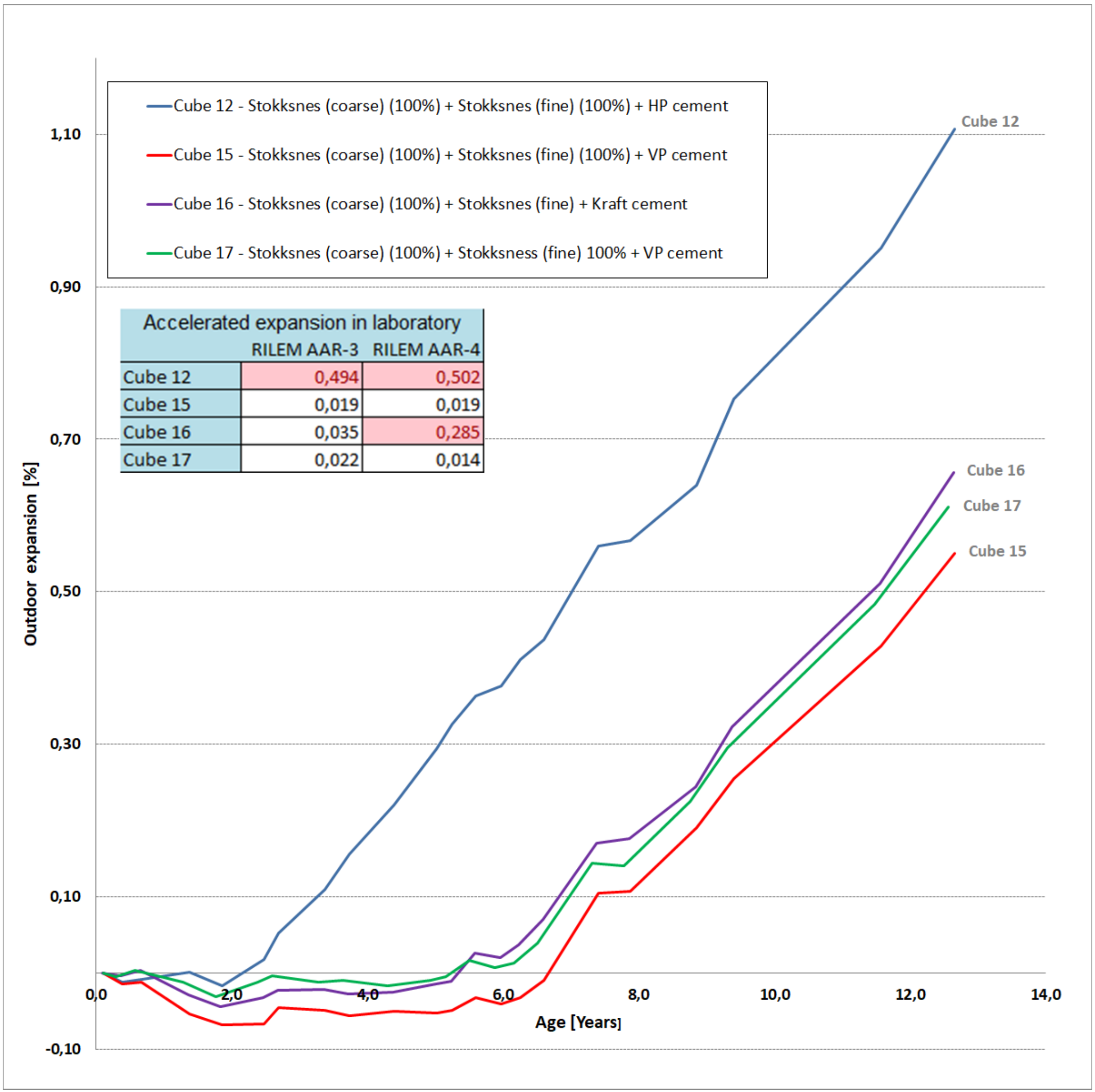

Figure 4.3: Effect of type of cement with “worst case” alkali reactive aggregates from Stokksnes

4.2.3 Effect of reactive coarse vs. reactive fine aggregates

The issue of varying amount of reactive fine or reactive coarse aggregate in concrete mixes was investigated in this study. This was carrying out by mixing various proportion of the amount of reactive aggregates in the coarse or fine aggregate size fractions, combined with the non-reactive Norwegian aggregate. The HP cement was used in all mixes.

Results from both of the concrete prism tests (AAR-3 and AAR-4), in the laboratory, exhibited very clear that the concrete mix, cube 21, with 100% reactive fine aggregate and 0% reactive coarse aggregates obtained the highest expansion. Consequently, it was from the laboratory results concluded that the reactive fine contributed most to the overall expansion, at least for this kind of reactive aggregate. The high expansion by cube 21 was in the laboratory followed by cube 19 with 75% reactive fine and 0% reactive coarse, and cube 18 with 50% reactive fine and 0% reactive coarse. The concrete mix, cube 20, with 0% reactive fine and 100% reactive coarse showed a relatively low expansion.

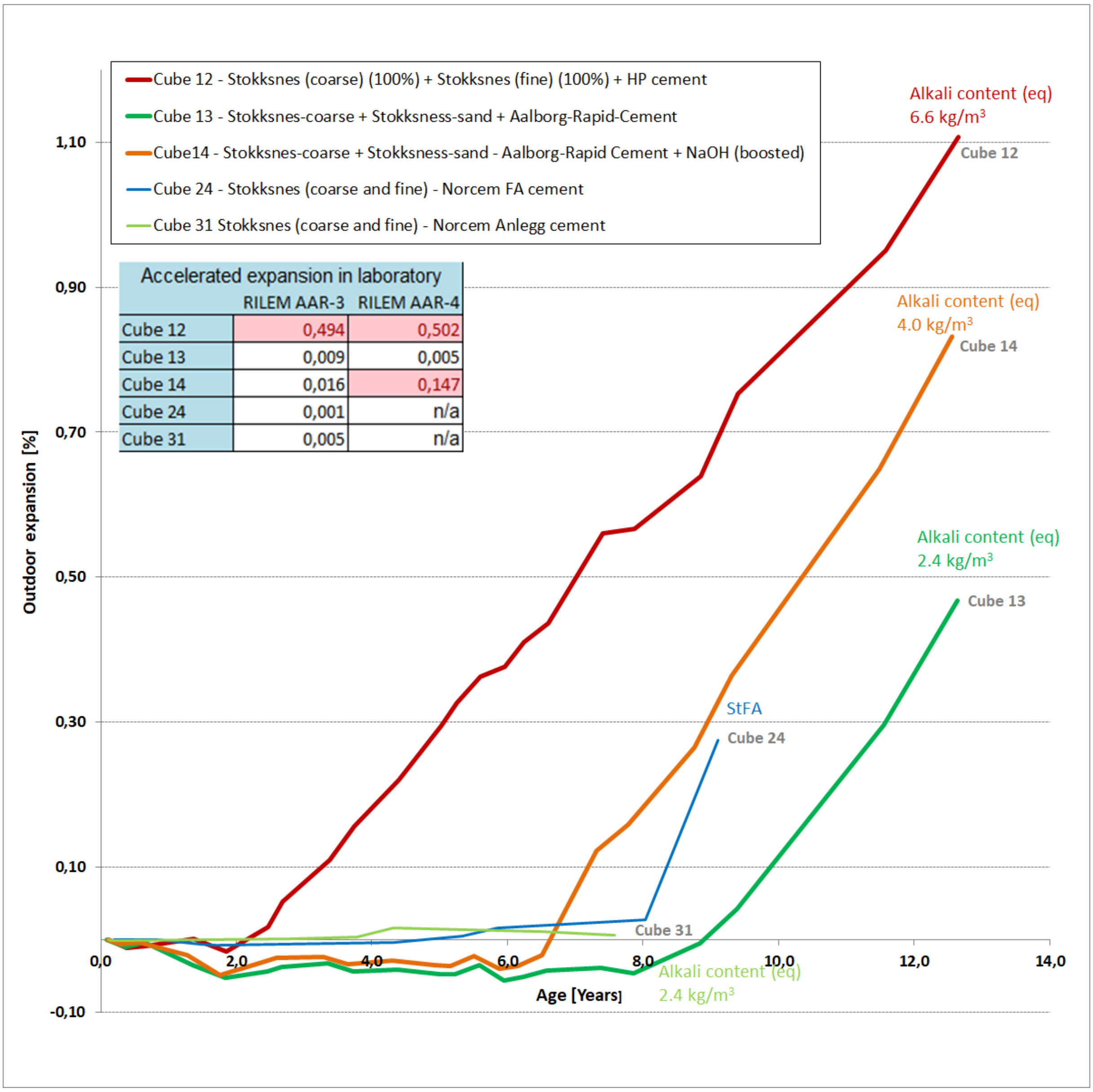

Figure 4.4: Effect of alkali content – alkali release from aggregates?

However, as clear in Figure 4.5, 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. Cube 20 exhibits higher expansion than both cube 21 and cube 19, where cube 18 show postponed expansion, starting after around 8 years. 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 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.

As cube 12, with 100% reactive aggregates in both the fine- and coarse fraction is exhibiting the highest outdoor expansion, it is no reason to believe that there exist any pessimum-effect for this type of highly reactive Icelandic aggregates.

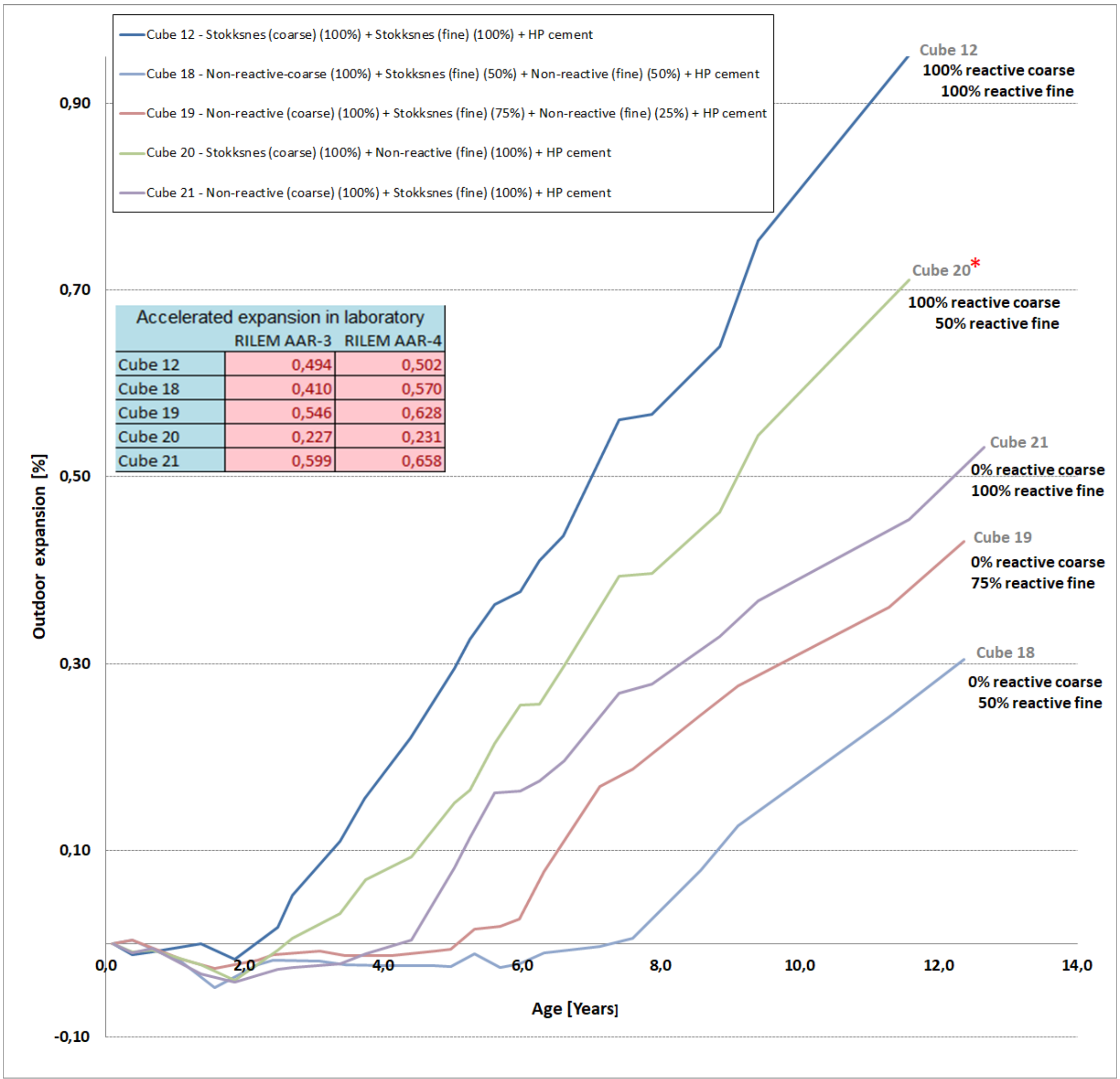

Figure 4.5: Effect of reactive coarse vs. reactive fine aggregates
(Cube 20 is not measured anymore due to very wide cracks, and stored inside for further examination)*

5. CONCLUSION

In general, it is not a good relationship between accelerated expansion results measured in the concrete prism tests (RILEM AAR-3 and AAR-4), and expansion results measured in the same concrete batches in the cubes stored outside. It is however now known that the old version of the AAR-3 concrete prism test used, with cotton-wrapped prisms, exhibited high level of alkali-leaching, reducing the ultimate expansion, compared to a newer (2016) version of the method, which exclude the cotton-wrapping. In addition, the blocks stored outdoors will also be subjected to freezing and thawing cycles, which will tend to contribute to the damage (and expansion) once cracking has initiated even if the concrete is properly air-entrained. It seems promising to use cements with a low alkali content (e.g. Norcem Anlegg cement) to mitigate the expansion of the medium reactive aggregates from Hvalfjörður. However, subsequent sampling (coring) and testing of the alkali-content in cube 2 vs. cube 11 need to be carried out. This will increase the feasibility of using Hvalfjörður coarse aggregates in concrete. It is however very positive to realise that the aggregate from Kollafjörður is non-reactive, even when used in combination with the HP cement.

It is not sufficient to neither limit the alkali-content, nor use cements with silica-fume (like VP- and HP cements), in order to mitigate the expansion of the highly reactive aggregate from Stokksnes. There is reason to believe that the aggregate from Stokksnes is releasing alkalis over time. It is of great global research interest to follow up the measurement of this potential alkali-release in laboratory, by the RILEM AAR-8 method, and compare with alkali-levels measured in the cubes. It will also be very interesting to register if cube 31 will start expansion or not, after 8 years of exposure outside. The potential alkali-release from the aggregates from Hvalfjörður should also be measured.

It is clear that for the Stokksnes aggregate, the highest expansion in cubes stored outside, is when using 100% of reactive coarse aggregate. This is in contrast to what is found for accelerated expansion by concrete prisms, where the fine part of the aggregate contribute most to the expansion. The worst case expansion with 100% reactive aggregates in both fine- and coarse fractions of the aggregates, indicates no pessimum behaviour for this type of aggregate.

6. ACKNOWLEDGMENTS

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