ALKALI AGGREGATE REACTION IN ICELAND – NEW TEST METHODS

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Abstract

In this project, four different test methods for Alkali Aggregate Reactions were examined. For each method, eight different Icelandic aggregates were tested and in addition one of the eight aggregates was tested in all four methods with nine different cement- and pozzolanas combinations.

The results show that the RILEM AAR–2 test exhibits relatively higher expansion than the other test methods. The new concrete prism tests from RILEM appear to reflect well the effects of types of aggregates, cement and pozzolanas. The mortar bar test ASTM C227 also reflects well the effect of pozzolanas, however, it exhibits very low expansion for mixes with low alkali cement.

Based upon the results from this project it is considered necessary to review the current Icelandic Building Regulations. Recent results, along with continuous research will enable the development of an Icelandic national document providing guidelines for production of durable concrete regarding AAR.

KEYWORDS: Test methods, pozzolanas, volcanic Aggregates

1 INTRODUCTION

Extensive researches have been carried out regarding AAR (Alkali Aggregate Reaction) in Iceland, especially in the seventies and eighties. It was common belief that only structures in constant contact with water such as dams, harbours and bridges were in danger of such damages but in 1978 it was proven that AAR was a wide spread problem in exterior walls of houses. The reasons for these damages were traced mainly to the aggregate sources and the use of high alkali cement.

In structures such as dams, harbours and bridges precautions were taken, prescribing unreactive aggregates and/or low alkali cement. Special Icelandic cement was developed, having 25% of rhyolite and 10% silica fumes intermilled, for these structures.

In July 1979 the following measures were taken: High quality silica fume was intermixed with the cement in the grinding process, first 5% replacement and then 7.5%. The criteria for reactivity according to the ASTM C227 mortar bar method was changed to 0.1% expansion after 12 months instead of 6 months recommended in the method. Additionally all sea dredged materials should be washed and criteria set on the chloride content. This significantly decreased the possibility of deleterious AAR in Icelandic concrete structures. The situation now is however more complicated:

- Some new concrete structures in Iceland are now designed for specified working lifetime of 100 years, instead of 50 years working lifetime previously specified.
- There are more variations of types of cement on the market. The original 7.5% adding of silica fume, in Icelandic cements, is now reduced to 4-6% depending on type of cement. A special cement with 10% silica fume and 25% rhyolite interground is only manufactured on large orders and therefore no longer available on the market. Cements, aggregates and various admixtures for concrete are imported on a large scale.
- Iceland, as part of the European Economic Area (EEA), is required to employ the new European production standards for aggregates and concrete. New European testing standards regarding AAR are in preparation and these standards will diverge from mortar bar testing methods used in Iceland and in which the Icelandic Building Regulations are based upon.

The Icelandic Building Regulations from 1998 [1] require that all aggregate for concrete shall be tested with respect to AAR. The aggregate producer shall test his aggregates on a regular basis, and obtain a certificate from an independent laboratory, classifying the aggregate as reactive or innocuous. The testing shall be carried out according to ASTM C227 and/or ASTM C1260. Summary of the limits is presented in Table 1.

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In the cases where aggregates are classified as reactive, it is the responsibility of the aggregate producer to prove that the prospected mix of aggregates and cement is non deleterious. This has recently been criticised, because no concrete performance tests are described in Iceland, and because this responsibility should belong to the concrete producer.

In order to maintain the security against deleterious AAR it is necessary to continue the research in Iceland, and assess new test methods developed internationally. Large values in concrete structures are at risk, with subsequent expensive repair if we do not can guarantee that all concrete produced in Iceland remains durable to deleterious AAR.

The main justification of this project was to enable the preparation of National Guidelines to prevent deleterious AAR in concrete structures. The necessity of such a document is due to the implementation of European aggregates- and concrete standards in Iceland (ÍST EN 12620, 2002 [2]; ÍST EN 206-1, 2000 [3]) and due to the changes in the Icelandic concrete industry during the last years. Efficient Icelandic regulation to combat AAR will lead to more durable concrete structures, and decrease the cost of maintenance in the future. The main objectives of this study were to:

- Examine the effectiveness and accuracy of the mortar bar test (ASTM C227, 1997 [4]) and the accelerated mortar bar test (RILEM AAR-2, 2000 [5]) for Icelandic aggregates, in order to evaluate the critical limits provided by the Building regulations in Iceland.
- Examine the new concrete prism tests (RILEM AAR-3, 2000 [6] and RILEM AAR-4, 2007 [7]) as tools to assess the effectiveness of silica fume, fly ash and low alkali cements in reducing expansion caused by AAR. Subsequently the objectives were to suggest critical expansion limits for the tests.

For detailed results from this study we refer to the final report [8].

2 MATERIALS AND METHODS

2.1 Testing methods

In this project four different test methods for AAR have been examined. These methods are:

- Mortar bar method (ASTM C227)
- Accelerated mortar bar method (RILEM AAR-2)
- Concrete prism method (RILEM AAR-3)
- Accelerated concrete prism method (RILEM AAR-4)
  - → Original method with reactor
  - → Modified method with cotton wrapping

The methods ASTM C227 and RILEM AAR-2 were performed according to the standards. For the concrete prism tests, RILEM AAR-3 and RILEM AAR-4, some amendments to the measurements were carried out. In addition to measurement of the longitudinal expansion, the prisms were unwrapped from the cotton wrapping and weighted in air and water. The reason for this was to examine if the volume expansion could be used as a significant measurement for the reaction. The unwrapping of the cotton frequently destroyed the cotton, especially in the RILEM AAR-4 test, and new ones were required. This may have had significant impacts upon the results, including the leaching of alkalis.

ASTM C227

ASTM C227 Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar Bar Method) was introduced in 1950, based on the testing methodology described by Stanton in 1940 [9]. The test was earlier widely used though it may require a year or more for completion. The mortar bars are made with cement that has more than 0.60% by weight of alkali as Na_2O equivalent and the bars are stored over water at 38°C +/- 1.7°C in 100% humidity.

The problem of alkali leaching in this test was already reported in 1946 by scientists [10] and in 1991 even more researchers [11] found the procedure to be unsatisfactory and explained the lack of expansion as due to leaching of alkalis by condensation on the surface of the mortar bars. The failure of the test to correctly identify the potential reactivity of a numerous rock types such as certain gneisses, greywackes, argillites, quartzites and metavolcanic rocks is now well established. Oberholster [12] quotes various published researches and an inter-laboratory study which shows that known reactive aggregates are not detected by the test. He also shows that the reproducibility of the method from the inter-laboratory study is highly variable (0,008-0,154) with means and standard deviation depending on the alkali content of the cement.

RILEM AAR-2

Numerous accelerated mortar bar tests have been developed, most of which centre on the procedure published by Oberholster and Davies [13], which is known as the South African NBRI method. In this procedure the mortar bar is immersed in an alkaline sodium-bearing solution at elevated temperature. Modified versions of the NBRI test were adopted in 1994 by ASTM as ASTM C1260-94[14] and in Canada as CSA A23.2-25A (1994) [15] and recently as RILEM AAR-2 (2000) [5].

Bérubé et al. [16] have pointed out that this test may be too severe in that some innocuous aggregates have been found to react expansively. On the other hand it is reported by Hooton **Error! Reference source not found.** that some reactive aggregates are not detected. Possibly these differences reflect slight differences in the way in which the test is carried out. Thomas et al. [17] suggest that the test should only be used to accept and not to reject aggregates. Furthermore, if an aggregate fails the test, a concrete prism test should be used to confirm the results before an aggregate is either rejected or conditions are put on its use.

RILEM AAR-3

Canadian scientists have been leading in developing concrete prism tests, both to identify reactive aggregates and evaluate preventive measures. Most methods are based on increased temperature and increased cement alkalis to accelerate the reaction. As the Canadians learned that the ASTM C227 did not identify correctly some alkali reactive rock types, they started to develop the concrete prism test. Since the first version, the test has been calibrated against field performance. As a consequence, Rogers et al. [18] claim that all known reactive aggregates are correctly identified. The current version of the Canadian concrete prism test [19], which has been adopted by ASTM (as ASTM C1293), uses a cement content of 420 kg/m^3 with the cement alkalis raised to 1.25% Na_2O_{eq} by the addition of NaOH to the mix water. The concrete prisms are stored at 38°C over water in sealed containers.

The Canadians have experienced that due to leaching, concrete prisms exhibited less expansion than concrete blocks stored outside that have the same aggregates and same level of alkalis. Research has showen that approximately 35% of the alkalis originally in the concrete prism leach out into the water reservoir after 1 year, and as much as 20% after just 90 days [17]. On the other hand Norwegian scientists have results showing that only 0.45% of the alkalis leached out in 1.5 years in the RILEM AAR-3 method [20].

The RILEM AAR-3 method is similar to the Canadian method except in that it uses cement content of 440 kg/m^3. The test prisms are wrapped in cotton and stored in a closed plastic bag over water in sealed container at 38°C. Limits for critical expansion are proposed by PARTNER project [21].

RILEM AAR-4

To shorten the test period for the concrete prism test Ranc and Debray [22] enhanced the exposure temperature to 60°C. The test has not yet been standardized by European standard organisations or ASTM, but several researchers have applied the test and Fournier et al. present a summary **Error! Reference source not found.**.

Touma et al. presented a reasonable correlation between the 3-month expansion of prisms stored at 60°C and the 12-month expansion of prisms at 38°C [23].

It has been observed by Fournier et al. **Error! Reference source not found.** that the elevated temperature increases the rate of alkali leaching during the test period, and reduces the pore solution pH due to sulphate ions replacing some of the hydroxyl ions in solution. This results in a lower expansion rate in the accelerated test compared to the standard concrete prism test. In the same research it was shown that using a 13-week 0.04% expansion limit at 60°C, the accelerated concrete prism test gave the same assessment as the conventional concrete prism test (0.04% expansion limit at one year) in more than 95% of the cases in Canada. Limits for critical expansion are proposed by PARTNER project [21].

2.2 Testing materials

The original scheme of this study included the use of the four different test methods. A total of eight different aggregates (A-H) were tested (see Table 2). All aggregates except aggregate C are used in concrete mixes in Iceland. Aggregate C is highly alkali reactive rhyolite used in cement production.

Aggregate B was tested with nine different cement/pozzolanas combinations (see Table 3). In addition some tests were carried out with some additional aggregates and some modifications to the test methods were also applied.

3 RESULTS

3.1 Various aggregates – same cement

The expansion results obtained in the different tests for the various aggregates (A-H) with the same type of high alkali cement without any silica fume are presented in Table 4. Results have been coloured red or green according to critical limits given by the Icelandic Building Regulation [1] (mortar bar tests) or by critical limits proposed by the PARTNER project [21].

Results for weight changes in RILEM AAR-3 and RILEM AAR-4 tests are shown on Figure 1 and Figure 2. Aggregate A which exhibits very high weight increase in both of the tests, is a very porous aggregate with a high water absorption. Filling the voids with water is probably the reason for this high weight increase. The H aggregate, exhibited relatively high weight increase in RILEM AAR-3 and RILEM AAR-4. Aggregate H is a very dense aggregate, with a low value for water absorption and at this time we have not found a reason for this weight increase during testing.

3.2 Various cement and pozzolanas – same aggregate

The expansion results obtained in the different tests for the same aggregate (B) with various types of cement, are presented in Table 5. Results have been coloured red or green according to critical limits given by the Icelandic Building Regulation [1] (mortar bar tests) or by critical limits proposed by the PARTNER project [21]. The ambiguous effects of blending silica fume in the laboratory were evident for both B7 (4%) and B3 (7%) in the RILEM AAR-2, RILEM AAR-3 and RILEM AAR-4 tests. It is believed that adding silica fume in the mix at the laboratory is insufficient as the silica fume probably is not well dispersed. Possible occurrence of lumps of silica fume particles could be investigated further by thin-sections of concrete prisms. However, this has not been carried out in this project. The results from these tests are left out here.

It is evident in the tests, ASTM C227, RILEM AAR-3 and RILEM AAR-4, that the mix with the highest alkali cement (B_0), and no added pozzolanas, gives the highest expansion. It is also evident that the RILEM AAR-2 test does not exhibit any clear effects of lower expansion with pozzolanas or low alkali content in the cements. Although the mixes with high alkali content exhibited slightly higher expansion than those with low alkali cement and the mix with cement containing 15% fly ash exhibits lower expansion than all other mixes, all mortar mixes with different types of cements are in excess of the critical limits after 14 days.

In Figure 3**Error! Reference source not found.** the relative effect of silica fume on the expansion for the different test methods is presented. The expansion for test samples without silica fume is set to 1.0 whereas expansion for samples with added silica fume is calculated as a ratio of the 1.0 expansion. In the same way, results for the effect of alkali content are presented in Figure 4**Error! Reference source not found.**. It is apparent from this that adding silica fume or using low alkali cements has minor effect in the RILEM AAR-2 method. This is possible due to the fact that the mortar bars have an unlimited access of alkalis during the test period.

The effect of adding silica fume in the ASTM C227 method decreases the expansion by a factor of approx 0.5. However, the effect of using low alkali cements decreases the expansion dramatically. It is believed that due to the effect of leaching of alkalis in this method the effect is exaggerated. There is no bar showing the effect of 6% silica fume and 3% rhyolite added where as the test failed.

Cement with 6% silica fume in the RILEM AAR-3 method decreases the expansion significantly more than cement with only 4% silica fume. This is believed to reflect more the true situation. Mixes with low alkali cements exhibit lower expansion, however, a little less extreme than in the ASTM C227 method. However, due to the long testing period, it is possible that alkalis are leached from the prisms.

The effect of cements with silica fume in the RILEM AAR-4 method gives similar reduction in expansion as in the ASTM C227 method. However, effects of low alkali cements gives less reduction in expansion compare to ASTM C227 and RILEM AAR-3. This could be due to the relative short testing period (20 weeks) which limits the possibilities of leaching of alkalis.

4 DISCUSSION

The critical limits for the two different concrete prism method are not yet fully established. The PARTNER project has proposed a limit of <0.05% expansion after one year for RILEM AAR-3 and 0.03% after 20 week for the RILEM AAR-4 method. Canadians, however, which have done a great deal of research of these methods, have proposed a limit of 0.04% expansion after one year for method similar to the RILEM AAR-3 and 0.04% expansion after 13 weeks for a method similar to the RILEM AAR-4 method. Using the critical limits from the PARTNER project, only aggregate B and H are classified as reactive in all four methods.

ASTM C227, RILEM AAR-3 and RILEM AAR-4 mirror the expected effects for the various types of cements and pozzolanas. However, the relatively (quantitative) effects exhibit variations between the tests.

In the RILEM AAR-4 test the overall expansion is surprisingly low. Samples in this test exhibit shrinkage between 8 and 12 weeks. This, along with the overall low expansion (compared with the other methods) indicates that the humidity has not been sufficient in this alternative method (wrapped prisms). Some of the samples were re-tested in the original RILEM AAR-4 method applying the reactor, see Figure 5**Error! Reference source not found.**. It is evident that less shrinkage occurs when testing according to the original method at 8-12 weeks but difference in expansion is, at this point, unexplained.

Some shrinkage occurs in some mixes during the first 2 weeks in the RILEM AAR-3 test. Under such circumstances it is a question how the final expansion should be evaluated, if e.g. the total expansion should be calculated from where the shrinkage reaches the lower limit.

5 CONCLUSIONS

The ASTM C 227 method appears to mirror well the effect of silica fume in reducing expansion. For cements with low alkali content this test method appears to exhibit little expansion. One explanation for this could be the effect of leaching of alkalis below a critical limit, which will be more in long and thin mortar bars, and due to the long testing period. As a consequence the method is not recommended to evaluate the effect of low alkali cements.

The RILEM AAR-2 method is similar to the method ASTM C 1260 as described in the Icelandic Building Regulations. The use of silica fume and cements with low alkali content exhibit little influence on the results of the accelerated mortar bar expansion. An exception appears to be the cement containing 15% fly ash. Hence it is proposed that it should only be used for assessing the reactivity of Icelandic aggregates and not as an assessment of the effects of the additives and types of cement. Furthermore, if an aggregate fails the test, a concrete prism test should be used to confirm the results before an aggregate is either rejected or conditions are put on its use. Comparison of results from the two mortar bar tests, RILEM AAR-2 and ASTM C227, shows a poor correlation.

All of the 8 aggregates exhibited remarkable high expansion after 14 days in RILEM AAR-2 method, indicating that all the aggregates should be regarded as highly reactive, according to existing limits in Iceland. However, with respect to the results obtained by the other test methods, it is clear that mortar mixes exhibiting expansion greater than critical limits in this test will not necessarily develop deleterious expansion in concrete mixes. As a consequence it is obvious that the critical limits for the accelerated mortar bar test need to be reviewed in the Icelandic Building Regulations.

Longitudinal expansion results from the two new concrete prism tests from RILEM (AAR-3 & AAR-4) appear to reflect well the effects of aggregate, cement and adding pozzolanas. Results from the modified version of the RILEM AAR-4 test (with cotton wrapping), exhibit shrinkage between 8 and 12 weeks of exposure. This, along with the overall low expansion (compared to the other methods), indicates that the humidity has not been sufficient in this alternative method (wrapped prisms). Less degree of shrinkage was observed when re-testing 4 samples by the original version of the RILEM AAR-4 method (with humidity reactor). It is recommended to use the original RILEM AAR–4 method in future testing, and it is the ambition to continue the development of this method in Iceland.

Further research needs to address the following:

- Make sure that the humidity in the storage conditions is constantly kept close to 100% Rh, ensuring sufficient humidity supply for concrete prism specimens.
- Measure and evaluate the effect of leaching.
- Evaluate the role of fine aggregates at elevated temperatures.
- For future evaluation of particular concrete mixes, and for assessment of potential deleterious

expansion, it is required to establish a relationship between the critical limits and to what to expect in the field.

6 REFERENCES

[1] Umhverfisráðuneytið (2002): Byggingarreglugerð nr. 441/1998 með síðari breytingum. [in Icelandic; Icelandic Building Regulations from 1998]: pp 52.

[2] ÍST EN 12620 (2002): Aggregates for concrete.

[3] ÍST EN 206-1 (2000) +A1:2004 + A2:2005: Concrete – Performance, production, placing and compliance criteria.

[4] ASTM C227-97a (1997): Standard test method for potential alkali reactivity of cement-aggregate combinations (Mortar-Bar Method), Annual book of ASTM Standards. American Society for Testing and Materials, West Conshoshocken, PA.

[5] RILEM Recommended Test Method AAR-2 (formerly TC-106-2) (2000): Detection of Potential Alkali-Reactivity of Aggregates: A - The Ultra-accelerated Mortar-bar Test. Materials & Structures (33): 283-289. (complete revised edition in preparation).

[6] RILEM Recommended Test Method AAR-3 (formerly TC-106-03) (2000): Detection of potential alkali-reactivity of aggregates: B - Method for aggregate combinations using concrete prisms. Materials & Structures (33): 290-293. (revised edition in preparation).

[7] RILEM Recommended Test Method AAR-4 (2007): Detection of Potential Alkali-Reactivity - 60°C Accelerated Method for Testing Aggregate Combinations using Concrete Prisms - Committee Document RILEM/TC-ARP/06/15 (in preparation).

[8] Wigum, BJ, Björnsdóttir VD, Olafsson, H, and Iversen, K (2007): Alkali Aggregate Reaction in Iceland – New Test Methods, VGK-Hönnun Consulting Engineers.

[9] Stanton, TE (1940): Expansion of concrete through reaction between cement and aggregate. Proceedings of the American Society of Civil Engineers (66/10): 1781–1811.

[10] Blanks, RF, and Meissner, HS (1946): The expansion test as a measure of alkali-aggregate reaction. Journal of the American Concrete Institute (17/5): 517–539.

[11] Hooton, RD (1991): New aggregate alkali-reactivity test methods. The Research and Development Branch, Ontario Ministry of Transportation, MAT-91-14: pp 54.

[12] Oberholster, RE (1987): Results of an international inter-laboratory test program to determine the potential alkali reactivity of aggregates by the ASTM C227 mortar prism method. In: Grattan-Bellew, PE (editor): Proceedings of the 7th International Conference on Alkali-Aggregate Reaction in Concrete, Ontario, Canada (Noyes Publications, Park Ridge, NJ): 368-373.

[13] Oberholster, RE, and Davies, G (1986): An accelerated method for testing the potential alkali reactivity of siliceous aggregates. Cement and Concrete Research (16): 181-189.

[14] ASTM C-1260-94 (1994): Standard test method for potential alkali reactivity of aggregates (mortar-bar method). Annual book of ASTM Standards. American Society for Testing and Materials, West Conshoshocken, PA.

[15] CSA (1994): Test method for detection of alkali-silica reactive aggregate by accelerated expansion of mortar bars. A23.2-94. Methods of test for concrete. Canadian Standards Association, Mississauga, ON, Canada, 236-242, A23.2-25A.

[16] Bérubé, MA, Fournier, B, Mongeau, P, Dupont, N, Quellet, C, and Frenette, J (1992): Effectiveness of the accelerated mortar bar method, ASTM C-9 proposal P 214 or NBRI, for assessing potential AAR in Quebec (Canada). In: Poole, AB (editor): Proceedings of the 9th International Conference on Alkali-Aggregate Reaction in Concrete. Concrete Society, London, Publication CS.104(1): 92-101.

[17] Thomas, M, Fournier, B, Folliard, K, Ideker, J, and Shehata, M (2006): Test methods for evaluating preventive measures for controlling expansion due to alkali–silica reaction in concrete. Cement and Concrete Research (36): 1842-1856.

[18] Rogers, CA, Grattan-Bellew, PE, Hooton, RD, Ryell, J, and Thomas, MDA (2000): Alkali-aggregate reactions in Ontario. Canadian Journal of Civil Engineering (27): 246–260.

[19] CSA (2000): potential expansivity of aggregates (procedure for length change due to alkali-aggregate reaction in concrete prisms). CSA A23.2-00: Methods of Test for Concrete. Canadian Standards Association, Mississauga, Ontario, Canada: 207-216.

[20] Kjær Bremseth, S (2007): Kjemisk analyse av oppbevaringsvannet ifm funksjonstest av betongprismer med alder 1,5 og 9,5 år, Norcem Heidelberg Cement Group, Rapport nr. 9D4/R07039. (in Norwegian)

[21] Nixon, P, and Lane, S (2006): Report 3.3. Experience from testing the alkali reactivity of European aggregates according to several concrete prism test methods. SINTEF Building and Infrastructure, Concrete, Report no. SBF52 A06021: pp35.

[22] Ranc, R, and Debray, L (1992): Reference test methods and a performance criterion for concrete structures. In: Poole, AB (editor): Proceedings of the 9th International Conference on Alkali-Aggregate Reaction in Concrete. Concrete Society, Publication CS.104(1): 110-116.

[23] Fournier, B, Nkinamubanzi, PC, Lu, D, Thomas, MDA, Folliard, KJ, and Ideker, JH (2006): Evaluating potential alkali-reactivity of concrete aggregates: how reliable are the current and new test methods? In: Fournier, B (editor): Marc-André Bérubé Symposium on alkali-aggregate reactivity in concrete. 8th CANMET/ACI International Conference on Recent Advances in Concrete Technology, May 31 - June 3, 2006, Montréal, Canada: 21-43.

[24] Touma, WE, Fowler, DF, and Carrasquillo, RL (2001): Alkali–silica reaction in Portland cement concrete: testing methods and mitigation alternatives, Report ICAR 301-1F, International Center for Aggregates Research, Austin, Texas: pp 520.

Table 1: Critical limits for testing alkali reactivity according to the Icelandic Building Regulation.

Test methods	Type of cement	Critical expansion limits		
		14 days	6 months	12 months
ASTM C1260	Icelandic Portland cement without pozzolanas	< 0.2%		
ASTM C1260	The cement to be applied, or cement with silica fume.	< 0.1%		
ASTM C227	Icelandic Portland cement without pozzolanas		< 0.05%	< 0.1%
ASTM C227	The cement to be applied			< 0.1%
ASTM C227	Cement with silica fume			< 0.06%

Table 2: Overview of aggregates tested.

Aggregates	Location	Description
A	Reykjavik region	Crushed Rock/Pillow lava
B	West region of Iceland	Natural Sand & Gravel
C	Hvalfjörður	Crushed Rock/rhyolite
D	Northern Iceland	Natural Sand & Gravel
E	Reykjavik region	Natural Sand & Gravel
F	Eastern Iceland	Natural Sand & Gravel
G	West region of Iceland	Natural Sand & Gravel
H	South eastern Iceland	Natural Sand & Gravel

Table 3: Various types of cements and pozzolanas used.

Labelling of cement used	% silica fume[3]	% rhyolite	% Fly ash	Na_2O_{eq}	Alkali content in concrete (kg/m^3)
0	-	-	-	1.5	6.60
1	6	3	-	1.5	6.60
2	4	-	-	1.6	7.04
3	7[1]	-	-	1.5	6.60
4	-	-	-	0.4	1.76
5	-	-	-	0.6	2.64
6	-	-	-	0.6	2.64
7	4[1]	-	-	0.6	2.64
8	-	-	15[2]	0.6	2.64

1. Silica fume added in laboratory
2. Fly ash added in laboratory
3. Characteristic chemical composition of Icelandic silica fume:
SiO_2 (93,7%), Al_2O_3 (0,81%), Fe_2O_3 (1,62%), MgO (0,65%), CaO (0,39%), Na_2O (0,53%), K_2O (0,9%)

Table 4: Final expansion results from the four different test methods for 8 different types of aggregates (A-H).

Concrete Mixtures; Different aggregates – Same type of cement	C227 (52 weeks) Critical limit 0.10%[i]	AAR-2 (14 days) Critical limit 0.20%[i]	AAR-3 (52 weeks) Critical limit 0.05%[ii]	AAR-4 (20 weeks) Critical limit 0.03%[ii]
A	0.05	0.29	0.02	0.02
B	0.32	0.51	0.06	0.03
C	0.04	0.34	0.03	0.05
D	0.37	0.80	0.03	0.03
E	0.08	0.29	0.04	0.03
F	0.04	0.33	0.02	0.03
G	0.38	0.62	0.02	-0.01
H	0.66	0.71	0.52	0.42

i: Critical limits according to Icelandic Building Regulation.
ii: Critical limits proposed by the PARTNER project.

Table 5: Final expansion results from the four different test methods for seven different types of cements and additives using the same aggregate (B). Results for B_3 and B_7 are left out, see text for further explanation.

Concrete mixtures; Aggregate B – Different types of cements	C227 (52 weeks) Critical limits 0.10%[i]	AAR-2 (14 days) Critical limits 0.20%[i]	AAR-3 (52 weeks) Critical limits 0.05%[ii]	AAR-4 (20 weeks) Critical limits 0.03%[ii]
B_0; Na_2O_{eq}1.5% (0% silica fume)	0.32	0.51	0.06	0.03
B_1; Na_2O_{eq}1.5% (6% silica fume and 3% rhyolite)	- [iii]	0.44	0.02	0.02
B_2; Na_2O_{eq}1.6% (4% silica fume)	0.15	0.54	0.03	0.02
B_4; Na_2O_{eq}0.4% (0% silica fume)	0.01	0.37	0.01	0.01
B_5; Na_2O_{eq}0.6% (0% silica fume)	0.01	0.43	0.01	0.01
B_6; Na_2O_{eq}0.6% (0% silica fume)	0.01	0.42	0.01	0.00
B_8; Na_2O_{eq}0.6% (15% fly ash)	0.00	0.21	0.01	0.00

i: Critical limits according to Icelandic Building Regulation.
ii: Critical limits proposed by the PARTNER project
iii: Test failed
$Na_2Oeq = Na_2O + 0.658 * K_2O$

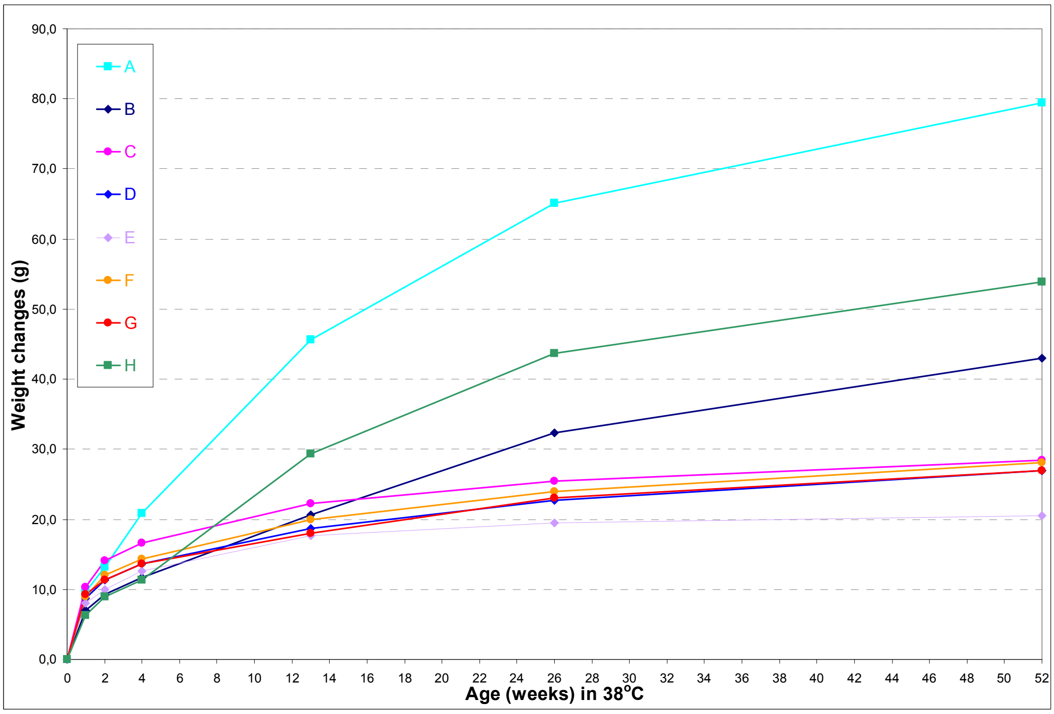

Figure 1: RILEM AAR-3; Weight changes - various aggregates, with same high-alkali cement

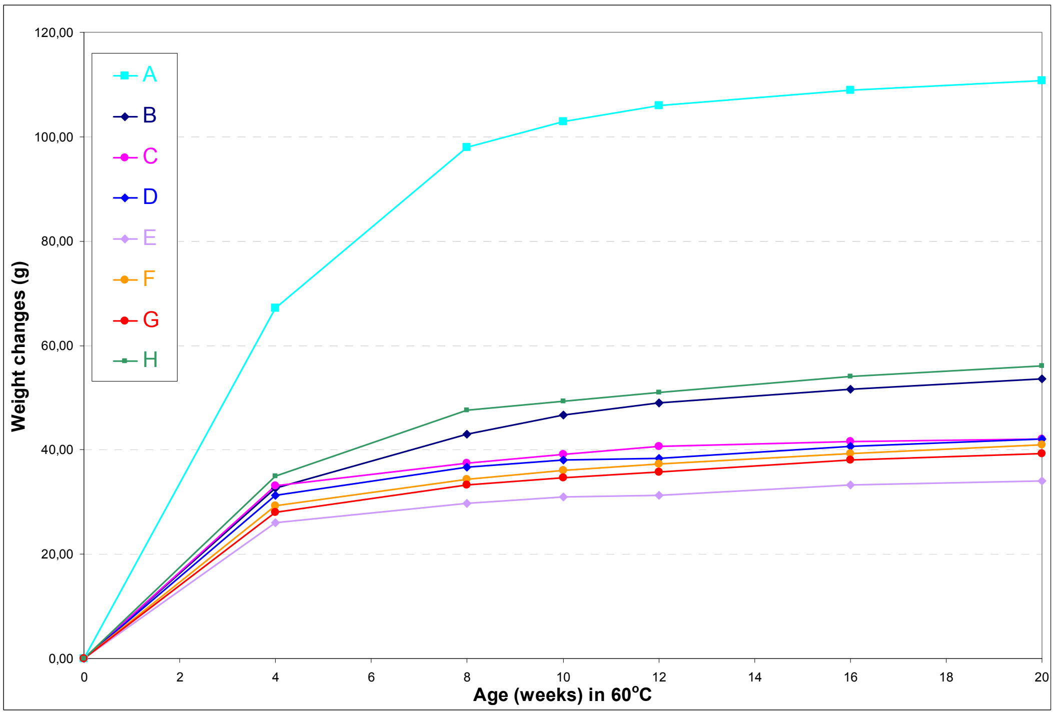

Figure 2: RILEM AAR-4; Weight changes - various aggregates, with same high-alkali cement

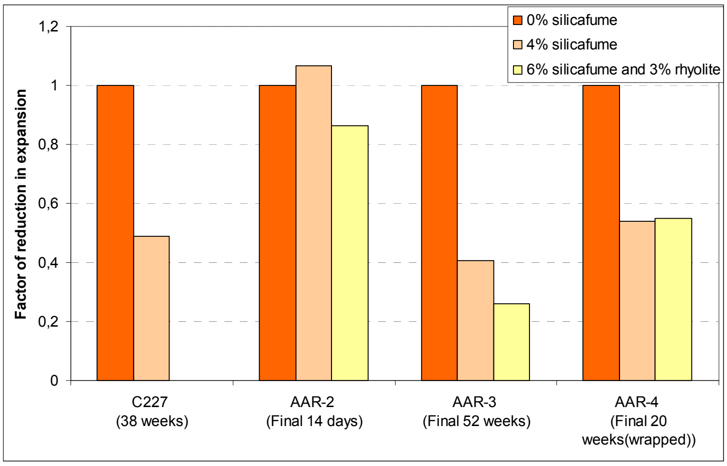

Figure 3: Relative effect of silica fume on the expansion for the different test methods. Test with 6% silica fume and 3% rhyolite according to ASTM C 227 failed.

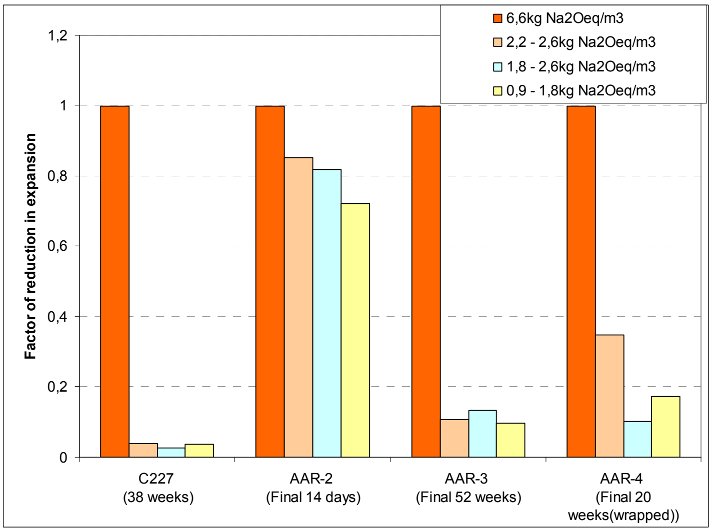

Figure 4: Relative effect of alkali content on the expansion for the different test methods.

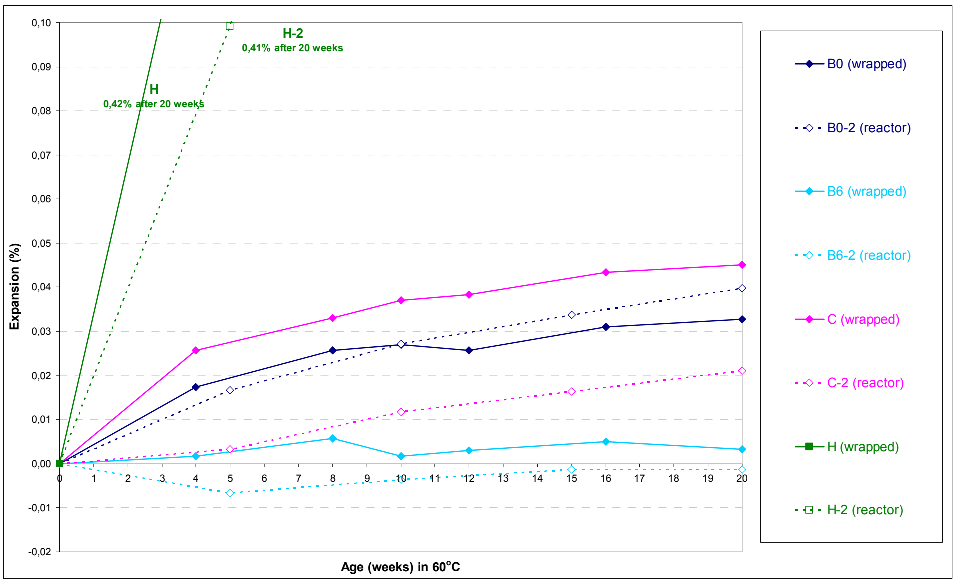

Figure 5: RILEM AAR-4; Comparison of original method (reactor) and alternative method (wrapped).