EXPERIENCE USING THE NORWEGIAN 38°C CONCRETE PERFORMANCE TEST EVALUATING THE ALKALI REACTIVITY OF CONCRETE MIXES AND DIFFERENT BINDER COMBINATIONS

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Abstract

Three methods have been applied in Norway for classifying the alkali reactivity of aggregates; a petrographic method, an 80°C AMBT and a 38°C CPT. According to the Norwegian regulations, the CPT is also specified for performance testing of concrete mixes. For testing of different binders' ability to hinder development of ASR, the assumed most alkali reactive Norwegian aggregates were chosen as reference. During the last ten years almost 150 concrete mixes with binders composed of Portland cement, fly ash, silica fume, ggbfs, LWA fines and different filler types have been tested. This paper summarizes the results, with focus on the advantages of using the Norwegian performance test.

One main finding is that the approved acceptance limits of 3.0 and 6.5 kg Na_2O eq./m^3 for binders with CEM I and Norcem Standard-FA cement, respectively, in combination with all Norwegian aggregate types in common use are regarded as a safe tool.

Keywords: alkali-silica reactions, performance testing, Norwegian experiences, critical alkali limit

1 INTRODUCTION

1.1 Background

Since Alkali-Silica Reaction (ASR) was accepted as a deterioration problem in Norway about 1990, several comprehensive national research projects have been carried out on this subject. These projects have strongly focused on test methods for aggregates and corresponding criteria for the prediction of ASR as observed on Norwegian concrete structures.

The research projects have provided reliable and reproducible testing methods regarding ASR of Norwegian aggregates. Three methods have been applied since the early 90's, a petrographic method (similar to the RILEM AAR-1 method [1]), an 80°C accelerated mortar bar test (AMBT – prism size 40x40x160 mm; similar to the RILEM AAR-2 method [2]) and a 38°C concrete prism test (CPT - prism size 100x100x450 mm – no wrapping of the prisms; similar to the old Canadian CPT [3]). These methods are included in the current Norwegian system for handling the alkali reactivity problem [4,5,6].

More than 15 years of commercial testing of Norwegian aggregates has provided SINTEF a very good overview over the alkali reactivity of aggregates across Norway. In most parts of Norway alkali silica reactive rock types are present in varying quantities in many commonly used concrete aggregates. To be able to utilize these alkali-silica reactive aggregates for production of durable concretes, there is a need for a reliable performance test to evaluate the alkali reactivity of concrete mixes and/or binders resistant to alkali aggregate reactions. Several such performance tests have been used world wide for at least 15 years, mainly to evaluate supplementary cementing materials (SCMs) and Lithium as means for avoiding damaging ASR in concrete. Thomas et al. [7] have recently 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. For example, the main shortcoming of the Canadian 38°C concrete prism test (prism size 75x75x250 mm^3) [8] is the duration of the test (2 years) and that addition of alkalis are required to compensate for leaching effects. Thus the method cannot be used to determine the "critical" alkali content for an alkali reactive aggregate, nor determine how the minimum level of a SCM changes with the concrete

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alkali content. However, research are going on towards improving current test methods and developing alternative tests, for instance within the RILEM technical committee "TC ACS" (2006-2011). Similar work has also been started in USA by the U.S. Department of Transportation [9].

The Norwegian 38°C CPT [5] was in 1996 also specified in the Norwegian guidelines for performance testing of concrete mixes and/or binders [10]. Since then a large number of "job mixes" and binders have been "performance tested" in Norway, mainly on a commercial basis. This paper summarizes and discusses the results from these test series. The main objectives are to reveal the main trends from the tests performed and to document the advantages of using the Norwegian performance test, rather than presenting detailed test results.

1.2 The Norwegian system for performance testing

In 1996 the Norwegian Concrete Association produced a publication ("NB21") giving guidelines for handling ASR in Norway [11]. Based on knowledge gained after 1996, and the fact that the publication now is a harmonised normative reference document to the new concrete materials standard, NS-EN 206-1 [11], a revised version of the publication was provided in 2004 [4,6].

The 2004 edition of "NB21" is divided into two major parts. Part 1 is in formal terms describing the mandate and the use of the publication, and how concrete constituents and concrete recipes shall be tested and evaluated with respect to potential ASR. Individual aggregates and blends of aggregates shall be evaluated by the petrographic analysis as a first step. The evaluation based on result from these analyses can be reassessed by the 80°C AMBT, while the 38°C CPT can be used to reassess the evaluation from any of these tests. For the evaluation of binders and concrete compositions (incl. mortars and shotcrete), only the CPT can be used. The three methods are described in detail in a corresponding publ. from the Norwegian Concrete Association ("NB32") [5].

Part 2 of "NB21" gives advisory guidelines for how the concrete industry can fulfil the requirements given in the Part 1 specifications. It also provides a survey of binders and corresponding alkali contents documented to be suitable for production of ASR resistant concrete containing all types and amounts of Norwegian reactive aggregates. This survey is updated whenever new binders obtain satisfactory documentation.

Based on performance testing combined with field experience [12,13] "NB21" states that all CEM I binders shall be considered to be suited for production of non-reactive concrete containing all types of reactive and/or non-documented Norwegian aggregates up to an alkali content of 3.0 kg Na_2O eq./m^3. If alkali reactive or non-documented aggregates are to be used in CEM I based concretes with a higher alkali content or in concretes containing other binders, the Norwegian regulations require performance testing of the actual "job mix" or the actual binder. In such general testing of different binders' ability to hinder the development of alkali silica reactions, the binders are tested in concrete containing a specified aggregate composition that for Norwegian conditions is considered to be "worst case" with respect to reactivity [5] – see Table 1.

The validity of documentation supplied by performance testing is limited to concrete with composition considered to be no more reactive than was the concrete used for the testing. The reactivity is considered to increase if:

- Alkali content is increased.
- Content of pozzolanic material or other SCMs is decreased.
- Content of reactive rock types is increased beyond the limits specified in the publication.

The acceptance criteria for different types of binders and concrete recipes are differentiated. In general it can be said that:

- CEM I binders and CEM I based concrete compositions containing no pozzolans or other SCMs shall be considered non-reactive if showing 1 year expansion less than 0.050 %.
- CEM I based concrete compositions containing silica fume, concretes based on the fly ash blended CEM II/A-V cement produced by NORCEM in Norway (co-grinding of PFA and clinker) and / or blends of this cement and CEM I shall be considered non-reactive if showing 1 year expansion less than 0.030 %.
- Concrete recipes based on other binders than those mentioned above shall be considered non-reactive if showing 1 year expansion less than 0.030% and at the same time 2 years expansion less than 0.060 %.

A performance test shall be based on one or more mixes. If based on more than one mix, test results shall be plotted in an expansion versus alkali content-diagram as illustrated by Figure 1. Based on the assumption that a linear relation exists between expansion and alkali content, straight lines connecting the plots shall be drawn. If a connecting line and the line illustrating the accepted limit for expansion cross each other, the alkali content limit value for acceptance of non-reactivity is given by the alkali content at the point of intersection subtracted a "safety factor" amounting to 0.2 kg Na_2O eq./m^3. If the above-mentioned crossing of lines does not occur, the alkali content limit value for acceptance of non-reactivity shall be:

- 3.0 kg Na_2O eq./m^3 when all the mixes show expansions exceeding the acceptance value.
- Equal to the highest individual alkali content used within the mixes involved when all the mixes show expansions less than the acceptance value.

In the Norwegian regulations no further "safety factors" are added to take into account any possible alkali leaching from the concrete prisms during testing. This uncertainty in our testing system is currently focused on in the on-going national research activities, as well as in the RILEM task group ACS-P "Performance testing". This is also the case regarding the question if some aggregate types may leach alkalis into the concrete pore water during the test period.

2 OVERVIEW OF PERFORMED TEST SERIES IN NORWAY

2.1 Available test results

Since the performance testing by use of the Norwegian 38°C CPT started in Norway in 1996, the detailed testing procedure has been unchanged [5]. Only a few testing laboratories are approved to perform such performance testing on a commercial basis. As part of the PhD study of Jan Lindgård all available results from the performance test series performed by the two most experienced approved Norwegian laboratories, SINTEF Building and Infrastructure (Trondheim) and NORCEM (Brevik) have been compiled and evaluated. SINTEF has primary performed the testing on a commercial basis for the industry, while NORCEM mainly has tested the performance of various cements in trade or under development [14,15,16,17,18]. All the about 30 concrete prisms test series being part of the PhD study of Bård Pedersen [19] are also included in the review. SINTEF performed all the test series in his study, focusing of the possible mitigating effects of different filler types on ASR.

In total, the review contains results from almost 150 performance test series. These test series include some "job mixes" (i.e. real concrete recipes) and several mixes to determine the critical alkali limit for different aggregate types. However most of the performance test series have aimed at documenting different binder combinations ability to hinder ASR. Reference reactive aggregates are used in these tests series. In addition to different CEM I cements, the binders tested have included fly ash (PFA), silica fume (CSF), ground granulated blast furnace slag (ggbfs), light weight aggregate fines and/or different filler types (mainly produced from alkali silica reactive rock types). The water/binder ratio in the test series has mainly varied between 0.45 and 0.48. If needed to boost the alkali content, NaOH has been added to the concrete mixes.

Table 1 and 2 give an overview of the different aggregate types and the different binder types tested. 45 of the 144 test series are still on-going. Of these, 25 mixes have run for four to 10 years. Of the about 100 finalised mixes, the testing time varied from one to eight years.

2.2 Alkali leaching

In Norway, no systematically measurements have earlier been performed to document if alkalis may leach out from the concrete prisms during testing according to the Norwegian CPT. However, some preliminary measurements have been performed at NORCEM and SINTEF. Leaching measurements were in 2007 included as part of the performance test procedure at SINTEF. To get reliable measurements, all the equipment and storage containers are washed properly and a new lining is applied before new test series are started. At every standard measuring points of time, a 20 ml sample of the water in the bottom of each storage container is collected. At the same time the total amount of water is measured, both by weighing the containers (after removing the prisms) and by measuring the depth of the water. If some of the water has evaporated since the last measurement, water is added after sampling.

Since the middle of 2007 water samples have been collected from all the on-going performance test series at SINTEF. The content of alkalis, Na^+ and K^+, were measured by use of atomic absorption spectroscopy. As a quality control some of the samples were parallel tested in a laboratory at NTNU (the Norwegian University of Science and Technology) using inductively coupled plasma mass spectrometry (ICP-MS). On the basis of these measurements the content of alkalis leached out of the prisms were calculated.

3 RESULTS

3.1 Reproducibility of results

Variation between the three prisms within one test series

To get a view of the reproducibility of the Norwegian CPT, standard deviations and coefficients of variation (c.o.v) for the measured expansions and weight increases of the three prisms within one test series were determined for the about 100 test series performed in SINTEFs laboratory (included the about 30 test series being part of the PhD study of Bård Pedersen [19]). The outcome of these calculations is shown in Table 3, Figure 2 shows a graphical view of the calculated c.o.v. for the measured expansions versus the calculated mean expansions. Figure 3 shows a corresponding graphical view of the calculated c.o.v. for the measured weight increases versus the calculated mean weight increases.

Within laboratory – and multi laboratory variations

A few concrete mixes tested by SINTEF were repeated, some of them up to three times. In addition SINTEF and NORCEM have performed several parallel test series using identical concrete compositions. Figure 4 shows the measured expansion versus exposure time for six such "pairs of concrete mixes". For all the "pairs of mixes", except one, one of the test series is performed by SINTEF and the other test is performed by NORCEM.

3.2 Expansion and weight increase versus exposure time – overall results

Tables 1 and 2 give an overview of the different aggregate types and binder combinations included in the current review of the about 150 Norwegian performance test series performed. In Figure 5, all the measured mean expansions are plotted versus the exposure time (up to 10 years). The same data are given in Figure 6, but only for exposure time up to two years. The corresponding plots of the measured mean weight increases versus the exposure time (up to 10 years) are given in Figure 7.

3.3 Performance testing of binders

As shown in Table 2, most of the performance test series have aimed at documenting different binder combinations ability to hinder ASR. About 60 of these test series have included NORCEM "StandardFA" cement, a CEM II/A-V Portland - fly ash cement with a PFA content of approx. 20 % by weight of binder. In contrast to usual CEM I - PFA combinations, this product is manufactured by co-grinding clinker and PFA, a process that has shown to enhance the ASR mitigating effect. An example of the effectiveness of this cement to suppress ASR is given in Figure 8. All the alkalis in the fly ash are included in the calculated total alkali content of the concrete mixes containing the Portland - fly ash cement. The expansion of these mixes increases with increasing alkali content.

The influence on ASR of adding different filler types produced from alkali reactive rock types was the issue of the PhD work of Bård Pedersen [19]. Selected results are given in Figure 9.

3.4 Critical alkali limit for different aggregate types

Some of the alkali reactive aggregate types in common use in Norway have been "performance tested" to determine the critical alkali limit for different aggregate types. The results from such testing of four of these aggregate types are given in Figure 10.

3.5 Weight increase

Both Norwegian laboratories have been measuring the weight change in addition to the expansion for more than 10 years. The measured mean weight increases versus the exposure time are given in Figure 7. Figure 11 shows a plot of the measured mean weight increase versus the corresponding measured mean expansions at the ages 0.5, 1, 2, 3 and 4 years, respectively.

3.6 Alkali leaching

Most of the water samples collected in the bottom of the storage containers over the last half year in the performance test series at SINTEF have been analysed with respect to alkali content. However, several of the tests are still on-going. Thus, it is too early to present detailed results from these test series in the current paper. The few leaching results from the Norwegian CPT method performed at NORCEM (presented at a RILEM TC ACS meeting in 2007) show some, but limited leaching compared with other concrete prism methods using smaller prisms [7].

4 DISCUSSION

4.1 Reproducibility of results

Variation between the three prisms within one test series

The shaded rows in Table 3 give the standard deviations and the coefficients of variation (c.o.v.) calculated on the basis of all the about 100 SINTEF test series included in the review. In the non-shaded rows all results from test series with mean prism expansion less than 0.010 % are excluded, leading to more reliable results for the calculated c.o.v. for the expansion. This becomes even clearer by looking at Figure 2. As can be seen, calculation of a c.o.v. becomes meaningless for very low expansion values (varies from -200 to +200 %). However, for mean expansion values higher than approx. 0.025 % the calculated values of c.o.v. for the expansion varies in general between 0 and 10 %, with mean values in the range from 6 to 9 %. The variation between the three prisms within one test series is thus regarded to be satisfactory with respect to measured expansion values.

As shown in Table 3 and Figure 3 the variation between the three prisms within one test series is also regarded to be satisfactory with respect to measured weight increases. For expansion values higher than approx. 0.025 % the calculated mean values of c.o.v. for the weight increase are in the range approx. 5.5-7 %, with most single values varying from 0 to 15 %. In general the calculated c.o.v. for the weight increase decreases with increasing weight increase, thus also with increasing expansion (see Figure 11).

Within laboratory – and multi laboratory variations

As shown in Figure 4, the within laboratory variation for parallel test series performed at SINTEF and Norcem is satisfactory. Several other test series (not included in the figure) also confirm this finding, among these the parallel testing performed by the two laboratories within the European research project PARTNER [20].

On tests series cast and measured by SINTEF, Pedersen [19] reported an estimated standard deviation of 0.01 % for the 1-year expansion as based on replicate tests.

4.2 Expansion and weight increase versus exposure time – overall experience

78 of the total 144 performance test series have run for at least 2 years. Of these, 40 concrete mixes have been exposed for 3-10 years. As shown in Figure 5 and 6, the general tendency is that the expansion rates for the most alkali reactive mixes (mainly reference mixes with high alkali content) decrease after an exposure time of approx. 0.5 year. The expansion rates for these mixes become very low or even flatten out after about one to two years of exposure. The main reasons for the reduced expansion rate is assumed to be that some alkalis are consumed in the alkali reaction and the possible influence of alkali leaching.

The expansion rates for the medium reactive mixes, however, have shown to be rather constant up to about 2-3 years of exposure, before decreasing. Some of the approved non-reactive mixes, i.e. mixes with a lower expansion than the critical limits given in the Norwegian regulations [4], have expanded beyond the critical expansion level(s) at later ages. However, most mixes showing non-reactivity still show an expansion below the critical expansion level(s) even up to 10 years of exposure.

The weight increases with time show a similar tendency as the expansions do (see section 4.5).

4.3 Performance testing of binders

Figures 8 and 9 show examples of the advantage of using the performance test. Producers have the possibility to achieve approval for using different binder combinations (e.g. a CEM II Portland – fly ash cement) and/or possible new pozzolanic material (such as fillers produced from reactive rock types) in combination with alkali reactive Norwegian aggregates. In this way a number of actual "job mixes" may be pre-documented. However, normally a reference reactive aggregate combination is used in these tests [5], giving a general approval for using the tested binders in combination with all Norwegian alkali reactive aggregates up to the measured critical alkali limit subtracted a "safety factor" amounting to 0.2 kg Na_2O eq./m^3 (see section 1.2). No further "safety factors" are added to take into account any possible alkali leaching from the concrete prisms during testing. However, some extra security is built in the Norwegian regulations, since all the alkalis in the additions (such as fly ash, silica fume and ggbfs) are included in the calculated total alkali content of the concrete mixes.

4.4 Critical alkali limit for different aggregate types

The lines drawn in Figure 10 at the alkali content 3.0 kg Na_2O eq./m^3 and the expansion 0.050 %, respectively, represent the Norwegian critical limits for a fine/coarse aggregate combination combined with CEM I cements. This limit is based on testing of critical alkali limits for different aggregate types and on a comprehensive Norwegian research project that concluded that the Norwegian concrete prism test results appear to echo the field performance of concrete adequately [12,13].

One of the mixes with the highly reactive cataclasite revealed a disturbing high one year expansion for an alkali content of only 3.1 kg Na_2O eq./m^3. However, the cataclasite (included in the testing program in the PARTNER project, named "N1" [20]) is not in commercial use for concrete. Most alkali reactive aggregate types in common use in Norway are far less reactive than this cataclasite. Two examples of more moderate reactive Norwegian aggregates, with critical alkali limits between 4.5 and 4.8 kg Na_2O eq./m^3, are also shown in Figure 10. Thus, the general Norwegian acceptance alkali limit of 3.0 kg Na_2O eq./m^3 for CEM I binders are regarded as safe.

4.5 Weight increase as a quality control

Standard procedure in the Norwegian CPT is to measure both the expansion and the weight increase of the prisms. The weight increase is rarely reported, but acts as a quality control of the moisture conditions within the storage containers. As an example all the three prisms in one of the long term test series at SINTEF reduced some weight from one to two years of exposure. At the same time the expansion of the prisms decreased. By control of the storage containers a crack was observed in the cover, leading to a moisture content within the storage container less than 100 % RH.

As shown in Figure 11, the prism weight increases with expansions. In all the about 100 SINTEF test series, the mean weight increase after 0.5 to 4 years of exposure was at least 0.20 %, even for the concrete mixes that exhibited shrinkage. However, some of the mixes revealed a slight weight loss during the first weeks – see Figure 7. Some of the test series performed at NORCEM revealed a lower weight increase than 0.20 % at age 0.5 and 1 year of exposure. The reason for this is not known. The samples having weight loss were concrete mixes of CEM II/A-V and very fine ground CEM I (Blaine approx. 600 m^2/kg) that might cause early age shrinkage. The weight loss results are not typical for the NORCEM laboratory.

The calculated values for the correlation factor R^2 between the measured weight increases and the expansions in Figure 11 were approx. 0.80 at the ages 2, 3 and 4 years. R^2 was somewhat lower at the ages 0.5 and 1 year, mainly due to the lower measured weight increase as discussed above.

In the proposals for the two RILEM concrete prism tests, RILEM AAR-3 (38°C) [21] and RILEM AAR-4 (60°C) [22], requirements are given to the prism weights measured to ensure that sufficient water is present in the system. According to these two methods all the measurements relating to a single test prism (with cross-section 75±5 mm and length 250±50 mm) should be discarded if the weight loss recorded is greater than 20 g. This means that weight loss up to about 0.5-0.6 weight-% is allowed. In light of the results obtained in performance testing with the Norwegian CPT, this requirement seems far too little restrict. A little weight loss may be recorded in the first few weeks (up to maximum 0.2 weight-% was recorded after one week of exposure in a few mixes in the reviewed tests), but if the prisms still show a significant weight loss after a longer time of exposure this is most likely due to insufficient water present in the system. Thus, a too low expansion is recorded.

4.6 Alkali leaching

As mentioned in section 3.6, it is too early to present detailed results from the measured alkali content in the water samples collected in the bottom of the storage containers in the on-going performance tests at SINTEF. The preliminary results confirm the findings at Norcem. Further, they show that the possible influence of alkali leaching on the measured expansions in the Norwegian CPT can not be neglected, even though we use rather large concrete prisms (cross-section 100 mm and length 450 mm). Thus, the leaching issue must be looked further into, as we already has initiated at SINTEF during 2007.

5 CONCLUSIONS

Since the performance testing by use of the Norwegian 38°C CPT started in Norway in 1996, almost 150 performance tests have been performed by the two most experienced approved Norwegian laboratories, SINTEF Building and Infrastructure and NORCEM. These tests include some "job mixes" (i.e. real concrete recipes) and several mixes to determine the critical alkali limit for different aggregate types. However most of the performance tests have aimed at documenting different binder combinations ability to hinder ASR. In these tests reference reactive aggregates are used. Based on the review of the results from these tests the following conclusions may be drawn:

- Despite the long testing time required, the Norwegian system for performance testing has proven to be an advantageous tool to document critical alkali limits for binders and aggregates.

- The variation between the three prisms within one test series (with respect to measured expansion and weight increase) and the within laboratory variation for parallel tests performed at SINTEF and NORCEM are regarded to be satisfactory.
- The general tendency is that the expansion rates for all the concrete mixes are highest in the first 0.5-3 years of exposure, before decreasing considerable or for several mixes flatten out. The expansion rates decrease earliest for the most alkali reactive mixes.
- Most mixes showing non-reactivity still show an expansion below the critical expansion level(s) even up to 10 years of exposure.
- The weight increases with time show a similar tendency as the expansions do.
- The weight of the prisms increase with increasing expansions. In all the about 100 tests performed at SINTEF the mean weight increase after 0.5 to 4 years of exposure was at least 0.20 %, even for the concrete mixes that shrunk. However, some of the mixes revealed a slight weight loss during the first weeks
- The review strengthens the importance of using weight measurements as a quality control of the moisture conditions within the storage containers.
- Even though one of the mixes with the highly reactive reference cataclasite revealed a disturbing high one year expansion for an alkali content of only 3.1 kg Na_2O eq./m^3, the general Norwegian acceptance alkali limit of 3.0 kg Na_2O eq./m^3 for CEM I binders in combination with all Norwegian aggregate types in common use is regarded as a safe tool.
- By using the Norcem Standard-FA cement, containing about 20 % PFA, a general acceptance alkali limit of 6.5 kg Na_2O eq./m^3 are approved in combination with all Norwegian aggregate types in common use.
- The preliminary results of measured alkali content in the water samples collected in the bottom of the storage containers in the on-going performance tests at SINTEF show that the possible influence of alkali leaching on the measured expansions in our Norwegian CPT can not be neglected, even though we use rather large concrete prisms (cross-section 100 mm).

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Table 1: Overview of aggregates types included in the reviewed performance test series performed in Norway in the period 1996-2007

Aggregate type		**Number of tests** [1]
Fine (0-5 mm)	**Coarse (5-20 mm)**	
Reference-I (NR) [2]	Reference-II (R) [3]	26
Reference-III R [4]	Reference-II (R) [3]	40
Reference-IV R [5]	Reference-II (R) [3]	5
Reference-IV R [5]	Reference-I (NR) [2]	21
Different types [6]	Different types [6]	49
Recycled glass (R)	Recycled glass (R)	3
	Sum	**144**

[1] 102 of the tests are performed at SINTEFs laboratory (include the 29 tests being part of Bård Pedersens PhD study [15]). The remaining 42 tests are performed by Norcem.
[2] Non-Reactive (NR) natural gneiss/granite aggregate. [3] Reactive (R) chrushed cataclasite.
[4] Natural aggregate (R) with claystone, siltstone and phyllite as the main reactive rock types.
[5] Natural aggregate (R) with mylonite, cataclasite, greywacke and phyllite as the main reactive rock types.
[6] Primary alkali silica reactive aggregate types. 25 of the mixes include a crushed mylonite [19].

Table 2: Overview of binder types included in the reviewed performance test series performed in Norway in the period 1996-2007

Binder type	**Total number of tests**	**Number of the tests added CSF** [5]
CEM I [1]	47	8
CEM I + CEM II Portland fly ash cement [2]	39	16
CEM II Portland fly ash cement [2]	22	7
CEM II Portland slag cement [3]	4	---
CEM I + fly ash added separately	5	---
CEM I + added LWA fines	4	---
CEM I + added different filler types [4]	22	---
CEM I + other admixture added	1	---
Sum	**144**	**31**

[1] All the cements, except the Portland slag cement, are produced by Norcem (part of the Heidelberg Cement Company). Different types of CEM I have been tested.
[2] CEM II/A-V including about 20 weight-% fly ash of the binder.
[3] CEM II/B-S including at least 32 % ggbfs.
[4] Most filler types were produced from alkali reactive aggregates [19].
[5] CSF = Condenced Silica Fume.

Table 3: Calculated standard deviations and coefficients of variation (c.o.v) for the measured expansions and weight increases of the three prisms within one test series were determined for the about 100 test series performed in SINTEFs laboratory,

Exposure time (months)	Expansion				Weight increase				Comments
	4	6	12	24	4	6	12	24	
Standard Deviation (%)	0.002	0.002	0.005	0.008	0.027	0.030	0.032	0.035	Included all SINTEF results
	0.003	0.003	0.006	0.008	0.029	0.031	0.032	0.035	Excl. tests with expansion < 0.010 %
Coefficient of variation (%)	-11.5	6.0	10.7	6.8	8.8	7.8	6.4	5.3	Included all SINTEF results
	8.9	6.1	8.1	6.6	6.6	6.8	6.0	5.3	Excl. tests with expansion < 0.010 %

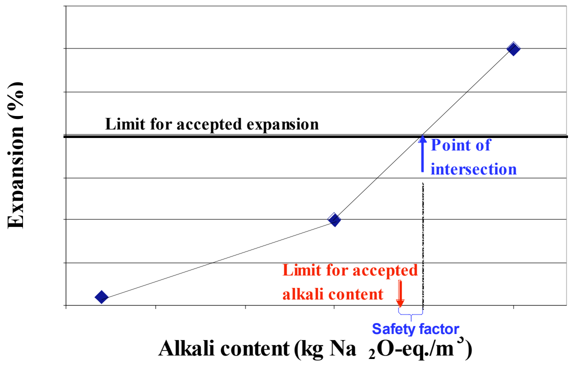

Fig. 1: Principle diagram for determination of acceptance limit for alkali content.

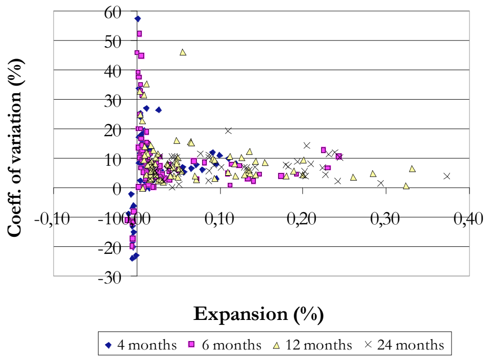

Figure 2: Coefficients of variation (c.o.v) for the expansions of the three prisms within one test series (about 100 SINTEF test series).

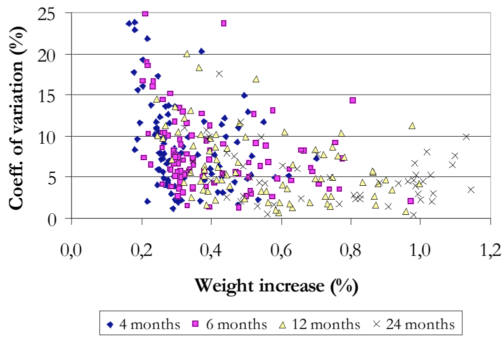

Figure 3: Coefficients of variation (c.o.v) for the weight increases of the three prisms within one test series (about 100 SINTEF test series).

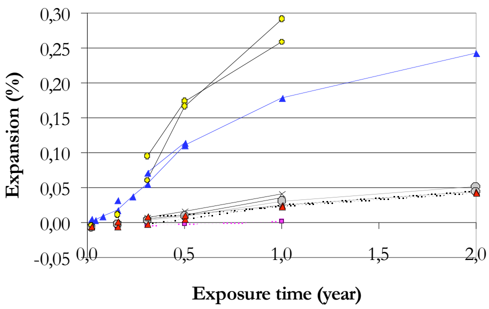

Figure 4: Expansion versus exposure time for six parallel concrete mixes.

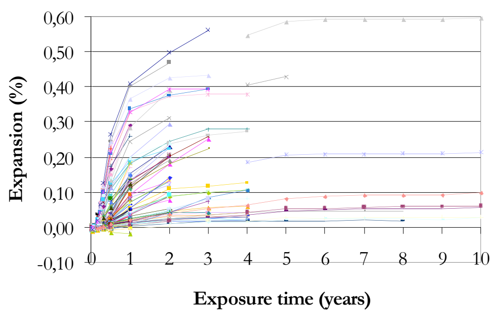

Figure 5: Expansion versus exposure time for 144 performance test series.

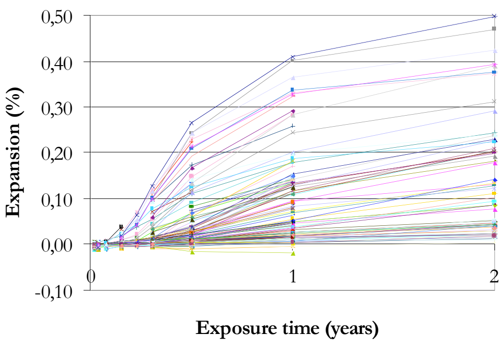

Figure 6: Expansion versus exposure time (up to two years) for 144 performance test series.

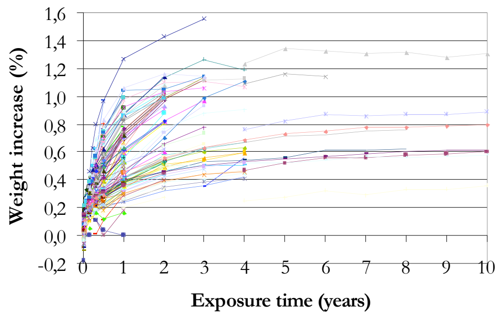

Figure 7: Weight increase versus exposure time for 144 performance test series.

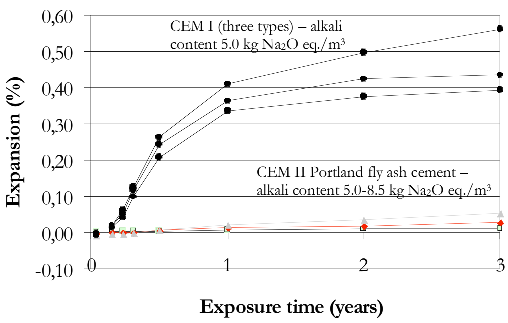

Figure 8: Expansion versus exposure time for 6 binders tested with the aggregate combination Ref-I (NR-fine) + Ref-II (R-coarse) -see Table 1. The CEM II Portland - fly ash cement contains 20 % PFA (80 kg/m³).

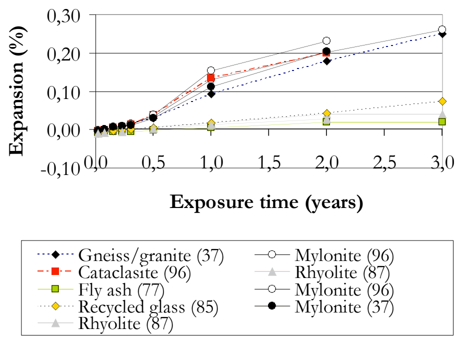

Figure 9: Expansion versus exposure time for concretes containing different fillers (0-0.125 μm) and a reactive mylonite aggregate [19]. The number in () is kg filler pr m³. The alkali content in all mixes was about 5.0 kg Na_2O eq. /m³

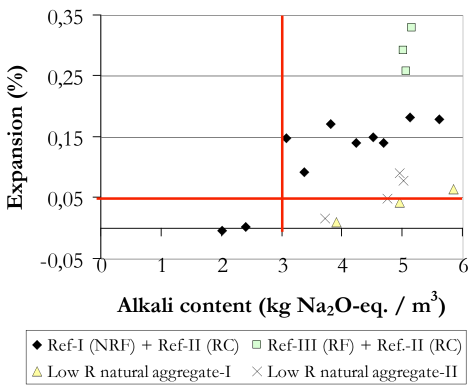

Figure 10: Expansion versus alkali content for four Norwegian aggregate types after one year of exposure (F=Fine and C=Coarse aggregate). The lines drawn at 3.0 kg Na_2O eq. /m³ and 0.050 %, respectively, represent Norwegian critical limits.

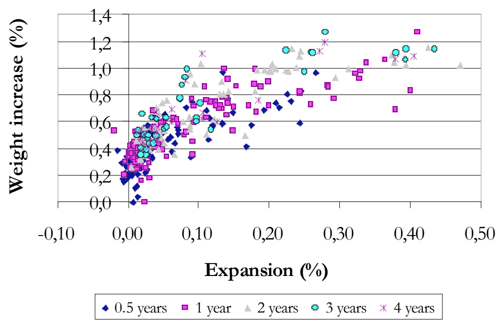

Figure 11: Weight increase versus expansion (at the ages 0.5, 1, 2, 3 and 4 years, respectively) for the 144 performance test series.