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THE EU “PARTNER” PROJECT- EUROPEAN STANDARD TESTS TO PREVENT ALKALI REACTIONS IN AGGREGATES. FINAL RESULTS AND RECOMMENDATIONS

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1 INTRODUCTION

This paper presents the main results of PARTNER (2002-2006), a project partly funded by the European Community, which had the overall objective of establishing a unified test procedure for evaluating the potential alkali-reactivity of aggregates across the different European economic and geological regions. It is intended that the results of the project will be implemented by CEN, European Committee for Standardization, in the form of new standard methods of test and specifications.

In the project the tests developed by RILEM, and some established regional tests, were evaluated for their suitability for use with the wide variety of aggregate and geological types found across Europe. The results of the accelerated laboratory tests were calibrated against the behaviour of these aggregates in real concrete structures and in field test sites. The precision of the tests was then determined by inter-comparison trials using a common set of materials. Additionally, a petrographical atlas of the potentially alkali-reactive rocks in Europe was produced and published, an education programme undertaken and recommendations made to the relevant technical committees of CEN. The project had 24 Partners from 14 countries, covering most of Europe, from Iceland to Greece. Some of the participating laboratories had no/minor experience with the actual methods in advance.

2 THE TEST PROGRAMME

2.1 General

Details of the test programme, the aggregates, the methods of test and the results are given in a series of technical reports published by the Norwegian research institute SINTEF [1], [2], [3] [4] [5]. These reports may be freely downloaded (www.farin.no/english). Additionally, four papers covering parts of the project in more detail were submitted to the 13th ICAAR conference in Trondheim [6], [7], [8] and [9].

The main candidate methods of test were those developed by the RILEM committees TC106 and TC191-ARP. Additionally, several methods of test that were already established in particular European regions were included in order to see if these could be replaced by the RILEM methods for the particular geological types of aggregate for which they had been developed.

The field site tests were included to provide a means of calibrating the accelerated tests against behaviour in conditions closer to those experienced by actual structures.

2.2 The aggregates

The aggregates to be used for testing were chosen on the basis of a questionnaire completed by each partner regarding local potentially reactive materials. The final list contained 22 different types of aggregates from 10 different countries (Table 1). The aggregates were selected with the purpose of covering most types of reactive aggregates throughout Europe. Additionally, non-reactive reference aggregates were tested.

2.3 The test programme for testing the aggregates with the different methods

Laboratory test methods – general

The full list of methods, with brief descriptions, and references to the original published methods [10-17] are given in Table (2). The tests were performed according to these methods, amplified by detailed instructions prepared for each method. Some supplementary information about the methods is given below.

RILEM AAR-1 Petrographic method

The petrographic method [10] is a test method used as a “first step” to assess the potential alkali-reactivity of concrete aggregates. The method is carried out by two mutually beneficial techniques; a standard petrographic examination of the aggregate particles and a detailed microscopical examination of thin-sections which may incorporate point-counting. An initial inspection of the aggregate material should be undertaken to assess which technique(s) should be employed.

This RILEM AAR-1 petrographic method allows for three different technique(s)/ procedure(s) to determine the potential alkali-reactivity of a particular aggregate sample:

1. Particle separation: After separation, selected particles can be thin sectioned to determine the microscopical reactivity related characteristics. The procedure is known to be somewhat uncertain and is not suited for unfamiliar or “complex” aggregate types.
2. Point counting technique: Considered to be the most accurate method for identification of the different rock types.
3. Whole rock petrography: If a crushed rock aggregate has uniform characteristics, then a thin section of the total aggregate particles can be produced for the determination of its potential alkali-reactivity.

All of these procedures are useful in establishing the potential alkali-reactivity of an aggregate, and none should be discounted as a technique of determining reactivity. The technique selected should be based on an initial macro-examination of the aggregate sample received. In reference to the RILEM AAR-1 method, it is not compulsory to use only one of these specified techniques. However, in the project report [1] and in the current paper only results from the point counting analyses are included.

When applying the point counting technique, an adequate number of representative particles must be included in the thin sections prepared. Guidance on minimum number of particles in the different fractions for thin sections of size 50x30 mm² is given in the method [10]. E.g. for the coarse fractions (>4 mm), two thin sections of the fraction 2/4 mm (after crushing) should be prepared (minimum 300 particles). For the sand fractions (≤4 mm) two thin sections of the fraction 2/4 mm (minimum 300 particles) and one thin section of the 1/2 mm fraction (minimum 800 particles) should be prepared. The method allows the analysis of one thin section of the fraction <2 mm (minimum 1500 particles) as an alternative to the 1/2 mm fraction. In the PARTNER project, one thin section of the 0.063/1 mm fraction was prepared for most fine aggregates (in addition to the 1/2 mm fraction).

The point counting technique is carried out along traverses in regular increments in two directions to form a virtual orthogonal grid. It is important that point-counting covers the whole thin-section. During the point-counting, the operator must identify and group all rocks and minerals (i. e. provide

an assessment of both the reactive and non-reactive ones) located under the cross hairs at each point on the grid. Note that a minimum of 1000 points (excluding points falling on to resin) should be counted for all the counted fractions. A statistically sound quantitative estimate of the various components can only be made if the entire thin section is covered and if the virtual grid is adapted to the size of the mineral crystals. Additionally, the number of points may significantly exceed the number of particles, as several points may be counted across some larger particles.

During the point counting process there are two different “procedures” in use. In some countries, it is common to determine the constituent and thus the reactivity assessment of the individual point which is directly under the crosshairs rather than a determination of the reactivity of the entire aggregate particle. An evaluation of the reactivity of the whole particle is, however, common to use in other countries, e. g in Norway. An example; all cross hair points placed within a sandstone particle is recorded as sandstone. However, when particles consist of more than one type of rock e.g. sandstone with quartz vein, the cross hair point falling on to the sandstone should be recorded as sandstone, and cross hair points falling on to quartz vein should be recorded as quartz vein material. To determine which procedure is to be used, the experience with the aggregates within each country should be taken into account.

As a basis for calculating the total percentage of “reactive/possible reactive” rock types in an aggregate, each of the rock types detected should be placed, based on the petrographers experience, in one of the three “reactivity classes”;

- I. very unlikely to be alkali-reactive
- II. alkali-reactive uncertain
- III. very likely to be alkali-reactive.

Experience within some regions and with particular materials (i.e. highly metamorphic rocks) has shown that a determination of the quartz grain size within a particle is important in the assessment of the reactivity potential of that material. In such a rock (aggregate), the percentage of the material containing these varying sizes of quartz crystals is essential in the overall determination of the potential alkali-reactivity. However, at this stage the RILEM AAR-1 Petrographic method should

primarily attempt to report the reactivity potential of such constituents based on the petrographer's own experience, which, however, can result in significant variability in the test results.

RILEM has presented various acceptance criteria for RILEM test methods in assessments of alkali-reactivity potential [18]. The criteria are partly based upon the outcome of the PARTNER project. Regarding the petrographic method, RILEM points out that acceptance and experience with reactive constituents differ between countries, and thus, final assessment and classification should follow any national or regional experiences, recommendations and specifications. Assessments of alkali-reactivity potential of the petrographic results obtained in the current research project were based upon evaluations among petrographers gathering together at workshops within this project. In addition, Norwegian petrographic acceptance criteria were considered, as Norway have used the petrographic method for many years, and have published a set of critical requirements for the quantity of reactive constituents in aggregates [19].

RILEM AAR-2 Accelerated mortar bar method

In the RILEM AAR-2 Accelerated mortar bar test [11], three mortar prisms are cast with the test aggregate and a reference high alkali cement. The aggregate is either natural sand or a crushed aggregate with a grading made to a certain specification. After demoulding, the prisms are stored for 24 hours in water at 80°C after which their initial length is measured. Then the prisms are submerged in 80°C 1M sodium hydroxide solution for 14 days during which at least three length measurements are taken. The expansion is calculated, and the mean of the expansions of the three prisms after 14 days are given as the result.

In this PARTNER test programme, in addition to testing the different aggregates, a comparison was made of the effects of using the short (40x40x160 mm – RILEM-type) and long (25x25x285 mm – ASTM-type) bars, and, for those aggregates where both coarse and fine fractions existed, the results of testing the crushed coarse fraction were compared with those of the fine fraction.

The RILEM acceptance criteria [18] for the interpretation of the results of AAR-2 have not yet been finally agreed. However, on the basis of trials carried out by RILEM on aggregate combinations of

known field performance from various parts of the world, it seems that results in the test (after the standard 14-days exposure time, using 'long thin' 25x25x250-300 mm specimens) of less than 0.10 % are likely to indicate non-expansive materials, whilst results exceeding 0.20 % are likely to indicate expansive materials. It is not currently possible to provide interpretative guidance for results in the intermediate range 0.10 % to 0.20 % and, for all practical purposes in the absence of additional local experience, aggregates yielding AAR-2 results in this range will need to be regarded as being potentially alkali-reactive.

Concrete prism methods

In this programme, five concrete prism tests were evaluated [14-17]:

- RILEM AAR-3 Concrete prism method (storage at 38°C)
- RILEM AAR-4 Accelerated concrete prism method (storage at 60°C)
- RILEM AAR- 4 Alternative accelerated concrete prism method (storage at 60 °C)
- German concrete test method (storage at 40°C)
- Norwegian concrete prism method (storage at 38°C)

The details of the methods are given in the references, see Table (2). In general, all the methods monitor the expansion and the weight change of concrete specimens containing the test aggregate and made with high contents of a high alkali cement and which are stored in conditions of high humidity and elevated temperatures. For RILEM AAR-3 and the German and Norwegian methods, the storage period is quite long, 9 months or a year, but for the RILEM AAR-4 methods the exposure period is reduced to 20 weeks (or even 15 weeks) by use of the higher temperature of storage (60°C). RILEM have recently renamed the AAR-4 method, and named it “AAR-4.1” when applied for testing aggregates [15]. However, in this paper, the method is consequently called “AAR-4”.

The RILEM acceptance criteria [18] for the interpretation of the results of AAR-3 and AAR-4 have not yet been finally agreed. However, on the basis of trials carried out by RILEM on aggregate combinations of known field performance from various parts of the world, it seems that results in the AAR-3 test (usually after 12 months) of less than 0.05 % are likely to indicate non-expansive materials,

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

The acceptance criterion for a non-reactive aggregate combination in the German test method [16], is expansion less than 0.06 % after nine months of exposure. The zero readings are taken at 20°C, while the other measurements are taken without cooling the prisms. Thus, the critical limit corresponds to a limit of approx. 0.04 %, if the prisms had been cooled to 20°C before measuring. In the Norwegian test method [17], the critical limit applied varies from 0.040 % to 0.050 % after one year of exposure depending on the aggregate combination tested [19].

Laboratory test programme

The test programme took into account the need for a sufficient number of tests on each aggregate type using each of the main (RILEM) methods and the experience and budgets of the participating laboratories. For the regional (i.e. Danish-, German- and Norwegian) methods, a reduced programme was undertaken in a few laboratories experienced with these methods.

The numbers of laboratories who participated in the evaluation of each method, the numbers of aggregate types tested according to the different methods, and the total numbers of single tests performed were as follows:

RILEM AAR-1	13 ¹ laboratories;	22 aggregate types;	in total 123 single analyses
RILEM AAR-2	16 ² laboratories;	22 ³ aggregate types;	in total 75 single tests
RILEM AAR-3	10 laboratories;	19 aggregate combinations;	in total 48 single tests
RILEM AAR-4	6 laboratories;	18 aggregate combinations;	in total 59 single tests
RILEM AAR-4 Alt.	3 laboratories;	14 aggregate combinations;	in total 22 single tests
Norwegian	2 laboratories;	10 aggregate combinations;	in total 13 single tests
German	1 laboratory;	10 aggregate combinations;	in total 10 single tests
Danish TI-B51	3 laboratories;	25 ⁴ aggregate types;	in total 37 single tests
Chatterji test	3 laboratories;	14 aggregate types;	in total 26 single tests

¹ Six of the laboratories classified themselves as experienced in performing petrographic analysis.

² Eight laboratories used the 40x40x160 mm prisms (RILEM-type) and eight used the 25x25x285 mm prisms (ASTM-type).

³ For some of these, both the coarse and the fine fraction were tested separately.

⁴ Included six extra aggregate types (five from Iceland and one from Norway).

In total, 413 individual tests were performed within the PARTNER project. The total amount of aggregate needed by the laboratories were calculated, collected by a partner in the particular country, grading, density and water absorption measured and appropriate amounts despatched to the participating laboratories. A reference high alkali cement (1.26 % Na₂O-eqv.) was provided by Norcem who despatched the needed amounts to the laboratories.

The field site tests

These tests were undertaken as a means of evaluating the reliability of different laboratory test methods. Different climatic conditions representative for Europe were covered in order to take into account the influence of different environmental conditions. Furthermore, it is unclear if concrete that is partly immersed in water will exhibit faster and higher degrees of deterioration due to alkali silica reaction (ASR) than a concrete that is only exposed to ambient rainfall. As a consequence, one cube was stored with its base in a tray filled with water (wet storage) and the other was exposed only to ambient rainfall (dry storage). In laboratory tests, it has earlier been found that samples containing

reactive aggregates showed higher degrees of reaction if exposed to salt solutions instead of water [20-22]. Therefore, de-icing salts may trigger and/or accelerate a deleterious ASR in concrete with reactive aggregates. However, results show that the reaction could be different at normal temperatures as compared to elevated laboratory temperatures [23]. To study the influence of alkali supply by de-icing salts under realistic condition, specimens were stored in southwest of Sweden without salt at a field test site in Borås and with salt alongside a highway between Borås and Gothenburg.

For the field site tests, all the cubes representing one concrete mix (i.e. one aggregate type) were cast at one laboratory (generally in the country of origin of the aggregate) and transported to all the other laboratories (field test sites). Thirteen aggregate combinations (Table 3) produced at five laboratories were evaluated in this way on eight different field sites from Norway to Spain (Figure 1). The mean monthly temperature and precipitations for each field site are given in Figure (2).

For each site, two 300 mm concrete cubes were prepared with the aggregate combination used in the concrete prism tests. The concrete mixes were the same as those used in the RILEM AAR-3 and AAR-4 specimens, i.e. they were made with relatively high cement content ($440\text{kg}/\text{m}^3$) and high alkali Portland cement (1.26 % Na_2O -eqv.). No air entraining agent was added to the concrete mix. The cubes were kept for one day in the moulds, de-moulded and stored indoors for 6 days in a humid environment before being transported to the different field sites.

At the different field sites, two pairs of reference studs were glued on the top surface and on two adjacent side faces, before the cubes were exposed outdoors. All cubes were stored in the same direction in relation to the four cardinal points to minimize deviations between the labs resulting from different exposure to direct solar radiation.

During exposure, one cube was stored with its base in a tray filled with water (wet storage) and the other was exposed only to ambient rainfall (dry storage) (Figure 3). The tray was filled with water to simulate a permanently wet concrete, so that the bottom of the first cube was immersed 50 to 60 mm in water during the whole testing time. The reference points at the bottom of the first cube were always above water level enabling length change measurements.

For the detection of possible deterioration due to ASR, the dimensions of the cubes at the top surface and two adjacent side faces as well as the crack width were determined periodically (first 2½ years every three months, afterwards every half year). Some laboratories have only measured once a year during the summer season. The measurements were done at the field site. Extreme temperatures should have been avoided, and in the procedure it is recommended to undertake the measurements at the same approximate time in the day, i.e. mid morning, and then at the same temperature as the reference measurements undertaken before exposure of the cubes.

3 RESULTS

RILEM AAR-1 Petrographic method

All the detailed results from the 123 single petrographic analyses were collected and evaluated. Table (4A) and (4B) present the results from all the point counting analyses performed by the participating laboratories. The following results are presented for each of the aggregate samples:

- Origin (country)/name of sample (see also Table 1)
- Type of aggregate (i. e. main rock type(s))
- Fraction investigated (e.g. 4/8 mm)
- Sum of suspicious rock types, i. e. the “reactivity classes” II and III (volume percentage within the aggregate fraction) [on the web page (www.farin.no/english) the detailed results for each of the three “reactivity” classes are available in an Excel file]
- Field performance (i. e. damage due to ASR documented?)
- Results in agreement with field performance?

For fine aggregates (F; < 4 mm) results from point counting of each of the fractions 2/4 mm, 1/2 mm and 0.063/1 mm were reported separately. However, this was not always the case by some laboratories. Some aggregates have been examined by up to eight different laboratories according to the same petrographic procedure.

RILEM AAR-2 Accelerated mortar bar method

The detailed results of the testing and expansion graphs for each aggregate are given in the published report on the method [2] and are summarized in Table (5).

Concrete prism methods

The detailed results for all the methods and expansion graphs for each aggregate combination are given in the published report on the concrete methods [3]. Two examples of expansion graphs for a “normally” reactive and a ”slowly” reactive aggregate combination are given in Figures (4 and 5), respectively. The results are summarized in Table (6), where the aggregates are grouped into three categories according to their reported field behaviour (Table 1); aggregate combinations that react in “normal” timescales (5-20 years), ”slowly” reactive aggregates (+15-20 years) and non-reactive aggregates.

The AAR-3 results obtained at two of the ten laboratories performing this test are omitted from the paper. The reason is that the one year values are missing from one of the laboratories (4 single tests). The other laboratory obtained zero expansion (i.e. 0.00 %) after one year of exposure for all the three aggregates tested (B1, F3 and It2, respectively). Thus, they have probably not been able to completely follow the testing procedure.

The field site tests

In 2008, the samples had been exposed in the field sites for approximately four years. This time is too short for “slowly” reactive aggregates to cause a deleterious ASR in concrete. Thus, only preliminary conclusions are possible. The maximum expansion and the maximum crack width of the cubes are summarized for each aggregate combination and field site in Table (7) for cubes that were partly immersed in water and in Table (8) for cubes that were exposed only to ambient rainfall. After approx. one year of exposure, a new “zero” measurement was necessary because some laboratories had problems with the determination of dimension changes of the cubes or the use of the provided result files. Thus, the expansion values presented in the two tables represent approx. three years of outdoor exposure.

Extensive expansions >0.04 % which have occurred since the new “zero” measurement in June 2005 and cracks ≥ 0.20 mm which occurred after four years of testing are highlighted (in grey) in the Tables (7) and (8). Expansion in excess of these levels is an indication that a deleterious ASR might have taken place. The Figures (6-11) show the mean expansions and crack widths for six of the reactive aggregates. In the Figures (12-15), detailed expansions values (i.e. on the top and on two adjacent side faces) for two of these aggregate types measured at three field sites are presented.

4 DISCUSSION

4.1 RILEM methods and field site tests

RILEM AAR-1 Petrographic method

Variation between laboratories with respect to evaluation of aggregate reactivity

Thirteen laboratories, both experienced and inexperienced, have performed petrographic analyses according to the AAR-1 method. Before the testing program started, about one half of the petrographers had participated in one or two internal petrographic workshops in the PARTNER project, where selected European aggregate types were examined microscopically and the observations “discussed”. No other co-ordination was made between the laboratories.

In the further discussion, focus is made on the variation between the laboratories with respect to the sum of rock types detected within the “reactivity classes” II+III (i.e. the suspicious rock types with respect to ASR).

The overall experience from the testing program is that the spread in results between the laboratories for about half of the aggregate types is very high, also between some of the six laboratories performing the test on a regular basis. For 8 of the 22 aggregate types (D1, D2, G1, G2, It1, It2, UK2 and P1), the number of rock types detected by the participating laboratories within the “reactivity classes” II+III varies from less than 15 % to more than 85 % (Table 4A and 4B). The rock names used also vary significantly.

However, for four of the six most experienced laboratories, the majority of the reported results seem to be more reliable. The cases where also these laboratories from time to time deviate from the average/median results, are mainly connected to the aggregate types D1, D2, It1 and UK2. These aggregate types are not familiar for most of these experienced petrographers, thus the importance of local knowledge about the reactivity of different alkali reactive aggregates is obvious.

The majority of the results reported from the two remaining experienced petrographers deviates much from the average/median results. For one of these laboratories, the sum of aggregate types classified in the “reactivity classes” II or III is in many cases somewhat lower than reported from the other laboratories. For the second of these laboratories, the percentage of aggregate types classified within the “reactivity classes” II or III is in most cases much higher than for all the other laboratories (also the inexperienced ones).

The other examined rock types were classified by different laboratories as follows:

- Sandstone: class I by several laboratories, class II or III by other laboratories
- Siltstone: class I by one laboratory, class II or III by other laboratories
- Flint: different types of flint detected/named by different laboratories (often named chert by several laboratories); the classification of reactivity also varies a lot - all three “reactivity classes” are used

This result is only valid for the examined aggregate sample of specific quarries. N.B. This is a general classification of rock types into reactivity classes according to RILEM AAR-1. However, a petrographer’s detailed knowledge of local aggregates can change this classification. Having said this, it is important to bear in mind the results from the field exposure sites. Some aggregates react slowly in one climate and much quicker in another climate. The regional knowledge about reactivity can’t therefore always be transferred to the use in another climate, e.g. when exporting aggregates.

Link to field performance

Information about the field performance of the 22 “PARTNER aggregates” is given in the last column in Table (1). The averaged results from the petrographic analyses of almost all the 22

aggregate types (Table 4A and 4B) correlate very well with the reported field performance (Table 1), based upon acceptance criteria discussed previously in this paper. The French aggregate F3 and the Spanish aggregate E1 are two exceptions. The F3 aggregate contains many reactive rock types. Despite of this, the French partners were not aware of any deteriorated real concrete structures containing this aggregates type.

The situation for the E1 aggregates is opposite. Only a minor amount of reactive constituents were detected, but serious damage is reported on a 30 years old precast concrete element. Several of the participating petrographers questioned whether E1 could lead to ASR.

In almost all known cases of Norwegian ASR-damaged structures, the damages are mainly caused by the coarse aggregate fractions (>8-10 mm) [24]. For several of the other European aggregate types included, there is a lack of information about which fractions that have proved to give ASR-problems in real concrete structures. This lack of information makes the evaluation of several of the fine aggregates uncertain.

Variation between aggregate fractions examined?

Overall, the content of suspicious rock types (“reactivity class” II+III) detected within the different fractions examined (i.e. >4 mm, 2/4 mm and 1/2 mm) for a given aggregate type does not vary much compared to the variations revealed between the different laboratories participating (see above). The fraction 0.063/1 mm is tested for most fine aggregates. In particular, point counting of this small fraction did not give any complementary information about the potential alkali-reactivity of any of the aggregate types included in the test programme. For many of the aggregates types, e.g. N3 and N4, free minerals were also to a large extent detected within this fraction. Taking into account the time consuming examination of this small fraction, for most (all?) fine aggregate types one should consider only counting the fractions 1/2 and 2/4 mm, as has been done in Norway for the last 15 years [17, 24].

Is the RILEM AAR-1 petrographic method a good tool to assess the potential alkali-reactivity of aggregates?

The reported results from the test programme within task 3.1 in PARTNER have detected large inter-laboratory variations, and revealed the following main issues to be dealt with and solved if the RILEM AAR-1 method aims to be a widely used and reliable testing method to assess the potential alkali-reactivity of aggregates both within Europe and world wide:

- The importance of education and round robin testing
- The importance of experience, both with the method and with the actual local aggregates
- The importance of calibrating the results with other RILEM methods and with field experience to be able to establish critical limits for acceptable content of suspicious rock types in different aggregate types
- The importance of accuracy, quality control and system for certification of laboratories and petrographers.

Final remarks

Both the internal workshops and the testing within task 3.1 in the PARTNER project have shown that geological evaluations across the frontiers are difficult. Both the European petrographic atlas developed within the PARTNER project [25] and any national petrographic atlases will hopefully contribute to reduce the spread in the future. The PARTNER project and in particular the internal workshops have established a very good network of contacts between several experienced and less experienced petrographers that may be helpful in the future to an informal education and “flow of experience” across the frontiers.

RILEM AAR-2 Accelerated mortar bar method

Overall, there is good agreement between the ranking of the expansion of the aggregates in the AAR-2 test method (Table 5) and their known reactivity in the field (Table 1), based upon acceptance criteria for AAR-2 presented by RILEM [18] and referred to previously in this paper. None of the non-reactive aggregates show any significant expansion. However, some of those aggregates which are reported to exhibit field reactivity also show very low expansions.

The ambiguous aggregates are presented below, and in each case, there is some uncertainty in the reports of their reactivity in the field which can account for the anomaly:

- E1, “Dolomitic limestone”
- N5, “Gravel with rhyolite and quartzite”
- P1, “Silicified limestone”
- F1, “Gravel with flint”

In the case of E1 and P1, there are uncertainties about the aggregate samples tested compared with those found in the structures reported to suffer damage. Additionally, for E1, the cause of the field damage is not certain. F1 is known to exhibit a strong pessimum behaviour, while N5 has only been found to produce damage at long ages.

It can be seen in Table (5) that there is quite a wide spread in the results for some of those aggregates where more than one laboratory performed the test. This points to the fact that, even though the methodology was explained thoroughly in the method and an accompanying instruction, it is still necessary to build up experience before testing is done in earnest.

“S/L-ratio”

An “S/L-ratio” of 0.54 between the expansion of 40x40x160 mm (S=short) and 25x25x285 mm (L=long) prisms (with the long prisms expanding more) has previously been given in the RILEM method [11], but the data obtained from this project does not support this. However, the data from this project suggests an “S/L-ratio” of 0.75 at 14 days, though with a large spread from 0.13 to 4.6. At 9 days and 28 days the mean ratios are 0.79 and 0.84, respectively. Although an “S/L-ratio” can be suggested from this data, the poor correlations means that for many of the aggregates the use of such a ratio would give a misleading result if used to extrapolate from one size of prism to another.

RILEM AAR-3 (38°C) and AAR-4 (60°C) Concrete prism methods

Identification of reactive aggregate combinations

In the overwhelming majority of cases, all the concrete prism methods correctly identified those aggregate combinations that had been shown by field experience to be involved in cases of damaging ASR, based upon acceptance criteria for the concrete prism methods presented by RILEM [18] and referred to previously in this paper.

Aggregates that react in “normal” timescales

The methods were particularly effective in identifying aggregate combinations that caused damage in “normal” time scales; 5 to 20 years. This is shown in Figure (16), where all the expansion results at the end of the test period for such aggregates are shown for all the methods.

The major exception was D1, where all the laboratories except one identified this aggregate combination as non-reactive, whereas it is known from field experience to cause rapid and severe damage to structures in Denmark. It is also known, however, that this aggregate type has a marked pessimum behaviour, and it is probable that the coarse and fine combination tested is well above the pessimum content of reactive silica.

Non-reactive aggregate combinations

Most methods correctly identified those aggregate combinations that were established from field experience as being non-reactive (Figure 17), according to acceptance criteria presented by RILEM [18] and referred to previously in this paper. However, some exceptions were observed. For aggregate combination N3(C+F) and P1(C+NRf), some of the 60°C test series by a small margin exceeded the critical limit. The 38°C test series did not exceed the critical limit.

In the case of S1(C+F), all methods showed this combination to be on the margins of reactivity. Although this aggregate has been involved in known failures; its composition and reactivity is known to be variable.

”Slowly” reactive aggregate combinations

The one class of aggregates where some uncertainties showed up, were those where the damaging reactions were known to be slow, i.e. damaging reactions after + 15-20 years (Figure 18). This was found in the following cases:

- D2(F+NRC); two of the three AAR-4 reactor test series (i.e. 60°C) did correctly identify the reactivity potential of this aggregate combination. However, the expansions in the third AAR-4 reactor test and in the two AAR-4 Alt. test series were just above the critical limit (i.e. expansions of 0.03 % after 20 weeks, as suggested below), whereas the expansion in the single AAR-3 test series was below the critical limit (i.e. 0.05 % after one year).
- It2(C+F); the AAR-3 tests again did not identify the long term reactivity of this aggregate. The AAR-4 tests did identify its potential alkali-reactivity, although in one case only after the normal final test date.
- N4(C+F); again, the AAR-4 tests more clearly identified the reactivity of this combination. Two of the three AAR-3 results identified this combination as reactive, but only by the smallest of margins. The third AAR-3 laboratory obtained a one year expansion below the critical limit, probably due to lack of moisture (also the weight changes for the concrete prisms were measured, but these results will be discussed later in a separate paper). The reason for the “moisture problems”, is that this laboratory did not follow the instructions prepared for the test. The only AAR-3 expansion below the critical limit for the N5(C+F) combination in the Figures (5 and 18), was also obtained at this laboratory.

Comments on the concrete prism methods

Comparison of test methods; as stated above, the various tests gave results that agreed in most cases. The main exceptions were the differences between the RILEM AAR-3 and RILEM AAR-4 results when very ”slowly” reactive aggregates were tested. In these cases, the AAR-4 reactor method more clearly identified the potential alkali-reactivity (see Figure 5 and 18), even though it did not necessarily show that the expansion would be slow.

The actual expansion values recorded were very variable for some aggregates, but quite consistent for others. The variability was greatest for the most expansive aggregates and least for the least expansive.

The expansions in the RILEM AAR-3 method seemed particularly variable (Table 6). See also the results and discussion relating to the precision of the laboratory tests in section 5.

In general, amongst the RILEM methods, the results from the 60°C AAR-4 methods, and in particular the AAR-4 reactor method, were the most consistent. The reactor version of this method was in all cases able to detect a potential alkali reactivity of the “suspicious” aggregate combinations included in the test programme, also the “slowly” reactive aggregates. The only exceptions were for pessimum aggregate combinations. The AAR-4 Alt. method (wrapped prisms, no reactor; see Table 2) seems to be far more vulnerable with respect to keeping the moisture content high during the testing. The weight measurements (not included in this paper) showed in general a lower weight increase, and sometimes also a weight loss, for the aggregates tested according to the AAR-4 Alt. method compared to the reactor version.

There is also evidence that the experience of the laboratories with a particular method has a significant effect on the variability of results. Where laboratories were carrying out procedures with which they were very familiar, for example the Norwegian method carried out by NORCEM and SINTEF, the expansion values were very close.

The field site tests

After approximately 4 years of outdoor exposure, the cubes of aggregate combination B1(C+F) and B1(C+NRF) show high expansion >0.04 % and cracks with maximum width ≥ 0.20 mm at all field sites from Norway to Spain independent of the type of storage (Table 7 and 8, Figure 6 and 7). B1(C+F) and B1(C+NRF) are in general the fastest reacting aggregate combinations. The concretes with the aggregates D2, G1, N1 and UK1 show in tendency higher expansions and large cracks when stored in medium (Düsseldorf, Watford) and hot climates (Milan, Valencia), whereas significant expansion and cracks developed later in colder climates (Figure 8-11). The influence of the climate on the expansion development is for the aggregate combinations D2(F+NRC) and N1(C+NRF) stronger than for B1(C+F), B1(C+NRF), G1(C+NRF) and UK1(C+F). Fournier et al. [26] suggest that a deleterious expansion occurs 4 to 5 times faster in warm climates (Austin, Texas, USA) than in cool climates (Ottawa, Ontario, Canada). They compare the expansion of concrete block after three and

four years. A general factor by which the ASR is accelerated cannot be derived in this study, because it differs for different aggregate combinations.

It can be assumed that the high expansions and crack widths can be attributed to a deleterious ASR that has taken place in the concrete cubes. Final confirmation will be given by the investigation of thin sections at the planned finalisation of the field site tests, i.e. when the slope of the expansion curves starts to flatten. Thus, the time depends on the reactivity of the aggregate combination.

All aggregate types (B1, D2, G1, N1 and UK1) that in advance were classified as “normally” reactive (Table 9A) and have caused damage in concrete structures, reacted at least at one outdoor exposure site in the timescale of 4 years. Except aggregate combination D2(F+NRC), all these aggregate combinations were identified as reactive with all laboratory methods. As discussed above, only two of the three AAR-4 reactor tests did clearly identify the reactivity potential of the D2 aggregate combination, whereas the single available 38°C test result (AAR-3) did not. The relative fast reaction in the field site test, in particular in Valencia (Figure 8) where the mean temperature is high (see Figure 2), of this assumed relative “slowly” reactive aggregate, can be attributed to the high cement content and the high alkali content of the cement. However, this is seldom the practice in real concrete constructions where the lower alkali contents will result in a slower reaction.

It is also noteworthy and surprising that there are no obvious differences between the specimens exposed only to ambient rainfall and those stored partly immersed in water.

The concrete cubes with aggregate combination B1(C+F) stored in an open forest and alongside a highway in the southwest of Sweden show similar expansions and cracks after four years. So far, there is no measurable influence of an external alkali supply by de-icing salts on the performance of this concrete composition containing alkali-reactive aggregate.

B1(C+NRF) seems to have slightly higher expansion and sometimes larger cracks than B1(C+F) (Figure 6 and 7). The latter contains reactive fines instead of non-reactive fines. The lower expansion

of B1(C+F) can probably be attributed to the reaction of fines, that may reduce the effective alkali content of the pore solution.

The Figures (12 to 15) show the expansion on the top surface as well as on the side surfaces in horizontal and vertical direction for the aggregate combination B1(C+NR) stored in Trondheim and Milan, as well as for G1(C+NR) stored in Trondheim and Düsseldorf. Additionally, the development of the maximum crack width is given. The highest expansion occurred in most cases on the top surface, that is most exposed to solar radiation. The horizontal and vertical expansion was less, but a significant difference between them does not exist. This is independent of the climate. With increasing expansion, the maximum crack width is always increasing.

The "slowly" reactive aggregates It2, N2 and N4 and the non-reactive aggregates F1, F2, S1 and P1 did not show any noticeable expansion or cracking after 4 years of outdoor exposure. The small cracks with a width of 0.05 mm, visible in most cubes, are presumably due to shrinkage. However, the testing time of 4 years is too short to draw conclusions for these "slowly" reactive aggregate combinations. To get conclusive results, the tests will be continued.

The field site tests show that a deleterious ASR can take place in all European countries from Norway to Spain, and it occurs independently of the climate condition within the range represented in this study. However, the speed of the ASR is higher for some aggregates in hot climates (Valencia) than in medium (Düsseldorf, Watford) or cold climates (Borås, Trondheim). Special considerations may therefore be necessary when using some aggregates in warmer climates.

4.2 Comparison of test methods

The summarised results for the laboratory methods are compared in Table (9A, 9B and 9C) with the preliminary results of the field site tests and with the reported reactivity in structures (see Table 1).

They are presented in three groups according to whether their reported reactivity is;

- "normally" reactive (5-20 years)
- "slowly" reactive (+ 15-20 years)
- non-reactive

There are, however, some aggregates where the information on their reactivity is uncertain or where there is known variability in the source. Thus, the sample tested may not reflect the compositions in the reactive structures.

RILEM methods

In the first group, of “normally” reactive aggregates, all of the methods agreed with each other and with the field site results and the reported reactivity, except for D1. In this aggregate, there is a known strong pessimum effect and it is presumed that the results for the concrete methods reflect the presence of an amount of opaline flint that takes the combination past the pessimum amount when the fine and coarse aggregates are used together. The field site tests confirm that all “normally” reactive aggregate combinations can be reliably identified with all methods, if the critical limits suggested below are applied.

In the second group, of “slowly” reactive aggregates, the petrographic method (AAR-1), the accelerated mortar bar method (AAR-2) and the accelerated concrete prism method (AAR-4, 60°) successfully identified the potential alkali-reactivity, but did not necessarily show that the expansion would be slow. The concrete prism method (AAR-3, 38°C) was better at demonstrating the slowness of the expansion of these aggregates, but in a few cases the expansion did not pass the critical limit within the one year timescale of the test. However, it can be seen from the expansion curves that the expansion in most of these cases is continuing, and more than a year may be needed for some “slowly” reactive aggregates to produce expansion over the critical limit in the conditions of this test [3]. In this respect therefore, the AAR-3 method, corresponds better with field experience for these “slowly” reactive aggregate types.

At the 12th ICAAR in China, Fournier et al. reported [27], based on data from various sources, a correlation of about 1-to-1 between 13 weeks at 60°C and 1 year at 38°C. According to Folliard [pers. comm.], the general experience in his laboratory in Austin, Texas, USA is that the 20 weeks expansion in the 60°C method is on average approx. 60 % of the one year expansion in the 38°C method. One main reason may be higher leaching in the 60°C method compared to the 38°C method [27 and 28]. In the PARTNER project (where unfortunately any leaching of alkalis was not measured), the

corresponding ratio between the 20 weeks 60°C expansion (reactor version of AAR-4) and the 1 year 38°C expansion was on average approx. 0.5 (varying from 0.25 to 0.7) for the six “normally” reactive aggregate combinations (excl. D1) with a 1 year 38°C expansion exceeding 0.20 % (see Table 6 and Figure 16). Most 60°C expansion curves for these aggregate types had the similar characteristic shape, being rather steep in the beginning, before more or less flattening out after approx 8-12 weeks. Thus, the 13 weeks 60°C expansion will almost be as high as the 20 weeks expansion.

In contrast to AAR-3, the AAR-4 method produced relatively higher expansions for “slowly” reactive aggregates compared with “normally” reactive aggregates. For the nine aggregate combinations with a 1 year 38°C expansion in the range 0.010-0.10 % (including both “slowly” reactive and non-reactive aggregates), the corresponding ratio between the 20 weeks 60°C expansion (reactor version of AAR-4) and the 1 year 38°C expansion was on average approx. 2.3 (varying from 1.1 to 4.6; see Table 6 and the Figures 17 and 18). Most 60°C expansion curves for these aggregate types were more linear (see Figure 5) compared to the “normally” reactive aggregates. As a consequence, the 13 weeks 60°C expansion will be significant lower than the 20 weeks expansion, a fact that has to be taken into account when critical limits are to be set (see discussion later in the paper).

On the other hand, the relatively high inter-laboratory variations make these comparisons somewhat uncertain. In the field site tests, the concrete compositions with “slowly” reactive aggregate combinations are not exhibiting any sign of expansion or cracking yet. The testing time of 4 years is too short to draw conclusions for these “slowly” reactive aggregate combinations. To get final results, the tests will be continued.

In the non-reactive group, the results of the concrete methods agreed with the reported reactivity in all cases where the information on reactivity in the field was clear cut. In the case of S1 and P1, there is uncertainty about the composition of the samples tested compared to the aggregates in the structures where damage was reported. Similarly, the accelerated mortar bar test (AAR-2) was effective in all cases, except with F3 (reactive in AAR-2, but no reports of any ASR in structures). This aggregate is reported to have a marked pessimum effect, and it is probable that the difference in result between the concrete and mortar methods reflects the fact that the proportion of reactive material in

the fines is within the pessimum proportion, but when the coarse and fines are tested together in concrete, the amount of reactive material exceeds the pessimum, and limited expansion is obtained. The petrographic method (AAR-1) is effective in identifying those aggregates which contain either no or very low amounts of reactive material, but is unable to identify correctly those aggregate combinations where possibly pessimum effects lead to such aggregates being innocuous in structures.

Overall, the accelerated mortar bar test (AAR-2) and the accelerated concrete prism test (AAR-4, reactor version) seemed the most effective of the RILEM methods across the whole range of European aggregates tested in this study, including the identification of "slowly" reactive aggregate combinations. Additionally, these methods have the advantage of producing (relatively) rapid results.

The petrographic method (AAR-1) can produce an even quicker result. The averaged results for this method seem quite effective at identifying reactive materials, but can conflict with field experience when pessimum effects operate. The consistency of individual results for this method is the main issue, however. The spread in results between the laboratories for about half of the aggregate types tested was very high, and this high variability even applied to the results from some of the six laboratories which carry out petrographic analyses on a regular basis. As discussed, in relation to the precision test, below, there is a clear need for more education and inter-laboratory comparisons if the petrographic method is to be used on a European scale to evaluate the reactivity potential of an aggregate.

Other test methods

The German and Norwegian concrete prism tests behaved almost exactly like the AAR-3 method; identifying the "normally" reactive aggregate combinations and non-reactive combinations effectively, but giving marginal results with some of the "slowly" reactive combinations.

The two Danish methods were effective with most materials. However, the TI-B51 test appears to underestimate the reactivity of some "slowly" reactive materials when the standard 8 or 20 weeks are used, although at 26 or 52 weeks the method generally agrees well with the other concrete methods.

The one exception is the result for Norwegian material N2, which was classified incorrectly by the TI-B51 method; so far no explanation for this discrepancy is obvious.

Critical Limits

Final evaluation of the critical limits will need to be undertaken when longer term results for the field site tests are available. When evaluating and deciding the final critical limits, it is important to bear in mind the importance of degree of precisions for the various tests. When providing test results for clients, in order to classify an aggregate, it is however necessary that the critical limits are absolute values. But, when deciding critical limits, this must be done taking into account the tolerance and the uncertainty of measurement of the various tests. Critical limits should mainly be decided on the basis of field performance. It could, however, be interesting to compare the results of the various methods as it provides information about the appropriate test period for the methods. The correlation will, however, probably vary for various types of reactive aggregates, due to different shape of the expansion curves (see previous discussion). Based on the preliminary results of the field trials and comparison of the laboratory results with the reported reactivity in field structures, together with previous work by RILEM, the following critical limits can be suggested:

- AAR-2: Expansions of less than 0.10 % after 14 days distinguishes a non-reactive and reactive aggregate when using the long thin prisms (ASTM-type). The short prisms (RILEM-type) initially expand more slowly, and either a lower limit (e.g. less than 0.08 %) or a longer test period will be necessary with these test specimens (if a 0.10 % limit should be applied also for this prism type).
- AAR-3: Expansions of less than 0.05 % after 1 year indicate that the aggregate combination can be regarded as non-reactive. This limit will be effective for aggregates that react in normal timescales, but with some "slowly" reactive aggregates a longer test period may be necessary. The shape of the expansion curve will help to identify such aggregates.
- AAR-4: Expansions of less than 0.03 % after 20 weeks indicate that the aggregate combination can be regarded as non-reactive. For this test, the standard time period of 20 weeks is sufficient for both normally and "slowly" reactive aggregates. The results of a separate RILEM inter-laboratory trial have suggested that the 15 weeks results can give an effective prediction of the potential alkali-reactivity of the aggregate. These PARTNER results support that assessment.

5 PRECISION TRIALS

The precision of the four RILEM methods has been established in an inter-comparison trial in which the laboratories carried out the methods using samples of the same aggregates together with the reference cement. The procedures strictly follow ISO 5725-94 [29]. The organisation and results of the trial are described in detail in reference [30] and are outlined below. It is important to know and understand the differences between a strict precision trial according to ISO 5725 and a “less regulated” inter-comparison trial. Both the organisation and mathematical evaluation are strictly regulated in the ISO standard. Inter-comparison trials can have many different objectives, while the here presented work was strictly done to evaluate the precision of the amended RILEM methods. Several reported studies of the multi-laboratory variability focus on a specific part of the test procedure, e.g. storage conditions or influence of different aggregates, i.e. rock types [27 and 31], while those found in the standards [e.g. 32 and 33] focus on the precision in relation to the average expansion and critical limits.

The precision of AAR-4 Alternative method rather than the AAR-4 method was assessed, because too few laboratories had the reactor necessary to perform the test according to the original method. In addition, the precision of the AAR-4 reference method, based on “reactor storage” of the prisms, is presently under evaluation within RILEM TC191-ARP.

Organisation

The laboratories and materials included in the precision trials were chosen based on the outcome of an enquiry, where the participants gave statements about their experience of the methods and the reactivity of the aggregates. Eight laboratories were chosen for each test along with three materials with expected low, medium and high reactivity, respectively. The low reactive material was a Norwegian natural gravel with rhyolite and quartzite (N5), fine and coarse from the same source. The medium reactive material was crushed Belgium silicified limestone (B1), fine and coarse from the same source. The expected high reactive material was a Norwegian crushed cataclasite (N1), mixed with non-reactive fines of Norwegian sand (N3: 0/4 mm). See Table (1) for more details of these aggregates.

Special instructions were prepared based on the outcome of other work packages. Templates for reporting were prepared, and no deviations from the instructions were accepted. All samples were divided by SP, Technical Research Institute of Sweden, and sent to the participants. The sample splitting procedure followed that of earlier EU-projects and EN 932-2 [34]. Rotary sample divider and fractional shovelling (Figure 19) were used to minimize the difference between the samples.

Overall precision

The overall precision of the four RILEM methods assessed in the trial is set out in Table 10. For many other aggregate test methods, the precision can be expressed as a fixed percentage of the mean value or the characteristic value. As can be seen in Table 10, the precision of each method is varying within its working range. The mathematical relationships, e.g. the best fit curves, are therefore recommended to be used instead of a fixed value. Another possibility is to give the precision value at each critical level, e.g. 0.10 % after 14 days for the AAR-2 method using long prisms (ASTM-type) etc. This can easily be done by extrapolation of the test results down to that level.

The importance of a good repeatability mostly lies in the quality control of each laboratory. The importance of a good reproducibility lies in the fact that it should be possible to send similar samples to different laboratories and still get similar results. In case of dispute, it would otherwise be very difficult or impossible to state what result is correct. Both repeatability and reproducibility are crucial when requirement limits are chosen. A poor precision leads to problems of differentiating between aggregates of different qualities. Some laboratories will inevitably classify aggregates as belonging to a different reactivity class than other laboratories if the precision is poor.

General definitions (simplified and related to this project)

r = repeatability. This is a measure to determine the spread in results obtained between the individual prisms, tested at the same laboratory, same aggregate combinations and same concrete.

R = Reproducibility. This is a measure to compare the difference in the mean value obtained between the different laboratories.

$COV(S_R)$ = Coefficient of variation for the Reproducibility. By using the coefficient of variation (COV) one relates the spread to the actual expansion. The COV is the standard deviation divided by

the mean value. The $COV(S_R)$ is thus used to compare the difference in the spread between the laboratories. Similarly, the $COV(S_r)$ is used to compare the spread within one single test carried out at one laboratory. In this case, it is the spread between the three prisms and whether it is correct to average their results or if the test has to be remade or only two part results shall be averaged, all depending on the instructions in the test method.

AAR-1 petrography

The results from the AAR-1 petrography showed a large spread between the different laboratories. Their identification of the rocks and minerals is similar, but the classification of the degree of alkali silica reactivity varies a great deal. This is probably due to the regional experience and inexperience of the different reactive rocks. Only porous/opaline flint and mylonite/cataclasite have been classified as reactive by all laboratories.

Overall, the results confirm the necessity of education. Petrographers need to get acquainted with the potentially reactive components in aggregates from different countries in order to use the most appropriate analytical techniques and to make a relevant assessment. Education, in combination with proficiency trials of individual laboratories, is therefore the way forward for future improvement in this area.

Expansion tests; RILEM AAR-2, AAR-3 and AAR-4 Alternative

Overall the precision is acceptable to good and it is possible to detect small differences in reactivity.

RILEM AAR-2

Both options, using the long and thin prisms (25x25x285 mm – ASTM-type) and the short and thick prisms (40x40x160 mm – RILEM-type) are working adequately. At the standard 14 days test age, the long and short prisms give different results, with the long prisms having the highest expansion. At 14 days, therefore, the short prisms would need a different (smaller) limiting requirement to differentiate between reactive and non-reactive aggregates. However, the results are equalising after 20 days and even more so after 28 days (Figure 20). The difference between laboratories is generally less than 1 standard deviation of the overall mean value. If the use of both prism sizes is still to be recommended

in the same method, it seems necessary to continue the test for 28 days or to be able to determine a usable correlation factor. The precision trial also indicates that using 3 prisms instead of 5 actually improves the precision data, probably because with only 3 prisms they can all be stored in the same container. At the proposed limiting value for differentiating between reactive and non-reactive aggregates, 0.10 % (for the long prisms), the band of uncertainty is less than 0.025%.

RILEM AAR-3

The results concerning this method indicated that the repeatability is good, whereas the reproducibility is quite poor, i.e. each laboratory produces results within a narrow range (i. e. between test prisms of the same set), but the difference in results between the laboratories is large. A coefficient of variation in the repeatability of up to 20 % is acceptable, but the results indicate that AAR-3 does not achieve this with the most expansive material (i. e. the aggregate with approx. 0.26 % expansion after 1 year of exposure – see Figure 20). Equally, a coefficient of variation in reproducibility, $COV(S_R)$, of above 50 % is unacceptably high. It is therefore concluded that the precision of AAR-3 is not sufficient to discriminate between different levels of reactivity. The results of the precision trial do, however, confirm that the method can be used to discriminate between non-reactive and reactive materials. The reproducibility is shown to be about half of the expansion value. At the level of 0.05%, suggested as the limiting value to differentiate between reactive and non-reactive aggregate combinations when using AAR-3, there is therefore a band of uncertainty of 0.025%, and the lowest result for a reactive aggregate should exceed 0.075 %. This was found to be the case for all the aggregates which react in normal timescales and where their record of field reactivity is well established. However, the AAR-3 method is not well suited to identifying “slowly” reactive aggregates. N.B! This statement relies on the assumption that all laboratories strictly followed the procedure described in the method and PARTNER amendments. During the prior test rounds in the project, important differences in the storage conditions were found.

RILEM AAR-4 Alternative

Testing according to the AAR-4 Alt. method resulted in a better overall precision than AAR-3, and was able to detect smaller differences in reactivity than the AAR-3 method. The “overlap” between the different materials (e.g. categories of reactivity) is less, approximately half that of the AAR-3 test.

The coefficient of variation in reproducibility, $COV(S_R)$, is about one third of the mean test result, while the repeatability COV is about 10 to 15 %, depending on the mean expansion. This is considered acceptable. In addition, this is an improvement over the figures reported by Sims & Nixon [35] from a RILEM initiated inter-comparison trial covering both AAR-4 reference method (reactor) and the Alternative wrapped version. It is obvious that participation in inter-comparison trials and practice will improve the precision. In some cases, there is no option but to use a mix of inexperienced and experienced laboratories despite the warning given in ISO 5725, simply because there are not enough laboratories available, and pre-test rounds are too expensive or time consuming.

Like AAR-3, the precision of the AAR-4 Alternative method is sufficient to distinguish between non-reactive and reactive materials, but not between smaller differences of reactivity. At the proposed limiting value for differentiating reactive and non-reactive aggregates, 0.03%, the band of uncertainty is less than 0.01%.

Precision statements from standards

For comparison, we have also compiled some information of precision data found in the most relevant national standards. According to the ASTM C-1260 [36], the within-laboratory COV is 2.94 % at 0.1 % 14-days expansion. The multi-laboratory COV at the same level of expansion is 15.2 %. As regards the precision of the concrete methods, no directly comparable data has been found. The most similar method to RILEM AAR-3 is the Canadian CSA A23.2-14A (the main difference is that AAR-3 applies wrapped prisms), which is also referred to in the ASTM C-1293. However, the precision is reported in a different way which makes a direct comparison difficult. For expansion levels less than 0.014 %, the expected difference between laboratories should generally not exceed 0.009 % (absolute percent). This means that if you sample an aggregate, with an expected expansion of 0.014 %, reduce it to several subsamples and send two of them to different laboratories, the expected expansion results (i.e. the average of three prisms) will most likely be between 0.023 and 0.005%. The multi-laboratory coefficient of variation for expansions greater than 0.014 % is 23 %. These data can be compared with the PARTNER results summarized in Table 10, e.g. the corresponding PARTNER data for AAR-3 is approximately between 15 and 20 %. Since only the AAR-4 Alternative method was included in this

study, we don't consider it relevant to compare with the precision statement of the French standard [37], based on the reactor type prism storage.

6 PETROGRAPHIC ATLAS

As part of the PARTNER project, a petrographic atlas of the potentially alkali-reactive rocks in Europe was produced and published. The aim of this petrographic atlas is to assist geologists who work in the field of the concrete degradations and in particular in the field of alkali-silica reaction to recognise potentially reactive rock types and to differentiate these from rock types that will be resistant to alkali aggregate reactions. It will particularly be of assistance to petrographers who carry out the AAR-1 petrographic method on aggregates that are from a part of Europe with which they are unfamiliar.

A paper version of the atlas is published by the Belgian Geological Survey [25]. It is planned to maintain the electronic version under the auspices of RILEM. The current version of the atlas is accessible on www.farin.no/english.

The rocks are firstly classified under their origin (sedimentary, metamorphic or igneous) using the international nomenclatures. Secondly, they have been grouped under families of similar species. For each rock family, a general description is given in the header including the most particular characteristics of the different rock species from different countries. The reactive components are emphasized within the descriptions and, when possible, within the pictures which illustrate the type of aggregate. Despite the fact that this atlas is not exhaustive, it is nevertheless representative of the majority of the European alkali-reactive rocks.

7 STATE-OF-ART REPORT

As part of the PARTNER project, a state-of-art report on key parameters influencing the alkali aggregate reaction was produced [38]. Annex A of the report includes a description of the existing national standards and requirements in the different European countries. The main objective of this report is to give an updated description of the mechanisms of AAR that can influence the results from the different test methods used in the PARTNER project. The ultimate challenge when testing for AAR in a laboratory, is to provide quick, reliable results regarding the potential alkali-reactivity of certain types of aggregate, or, even more important, an assessment of specific concrete job mixes (i.e. performance testing). The results are required to mirror the durability behaviour in real structures designed for a service life up to 100 years.

The report identified many parameters that will influence the alkali aggregate reactivity. Some of the parameters will only influence the reactivity in the laboratory, while others will have an overall contribution, both in the laboratory and in real structures. The following key parameters are discussed in the report in relation to AAR:

- Temperature
- Humidity, moisture and degree of saturation
- Content of alkalis
- Role of calcium hydroxide (CH)
- Types and content of reactive rock types
- Aggregate particle size / grading
- Size of test prisms
- Air entrainment, paste porosity and water/cement ratio
- Storage conditions - leaching

The influence of any changes in a parameter may vary a lot dependent of the situation, both when performing a laboratory test and in a real concrete structure. However, the experience has shown that in particular any variations in the humidity and/or the alkali content (due to leaching) in the test specimens can lead to incorrect results. It is also very important to bear in mind the influence of the

different parameters when undertaking a performance test to reflect how a given concrete mix will behave in a real concrete structure over a long service life.

8 CONCLUSIONS

- In the majority of cases, all the RILEM test methods were able to correctly identify the potential alkali-reactivity of each of the individual aggregates or aggregate combinations (a total of 22) investigated in this study. The tests were particularly successful in identifying aggregates that react in “normal” time scales (i.e. 5 to 20 years) and in identifying non-reactive aggregates. There was less certainty in identifying “slowly” reactive aggregates, i.e. those that react in greater than 15-20 years. Whether these experiences can be applied to all European regions will have to be verified by additional local examinations.
- Where there were discrepancies between the results of the tests and field experience, these can usually be attributed to either uncertainties about the field results, to variability in the aggregate source or to pessimum effects.
- Overall, the accelerated mortar bar test (AAR-2) and the accelerated concrete prism test (AAR-4, reactor version) seemed the most effective of the RILEM methods across the whole range of European aggregates investigated, including the identification of “slowly” reactive aggregate combinations. Moreover, these methods have the advantage of (relatively) rapid results. To get comparable results from both prism sizes allowed for in AAR-2, it seems necessary to continue the test to 28 days. However, critical limits after 14 days are suggested.
- The petrographic RILEM AAR-1 method can produce an even quicker result. The averaged results for this method seem quite effective at identifying reactive materials, but can conflict with field experience when pessimum effects operate. The consistency of individual results for this method is the main issue, however, due to a rather large spread in results between many of the laboratories.

- Overall, the results from the petrographic analyses confirm the necessity of education and round robin testing. Petrographers need to get acquainted with the potentially reactive components in aggregates from different countries in order to use the most appropriate analytical techniques and to make a relevant assessment. Education, in combination with proficiency trials of individual laboratories, is therefore the way forward for future constructive development in this area. An improvement of the common understanding between petrographers really calls for extensive and repeated workshops, e.g. as arranged as part of the PARTNER project. The petrographic atlas developed in the project will also be a good tool to help the petrographers to recognise potentially reactive rock types and to differentiate these from rock types that will be resistant to alkali reactions.
- Precision statements for the four RILEM methods have been made. These confirm the poor precision of the petrographic method, unless the laboratories carrying out the test are familiar with the materials being evaluated. The precision of the expansion methods is much better, and the results confirm the conclusion that the AAR-2 and AAR-4 methods are the most repeatable and reproducible despite some non negligible within and between laboratory variations.
- The field site tests were carried out in various climate zones representative for Europe in order to take into account the influence of different environmental conditions. However, the results indicate that a deleterious ASR occurs in the same way in northern and in southern Europe with the difference that with some aggregates the reaction may occur earlier in southern Europe, probably due to the higher mean temperature.
- Specimens were stored alongside a highway in Sweden to study the additional influence of alkali supply under severe conditions. So far, there is no difference in the performance of the concrete cubes stored in a nearby forest (without alkali supply) and alongside the highway (with alkali supply).

Table 1: Aggregate description and reactivity table

Aggregate combination	Origin	Brief petrographic description	Reported alkali-reactivity
B1 (C+F)	Western Belgium	Crushed silicified, dark-grey argillaceous limestone with fossil debris; reactive mineral is crypto-microcrystalline quartz with sometimes fibrous habit.	Aggregate has caused damage in several concrete structures such as bridges and water structures.
D1 (C+F)	Denmark	Glaciofluvial gravel containing white to creamy opaline flint; reactive mineral is opal.	Aggregate has produced severe deterioration in all types of concrete structures (can occur quickly under severe conditions, clear pessimum effect).
D2 (C+F)	Denmark	Sea dredged, polymictic gravel originally derived from glaciofluvial sediments; main component of interest is partly porous dense chalcedonic flint, in smaller amounts pure porous chalcedonic flint is included; reactive mineral is chalcedony.	Dense porous flint is considered to be non reactive, porous flint to be reactive. Aggregate has produced severe damage in all types of concrete structures (normally after 10-15 years). Not as severe as D1.
D3 (F)	Denmark	Non reactive siliceous sand.	No deterioration reported.
F1 (C)	France (Seine Valley)	Polymictic river gravel, mainly composed of flint/cherts; reactive mineral is micro-cryptocrystalline quartz.	In France is considered to be potentially reactive but with clear pessimum effect. No evidence of damage in structures.
F2 (C+F)	France	Fine grained limestone with some fossils; no reactive minerals.	Non-reactive. No damage reported.
F3 (C+F)	France (Rhine Valley)	Polymictic river gravel (partly crushed), mainly composed of quartzite, alkali reactive constituents are flint, greywacke and granitoids; reactive minerals are micro-cryptocrystalline quartz and strained, highly metamorphically sutured quartz.	No deterioration reported.
G1 (C)	Germany (Upper Rhine Valley)	Crushed polymictic river gravel, considerable variation in constituent lithologies; aggregates of interest are silicified limestone and chert; reactive minerals are micro- to cryptocrystalline quartz and chalcedony.	Considered to be reactive. Concrete pavements containing this aggregate have deteriorated due to ASR. (Damage observed after 10 years under very severe conditions).
G2 (C)	Northern Germany	Polymictic gravel from glaciofluvial deposit; alkali reactive due to opaline sandstone (with tridymite/christobalite) and flint (with crypto-crystalline quartz and chalcedony).	Has produced severe deterioration, very quickly (<10 years), in concrete structures, clear pessimum effect [39,40].
It1 (C+F)	Italy (Marche region in central Italy)	Polymictic river gravel, containing mainly micritic limestone, but also silicified limestone, flint, chert and strained quartz; reactive minerals are micro- to cryptocrystalline quartz and strained, high metamorphically sutured quartz).	Quick reaction (5-10 years) observed in all types of concrete structures.
It2 (C+F)	Italy (Piemont region)	Polymictic river gravel; aggregate of interest is fine grained quartzite with strained quartz; reactive mineral is strained highly metamorphically sutured quartz.	Considered to be "slowly" reactive, (one example is 50 years old water construction).
N1 (C)	Norway (middle)	Crushed cataclasite, homogeneous and fine-grained, feldspar particles lie scattered within a matrix of about 0.02 mm grain size; reactive mineral is crypto- to microcrystalline quartz.	Has caused severe damage in local areas (e.g. 11 years old airport pavement).
N2 (C)	Norway (south east)	Crushed sandstone, homogeneous and fine grained, with a sediment grain size ranging between 0.05 and 0.5 mm. These variously sized particles are embedded in a fine grained matrix; reactive mineral is crypto- to microcrystalline quartz.	Has caused severe damage in local areas (damage observed in bridges and dams after 15 to 20 years) [21].
N3 (C+F)	Norway (south western)	Natural gravel/sand from a glaciofluvial deposit, originally composed of Precambrian crystalline rocks, consists of granites and gneisses; no reactive constituents.	Non-reactive. No damage reported.
N4 (C+F)	Norway (south east)	Natural gravel/sand from a moraine deposit. Sandstones, siltstones and cataclastic rocks are reactive rocks; reactive mineral is crypto- to microcrystalline quartz.	The coarse fraction has caused moderate damage, if the humidity and the alkali content are high (e.g. 20-25 years old constructions, mainly bridges) [21].

Aggregate combination	Origin	Brief petrographic description	Reported alkali-reactivity
N5 (C+F)	Norway (south)	Sand and coarse gravel from a glaciofluvial deposit. Rhyolite and fine grained quartzite are reactive rocks; reactive mineral is microcrystalline quartz.	The coarse fraction has caused moderate damage, if the humidity and the alkali content are high (e.g. 20-25 years old constructions, mainly bridges) [21].
N6 (C+F)	Norway (south)	Sand and coarse gravel from a glaciofluvial deposit. The reactive rocks are mainly argillaceous rocks and sandstones in addition to small amounts of hornfels, rhyolite and mylonite. Reactive mineral is crypto- to microcrystalline quartz.	The coarse fraction has caused moderate damage, if the humidity and the alkali content are high (e.g. 20-25 years old constructions, mainly bridges) [21].
P1 (C)	Portugal	Crushed, poorly silicified limestone; reactive minerals could be micro- or cryptocrystalline quartz.	Similar limestone, probably with higher content of silica, has caused damage in several concrete structures like bridges and dams.
S1 (C+F)	Sweden	Polymictic glaciofluvial gravel and sand, primarily composed of meta-rhyolite and granite; aggregates of interest are meta-rhyolite and greywacke; reactive minerals are micro- or cryptocrystalline quartz or chalcedonic quartz.	Similar aggregate used as concrete material has caused moderate damage. The source is variable in composition.
UK1 (C+F)	United Kingdom	Crushed greywacke, poorly sorted; reactive minerals are micro- or cryptocrystalline quartz, possibly volcanic glass.	Concrete with this aggregate has demonstrated high damage at moderate to high alkali levels in many real structures (more than 20 years until observed damage).
UK2 (C+F)	United Kingdom	Polymictic mature river gravel and sand, composed primarily of metaquartzite, ortho-quartzite, quartz (vein) and chert, which is the reactive portion in the aggregate; reactive minerals are micro- or cryptocrystalline or chalcedonic quartz.	Both, fine and coarse constituents have demonstrated reactivity at moderately high alkali levels in many real structures, mainly bridges (damage after 10 to 15 years).
E1 (F)	Spain	Dolostone with prismatic dolomite chrystals cemented with calcite, also opal and clay are apparent in considerable amounts; reactive mineral is opal.	Serious damage reported in 30 years old precast water pipe. Uncertainty if caused by ASR.

C = coarse aggregate (> 4 mm); F = fine aggregate (\leq 4 mm)

Table 2: Summary of test methods

Test method	Brief outline of method
RILEM AAR-1 Petrographic method [10]	The potential alkali-reactivity of the aggregate is classified on the basis of its petrographic composition. Depending on the nature of the aggregate, this can either be by hand separation, crushing and point counting under a microscope or by microscopic examination in thin section.
RILEM AAR-2 Accelerated mortar bar method [11]	Mortar bars made with the aggregate and a reference high alkali cement are stored in 1M NaOH at 80°C and their expansion monitored over a 14 days period.
TI-B51 - The Danish mortar bar test [12]	Mortar bars made with the aggregate are stored in saturated NaCl solution at 50°C and their expansion is monitored for 52 weeks.
The Danish Chatterji method [13]	The degree of reaction between silica in the aggregate and KCl is determined by measuring the alkalinity after 24 hours reaction to a non-reactive standard.
RILEM AAR-3 Concrete prism method [14]	Accelerated expansion test for 12 months. Wrapped concrete prisms, (75±5)x(75±5)x(250±50) mm ³ , made with the aggregate and a reference high alkali cement are stored in individual containers within a constant temperature room at 38°C and measured at 20°C.
RILEM AAR-4 Accelerated concrete prism method [15]	Accelerated expansion test for 20 weeks. Concrete prisms, (75±5)x(75±5)x(250±50) mm ³ , made with the aggregate and a reference high alkali cement are stored in individual containers within a reactor at 60°C and measured at 20°C.
RILEM AAR-4 Alt. Accelerated concrete prism method [15]	Accelerated expansion test for 20 weeks. Wrapped concrete prisms, (75±5)x(75±5)x(250±50) mm ³ , made with the aggregate and a reference high alkali cement are stored in individual containers within a constant temperature room at 60°C and measured at 20°C.
German concrete method [16]	Test duration of 9 months. Concrete prisms (100x100x450 mm ³) and one cube (300x300x300 mm ³) are stored in a fog chamber at 40°C with measurements taken immediately with no cooling down period. The expansion of concrete prisms and the maximum crack width on the cube are determined.
Norwegian concrete prism method [17]	Accelerated expansion test for 12 months. Large concrete prisms (100x100x450 mm ³) made with the aggregate and a reference high alkali cement are stored in individual containers within a constant temperature room at 38°C and 100 % relative humidity and measured at 20°C.
Field site method [5]	300x300x300 mm ³ concrete cubes stored on outdoor exposure sites. Measurements of expansions and maximum crack widths.

Table 3: Aggregate combinations tested in the field site

Sample number	Origin	Aggregate details	Combinations *
B1	Western Belgium	Silicified limestone	C + F
B1	Western Belgium	Silicified limestone	C + NRF
D2	Denmark	Sea-dredged gravel semi-dense flint	F + NRC
F1	France (Seine Valley)	Gravel with flint	C + NRF
F2	France	Non-reactive limestone	C + F
G1	Germany (Upper Rhine Valley)	Crushed gravel with siliceous limestone and chert	C + NRF
It2	Italy (Piemont region)	Gravel with quartzite and gneiss	C + F
N1	Norway (middle)	Cataclasite	C + NRF
N2	Norway (south east)	Sandstone	C + NRF
N4	Norway (south east)	Gravel with sandstone and catacl. rocks	C + F
S1	Sweden	Gravel with porphyritic rhyolite	C + F
UK1	United Kingdom	Greywacke	C + F
P1	Portugal	Silicified limestone	C + NRF

* C = coarse aggregate; F = fine aggregate;
NRC = non-reactive coarse aggregate (= F2C, see Table 1); NRF = non-reactive fine aggregate (=N3F, see Table 1)

Table 4A: Summary results of all the point counting analyses performed by the 13 participating laboratories [1]. For origin (country), see Table (1). (Regarding abbreviations: see footnotes to Table 4B).

Sample	Aggregate type	Frac-tion ¹ (mm)	Statistics ²	Point counting (%)						Field performance ⁶	Results in agreement with field performance?
				TS 2/4 mm ⁵		TS 1/2 mm ⁵		TS 0.063/1 mm ⁵			
				Sum II+III	Comments	Sum II+III	Comments	Sum II+III	Comments		
B1 (F)	Silicified limestone	0/2	"average"					97	1 result (TS 0.125/2 mm)	R?	YES
B1 (C)		4/20, "coarse"	"average"	100	1 result (1 lab., 1 frac.) ⁴			100	1 result (TS 0.063/2 mm)	R	YES
D1 (F)	Gravel with opaline flint	0/4	average Median minimum maximum	36? 16? 6 85	7 results (7 lab., 1 frac.)	39 44 7 87	5 results (5 lab., 1 frac.)	48 35 28 81	3 results (3 lab., 1 frac.)	R (pessimism behavior)	YES
D2 (F)	Sea gravel semi-dense flint	0/4	average median minimum maximum	38 28 2 100	5 results (5 lab., 1 frac.)	50 40 9 100	3 results (3 lab., 1 frac.)	53 -- 6 100	2 results (2 lab., 1 frac.)	R	YES
D3 (F)	Non reactive silicious sand	0/2	average median minimum maximum			2 -- 0 3	2 results (2 lab., 1 frac.)			NR	YES
F1 (C)	Gravel with flint	6/20	"average" median minimum maximum	96 -- -- --	1 result (1 lab., 1 frac.)	96 -- -- --	1 result (1 lab., 1 frac.)	86 -- -- --	1 result (0/1 mm)	R (pessimism behavior)	YES
F2 (F)	Non reactive limestone	0/5	"average"	0	1 result (1 lab., 1 frac.)	0	1 result (1 lab., 1 frac.)	0	1 result (1 lab., 1 frac.)	NR	YES
F3 (F)	Silicious gravel	0/4	average median minimum maximum	53? 42 37 94	5 results (5 lab., 1 frac.)	54 35/70 30 82	4 results (4 lab., 1 frac.)	60 76 25 78	3 results (3 lab., 1 frac.)	NR?	NO
F3 (C)		4/20	"average" median minimum maximum	26? -- -- --	1 result (1 lab., 1 frac.) (TS > 4 mm)						NR?
G1 (C)	Crushed gravel with silicified limestone and chert	"4/22"	"average" median minimum maximum	46 -- -- --	1 result (1 lab., 1 frac.)	44 -- -- --	1 result (1 lab., 1 frac.)	33 -- -- --	1 result (1 lab., 1 frac.)	R	YES
G2 (C)	Gravel with opaline sandstone and flint	"2/8"	average median minimum maximum	50? 43 14? 92	3 results (3 lab., 2 frac.)					R (pessimism behavior)	YES
It1 (F)	Gravel with limestone, chert and flint	0/5	average median minimum maximum	32? 10 8 100	4 results (4 lab., 1 frac.)	61 -- 21 100	2 results (2 lab., 1 frac.)	55 -- 10 100	2 results (2 lab., 1 frac.)	R	YES
It1 (C)		"5/30"	"average" median minimum maximum	10? -- -- --	1 result (1 lab., 1 frac.?)						R
It2 (F)	Gravel with quartzite and gneiss	0/5	average median minimum maximum	51? 24?/81 14 100	5 results (5 lab., 1 frac.)	82 86 60 100	3 results (3 lab., 1 frac.)			R?	YES

Table 4B: Summary results of all the point counting analyses performed by the 13 participating laboratories [1]. For origin (country), see Table 1.

Aggregate	Aggregate type	Fraction ¹ (mm)	Statistics ²	Point counting (%)						Field performance ⁶	Results in agreement with field performance?		
				TS 2/4 mm ⁵		TS 1/2 mm ⁵		TS 0.063/1 mm ⁵					
				Sum II+III	Comments	Sum II+III	Comments	Sum II+III	Comments				
N1 (C)	Cataclastic	4/16	average	90?	3 results (3 lab., 1 frac.)					R	YES		
			median	98									
			minimum	71?									
			maximum	100									
N2 (C)	Sandstone	8/16	"average"	100	1 result (1 lab., 1 frac.)					R	YES		
N3 (F)	Non-reactive granitic sand	0/4	average	2	3 results (3 lab., 1 frac.)	2	1	3 results (3 lab., 1 frac.)	2	--	2 results (2 lab., 1 frac.)	NR	YES
			median	1									
			minimum	0									
			maximum	6									
N4 (F)	Gravel with sandstone and cataclastic rocks	0/7	average	27	2 results (2 lab., 1 frac.)						R?	YES	
			median	--									
			minimum	23									
			maximum	31									
N4 (C)		7/16	average	25	2 results (2 lab., 1 frac.)						R	YES	
			median	--									
			minimum	23									
			maximum	27									
N5 (F)	Gravel with rhyolite and quartzite	0/8	"average"	22	1 result (1 lab., 1 frac.)	17	1 result (1 lab., 1 frac.)				R?	YES	
		8/16	"average"	22	1 result (1 lab., 1 frac.)						R	YES	
N6 (F)	Gravel/sand with argillaceous rocks and sandstone	0/8	"average"	37	1 result (1 lab., 1 frac.)	23	1 result (1 lab., 1 frac.)				R?	YES	
		8/16	"average"	33	1 result (1 lab., 1 frac.)						R	YES	
S1 (F)	Gravel with porphyritic rhyolite	0/8	average	52?	5 results (5 lab., 1 frac.)	61	45	3 results (3 lab., 1 frac.)			R?	YES	
			median	44									
			minimum	35?									
			maximum	100									
S1 (C)		4/16	average	43?	1 result (1 lab., 1 frac.) (TS > 4 mm)						R?	YES?	
			median	--									
			minimum	--									
			maximum	--									
UK1 (F)	Greywacke	0/5	"average"	83	1 result (1 lab., 1 frac.)	66	1 result (1 lab., 1 frac.)	40	1 result (1 lab., 1 frac.)	R?	YES		
UK2 (F)	Gravel with quartzite and chert	0/5	average	52	5 results (5 lab., 1 frac.)	27	9	3 results (3 lab., 1 frac.)			R	YES	
			median	54									
			minimum	15									
			maximum	89									
UK2 (C)		5/20	average	54	3 results (3 lab., 1 frac.)						R	YES	
			median	48									
			minimum	15									
			maximum	98									
P1 (C)	Silicified limestone	4/19	"average"	100	1 result (1 lab., 1 frac.)					R	YES		
E1 (F)	Silicified and clayed dolostone	0/4	average	3?	3 results (3 lab., 1 frac.)	3?	--	2 results (2 lab., 1 frac.)			R?	NO	
			median	--									
			minimum	0									
			maximum	8									

¹ The fraction investigated in the petrographic analyses

² The **average** represents the mean results of all the investigated fractions at all laboratories. **"Average"** means less than three results available.

³ The numbers represent the sum of the "reactivity classes" II and III, i.e. the sum of all the rock suspicious.

⁴ Lab. = laboratories; frac. = fractions

⁵ TS = thin sections

⁶ R = proved to alkali reactive based on field performance ; NR = not observed damage due to ASR in real structures

 = something is not clear or uncertain

 = OK results (i.e. checked and found reasonable)

Table 5: Summarized results of the testing of the aggregates according to RILEM AAR-2, listed in order of expansion [2]. The number of laboratories having tested each aggregate type is given in brackets.

Aggregate	Results (14 days)		“S/L-ratio”	Reported reactivity in the field (see Table 1)
	Short (S) (40x40x160 mm)	Long (L) (25x25x285 mm)		
It1 (C) Gravel with limestone, chert and flint	X	0.62 – 1.06 (3)	X	Very high
G2 (C) Gravel with opaline sandstone and flint	0.51 – 0.56 (2)	0.68 (1)	0.75 – 0.82	Very high
It1 (F) Gravel with limestone, chert and flint	0.53 (1)	0.58 – 0.84 (2)	0.63 – 0.91	Very high
N1 (C) Cataclasite	0.42 – 0.46 (2)	0.42 (1)	1.00 – 1.10	High
UK1 (F) Greywacke	~0.43 (1)	X	X	High
G1 (C) Crushed gravel with silicified limestone & chert	0.27 – 0.41 (2)	0.46 (1)	0.59 – 0.89	High
B1 (F) Silicified limestone	0.20-0.28 (2)	0.42 (1)	0.47 – 0.67	High
F3 (F) Siliceous gravel	~0.17 (1)	0.36 – 0.42 (3)	0.40 – 0.47	No report
N2 (C) Sandstone	0.32 (1)	0.28 (1)	1.14	High
D1 (C) Gravel with opal, flint	0.25 (1)	0.18 (1)	1.39	Very high
D2 (F) Sea gravel with semi dense flint	0.25 – 0.27 (2)	0.32 (1)	0.78 – 0.84	High
D1 (F) Gravel with opal, flint	0.23 (1)	X	X	Very high
N4 (F) Gravel with sandstone & cataclastic rocks	0.21 – 0.23 (2)	0.05 (1)	4.2 – 4.6	Moderate
D2 (C) Sea gravel semi dense flint	0.13 – 0.31 (2)	0.25 (1)	0.52 – 1.24	High
It2 (F) Gravel with quartzite and gneiss	0.14 (1)	0.21 – 0.22 (2)	0.64 – 0.67	Moderate
It2 (C) Gravel with quartzite and gneiss	0.12 (1)	0.14 – 0.32 (2)	0.38 – 0.86	Moderate
N4 (C) Gravel with sandstone & cataclastic rocks	0.18 – 0.25 (2)	0.10 – 0.21 (2)	0.86 – 2.5	Moderate
S1 (F) Gravel with porphyritic rhyolite	0.20 – 0.27 (2)	0.08 (1)	2.5 – 3.38	Moderate
N5 (F) Gravel with rhyolite and quartzite	0.16 (1)	0.21 (1)	0.76	Moderate
UK2 (F) Gravel with quartzite and chert	0.18 - ~0.27 (2)	0.16 (1)	1.13 – 1.69	High
N5 (C) Gravel with rhyolite and quartzite	0.05 – 0.13 (2)	0.05 – 0.16 (2)	0.31 – 2.6	Moderate
P1 (C) Silicified limestone	0.06 (1)	0.07 (2)	0.86	Moderate
F1 (C) Gravel with flint	0.03 (1)	0.01 – 0.06 (2)	0.5 - 3	Low-Moderate (pessim)
E1 (F) Dolomitic limestone	0.01 (1)	0.01 – 0.08 (3)	0.13 – 1	High, but uncertain
D3 (F) Non-reactive siliceous sand	0.07 (1)	X	X	Non-reactive
N3 (F) Non-reactive granitic sand	0.05 (1)	0.05 – (0.10?) (2)	0.5 – (1?)	Non-reactive
F2 (F) Non- reactive limestone	X	0.01 (1)	X	Non-reactive

X = no data are available; ~ = data has been interpolated; C = coarse fraction; F = fine fraction

Table 6: Average and range of expansion at end of test period for all concrete prism methods. The number of laboratories having tested each aggregate type is given in brackets.

Aggregate * combination	RILEM AAR-3 (12 months)		RILEM AAR-4 (20 weeks)		RILEM AAR-4 alt. (20 weeks)		German (9 months)	Norwegian (12 months) (2 labs.)
	Average	Range	Average	Range	Average	Range		
Aggregates that react in "normal" timescales								
B1 (C+NRF)	0.254	0.146-0.362 (2)	0.136	0.084-0.170 (3)	0.149	0.120-0.178 (2)	--	--
B1 (C+F)	0.245	0.170-0.290 (3)	0.133	0.12-0.15 (3)	0.140	0.11-0.17 (2)	0.12 (1)	0.234 (1)
UK1 (C+F)	0.367	0.207-0.527 (2)	0.182	0.175-0.191 (3)	0.113	0.071-0.156 (2)	0.196 (1)	0.255 (1)
G1 (C+NRF)	0.564	0.164-0.963 (2)	0.143	0.140-0.168 (4)	0.141	0.121-0.162 (2)	0.166 (1)	--
It1 (C+F)	0.223	0.157-0.308 (3)	0.152	0.039-0.232 (3)	0.083	(1)	--	--
N1 (C+NRF)	0.361	0.288-0.435 (2)	0.197	0.175-0.241 (3)	0.139	(1)	0.174 (1)	0.316 (1)
UK2 (C+F)	0.090	0.073-0.118 (2)	0.098	0.058-0.157 (4)	0.054	0.050-0.058 (2)	--	--
D1 (C+F)	0.233	(1)	0.022	0.019-0.025 (3)	0.033	0.031-0.036 (2)	0.032 (1)	--
"Slowly"-reactive aggregate combinations								
D2 (F+NRC)	0.021	(1)	0.085	0.042-0.120 (3)	0.038	0.034-0.042 (2)	--	--
It2 (C+F)	0.036	0.036 (2)	0.067	0.045-0.097 (3)	0.071	(1)	--	--
N2 (C+F)	0.209	(1)	--	--	--	--	--	0.256/0.265 (2)
N4 (C+F)	0.052	0.040-0.066 (3)	0.100	0.097-0.105 (3)	--	--	0.056 (1)	0.061/0.068 (2)
N5 (C+F)	0.062	0.034-0.078 (3)	0.130	0.117- 0.149 (3)	--	--	0.060 (1)	0.083/0.087 (2)
N6 (C+F)	0.059	(1)	--	--	--	--	--	0.076 (1)
Non-reactive aggregate combinations								
F1 (C+NRF)	0.001	-0.0150-0.002 (3)	0.010	0.007-0.014 (4)	0.024	0.019-0.028 (2)	0.028 (1)	--
F2 (C+F)	0.008	0.001-0.012 (3)	0.006	-0.004-0.012 (3)	0.016	(1)	0.021 (1)	0.005 (1)
F3 (C+F)	0.015	-0.001-0.030 (2)	0.016	0.007-0.023 (4)	0.023	(1)	--	--
N3 (C+F)	0.012	(1)	0.036	0.032-0.039 (2)	--	--	--	0.012 (1)
S1 (C+F)	0.010	0.005-0.014 (2)	0.046	0.021-0.092 (4)	--	--	0.030 (1)	0.049 (1)
P1 (C+NRF)	0.018	0.011-0.027 (3)	0.023	0.003-0.034 (4)	0.036	(1)	--	--
* C = coarse aggregate; F = fine aggregate; NRC = non-reactive coarse aggregate (= F2C, see Table 1); NRF = non-reactive fine aggregate (=N3F, see Table 1)								

Table 7: Maximum average values of expansion measured after three years of exposure at 6 sets of embedded reference points and crack width of cubes stored for four years partly immersed in water on different European outdoor exposure sites.

Storage: Partly immersed in water			Location of outdoor exposure site/country/laboratory							
			Trond-heim	Brevik	Borås Forest	Borås Road	Watford	Düssel-dorf	Milan	Valencia
			N		S		GB	D	I	ES
Aggregate	Combination	Data	SINTEF	Norcem	SP		BRE	VDZ	CESI RICERCA	AIDICO
B1	C+F	Cracks		0.40	0.20	0.15		0.35		2.20
		Exp.		0.167	0.138	<i>0.106</i>		0.186		0.171
B1	C+NRF	Cracks	0.70		0.20		n. d.		1.00	1.50
		Exp.	0.368		0.177		0.197		0.323	<i>0.254</i>
D2	F+NRC	Cracks	0.10		0.05	0.05	n. d.			1.30
		Exp.	0.014		0.017	<i>0.008</i>	0.038			0.420
F1	C+NRF	Cracks					n. d.		0.05	
		Exp.					< 0.0		0.006	
F2	C+F	Cracks		< 0.20	0.05	0.05		0.05		0.00
		Exp.		0.018	0.013	0.005		0.006		<i>0.007</i>
G1	C+NRF	Cracks	0.10					0.20	0.30	
		Exp.	0.059					0.133	0.146	
It2	C+F	Cracks		< 0.20					0.05	
		Exp.		0.021					0.013	
N1	C+NRF	Cracks	0.05		0.05	0.10	n. d.	0.05		0.25
		Exp.	0.015		0.012	<i>0.014</i>	0.052	0.118		<i>0.160</i>
N2	C+NRF	Cracks		< 0.20			n. d.			
		Exp.		0.016			0.018			
N4	C+F	Cracks		< 0.2				0.05	0.00	
		Exp.		0.013				0.013	0.006	
S1	C+F	Cracks		< 0.20	0.05	0.05		0.05		0.00
		Exp.		0.022	0.006	<i>0.007</i>		0.014		0.010
UK1	C+F	Cracks	0.15		0.05	0.05	n. d.			0.20
		Exp.	0.117		0.015	<i>0.013</i>	0.023			0.146
P1	C+NRF	Cracks			0.05				0.00	
		Exp.			0.008				0.028	

Exp. = maximum expansion of cubes in % after approx. three years of exposure (new “zero” measurement in June 2005)
Cracks = maximum crack width of cubes in mm that occurred after approx. 4 years of testing
n. d. = no data provided; *Italic data* = Value is based only on 2 or 4 sets of embedded reference points
C = coarse aggregate; F = fine aggregate;
NRC = non-reactive coarse aggregate (= F2C, see Table 1); NRF = non-reactive fine aggregate (=N3F, see Table 1)

Table 8: Maximum average values of expansion measured after three years of exposure at 6 sets of embedded reference points and crack width of cubes stored for four years only exposed to ambient rainfall on different European outdoor exposure sites. (Regarding abbreviations: see footnotes to Table 7).

Storage: Exposed only to ambient rainfall			Location of outdoor exposure site/country/laboratory							
			Trondheim	Brevik	Borås Forest	Borås Road	Watford	Düsseldorf	Milan	Valencia
			N		S		GB	D	I	ES
Aggregate	Combination	Data	SINTEF	Norcem	SP		BRE	VDZ	CESI RICERCA	AIDICO
B1	C+F	Cracks		0.50	0.20	0.20		0.40		3.00
		Exp.		0.225	0.173	0.176		0.211		0.206
B1	C+NRF	Cracks	0.50		0.20		n. d.		1.00	0.90
		Exp.	0.299		0.248		0.208		0.420	0.220
D2	F+NRC	Cracks	0.05		0.05	0.05	n. d.			1.50
		Exp.	0.014		0.018	0.015	0.070			0.371
F1	C+NRF	Cracks					n. d.		0.05	
		Exp.					< 0.0		0.004	
F2	C+F	Exp.		< 0.20	0.05	0.05		0.05		0.00
		Cracks		0.018	0.002	0.007		0.007		0.008
G1	C+NRF	Cracks	0.30					0.25	0.10	
		Exp.	0.087					0.174	0.149	
It2	C+F	Cracks		< 0.20					0.00	
		Exp.		0.011					0.019	
N1	C+NRF	Cracks	0.10		0.10	0.10	n. d.	0.15		0.30
		Exp.	0.030		0.014	0.013	0.046	0.143		0.151
N2	C+NRF	Cracks		< 0.20			n. d.			
		Exp.		0.011			0.012			
N4	C+F	Cracks		< 0.20				0.05	0.00	
		Exp.		0.015				0.012	0.017	
S1	C+F	Cracks		< 0.20	0.05	0.05		0.10		0.00
		Exp.		0.022	0.006	0.005		0.014		0.031
UK1	C+F	Cracks	0.15		0.05	0.05	n. d.			0.25
		Exp.	0.110		0.032	0.014	0.060			0.089
P1	C+NRF	Cracks			0.05				0.00	
		Exp.			0.006				0.010	

Table 9A: Comparison of results of test methods with behaviour in field sites and structures
(regarding abbreviations: see footnotes to Table 9C).

Aggregate	Fraction/ combination	Reactivity/evaluation							Reported reactivity in structures?
		AAR-1	AAR-2	AAR-3	AAR-4/ AAR-Alt	TI-B51/ Chatterji	German/ Norwegian	Field site test after 4 years**	
“Normally” reactive aggregate combinations									
B1 - Silicified limestone	F	R	R			R/R			Yes
	C	R							
	C+F			R	R/R		R/R	R	
	C+NRF			R	R/R			R	
UK1 - Greywacke	F	R	R			R/R			Yes, normally +20 years
	C	R							
	C+F			R	R/R		R/R	R	
G1 - Crushed gravel with siliceous limestone and chert	C	R	R			R/-			Yes, 10 years if severe conditions
	C+NRF			R	R/R		R/-	R	
G2 - Gravel with opaline sandstone and flint	C	R	R			R/-			Yes, <10 years
It1 - Gravel with silicified limestone and flint	F	R	R			R/-			Yes, 5-10 years
	C	R	R						
	C+F			R	R/R				
N1 - Cataclasite	C	R	R			R/R			Yes, 10-15 years
	C+NRF			R	R/R		R/R	R	
UK2 - Gravel with quartzite and chert	F	R	R			R/R			Yes, 10-15 years
	C	R							
	C+F			R	R/R				
D1 - Gravel with opaline flint	F	R	R						Yes, quickly but pessimum effect
	C	R	R			R/R			
	C+F			?	NR/NR		NR/-		
D2 - Sea gravel semi-dense flint	F	R	R			R/R			Yes, 10-15 years
	C	R	R						
	F+NRC			NR/MR?	R/MR			R	

Table 9B: Comparison of results of test methods with behaviour in field sites and structures
(regarding abbreviations: see footnotes to Table 9C).

Aggregate	Fraction/ combination	Reactivity/evaluation							Reported reactivity in structures?
		AAR-1	AAR-2	AAR-3	AAR-4/ AAR-Alt	TI-B51/ Chatterji	German/ Norwegian	Field site test after 4 years**	
“Slowly” reactive aggregate combinations									
It2 - Gravel with quartzite	F	R	R			NR/-			Yes, 50 years
	C	R	R						
	C+F			NR	R/R			n.r.	
N2 - Sandstone	C	R	R			NR/R			Yes, 15-20 years
	C+NRF			R			-/R	n.r.	
N4 - Gravel with sandstone and cataclastic rocks	F	R	R			R/R			Yes, 20-25 years
	C	R	R						
	C+F			MR	R/-		MR/MR	n.r.	
N5 - Gravel with rhyolite and quartzite	F	R	R			R/R			Yes, 20-25 years
	C	R	MR						
	C+F			MR	R/-		MR/MR		
N6 - Gravel with sandstone, rhyolite and mylonite	F	R							Yes, 20-25 years
	C	R							
	C+F			MR			-/MR		

Table 9C: Comparison of results of test methods with behaviour in field sites and structures

Aggregate	Fraction/ combination	Reactivity/evaluation							
		AAR-1	AAR-2	AAR-3	AAR-4/ AAR-Alt	TI-B51/ Chatterji	German/ Norwegian	Field site test after 4 years**	Reported reactivity in structures?
“Non-reactive” aggregate combinations									
F1 - Gravel with flint	C	R	NR			NR/R			No, but known pessimism effect
	C+NRF			NR	NR/NR		NR/-	n.r.	
F2 - Non-reactive limestone	F	NR	NR						No
	C	NR							
F3 - Gravel with quartzite, flint, greywacke and granitoids	C+F			NR	NR/NR		NR/NR	n.r.	No, but likely pessimism effect
	F	R	R			NR/R			
	C	R							
S1 - Gravel with metarhyolite and greywacke	C+F			NR	MR/-		NR/MR	n.r.	Yes, but source variable in composition
	F	R	R			R/R			
	C	R							
P1 - Silicified limestone	C	R	NR			NR/-			Yes, but source and information uncertain
	C+NRF			NR	NR-MR/ MR			n.r.	
N3 - Granitic sand	F	NR	NR			NR/NR			No
	C	NR							
	C+F			NR	MR/-		NR/NR		
E1 - Dolomitic limestone	F	NR	NR						Information uncertain
D3 - Siliceous sand	F	NR	NR			NR/-			No

F = fine aggregate; C = coarse aggregate

NRF = non-reactive fine aggregate (=N3F, see Table 1); NRC = non-reactive coarse aggregate (=F2C, see Table 1)

R = reactive (according to the critical limits in the different testing methods)

NR = non-reactive (according to the critical limits in the different testing methods)

MR = marginally reactive (i.e. expansions just above the critical limits in the different testing methods)

n.r. = no rating yet possible

* = one result strongly reactive, second non-reactive

** = the evaluation of the preliminary results from the field sites is based on measurements of crack widths after about 4 years of exposure and of expansions during the last 3 years (the expansion measurements were re-started in 2005 due to problems with the zero measurements at some field sites).

Table 10: Precision statements for all assessed methods; m is the mean value.

Expected reactivity	Low to medium	Medium	High
AAR-2 Long prisms 14 days, 5 prisms, 1 recalculation			
General mean m	0.133	0.420	0.375
Repeatability $COV(\hat{\sigma}_d)$	6.80 %	2.70 %	1.9%
Reproducibility $COV(\hat{\sigma}_R)$	17.1%	22.0%	11.0%
AAR-2 Long prisms 28 days, 5 prisms, 2 recalculations			
General mean m	0.236	0.550	0.578
Repeatability $COV(\hat{\sigma}_d)$	2.5%	1.2%	3.0%
Reproducibility $COV(\hat{\sigma}_R)$	2.5%	6.6%	14.4%
AAR-2 Short prisms 14 days, 5 prisms, 1 recalculation			
General mean m	0.127	0.254	0.295
Repeatability $COV(\hat{\sigma}_d)$	5.5%	5.7%	4.2%
Reproducibility $COV(\hat{\sigma}_R)$	14.7%	19.8%	35.1%
AAR 2 Short prisms 28 days, 3 prisms, 2 recalculations			
General mean m	0.271	0.467	0.592
Repeatability $COV(\hat{\sigma}_d)$	3.4%	2.3%	2.5%
Reproducibility $COV(\hat{\sigma}_R)$	22.4%	24.3%	16.5%
AAR-3			
General mean m	0.059	0.181	0.260
Repeatability $COV(\hat{\sigma}_d)$	15.3%	13.8%	20.7%
Reproducibility $COV(\hat{\sigma}_R)$	49.3%	53.7%	54.3%
AAR-4 Alt.			
General mean m	0.107	0.130	0.170
Repeatability $COV(\hat{\sigma}_d)$	11.2%	9.1%	16.4%
Reproducibility $COV(\hat{\sigma}_R)$	33.1%	26.4%	24.2%



Figure 1: Location of outdoor exposure sites.

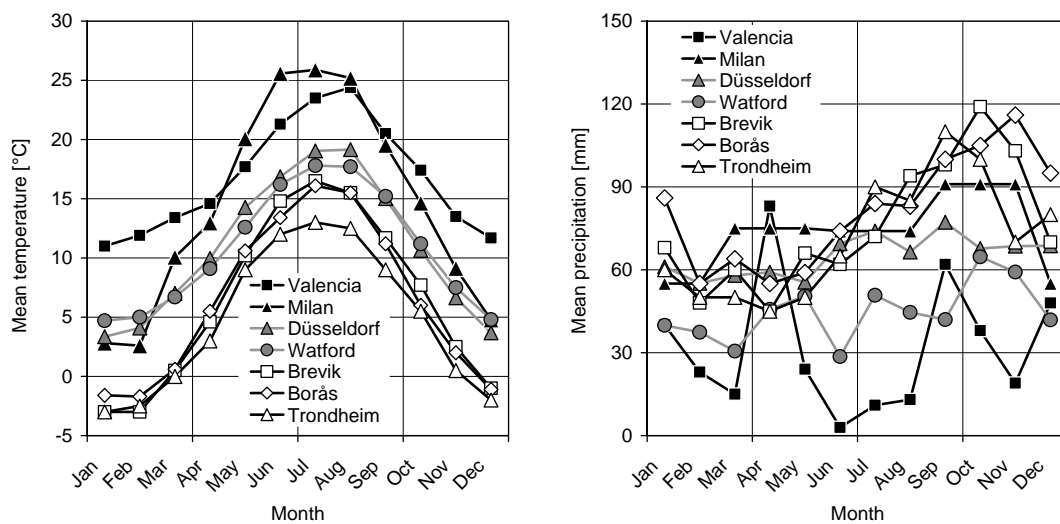


Figure 2: Mean temperature and precipitation at different field sites.



Figure 3: Concrete cubes located at the outdoor exposure site in Düsseldorf, Germany

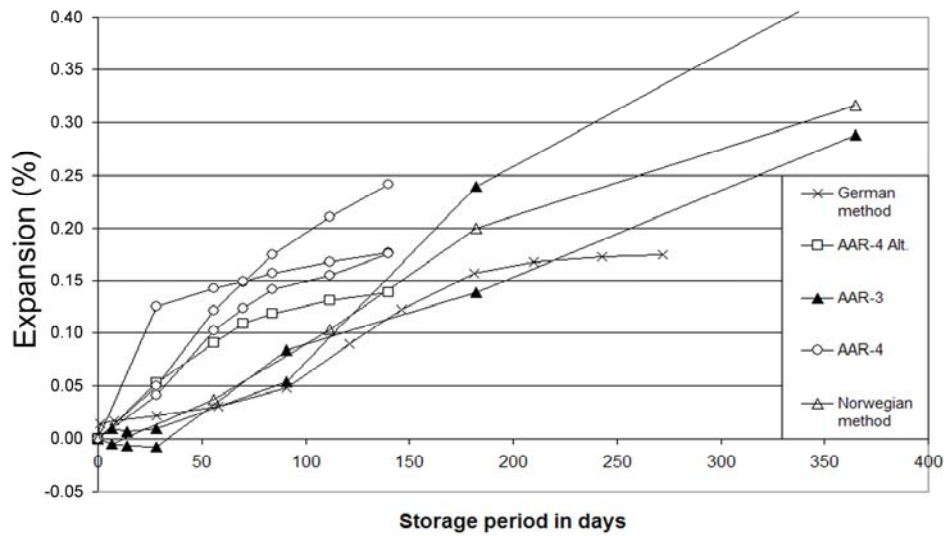


Figure 4: Expansion of the coarse “normally” reactive aggregate N1 (cataclasite) in combination with the non-reactive fine aggregate N3 (granitic sand) in the various concrete prism methods.

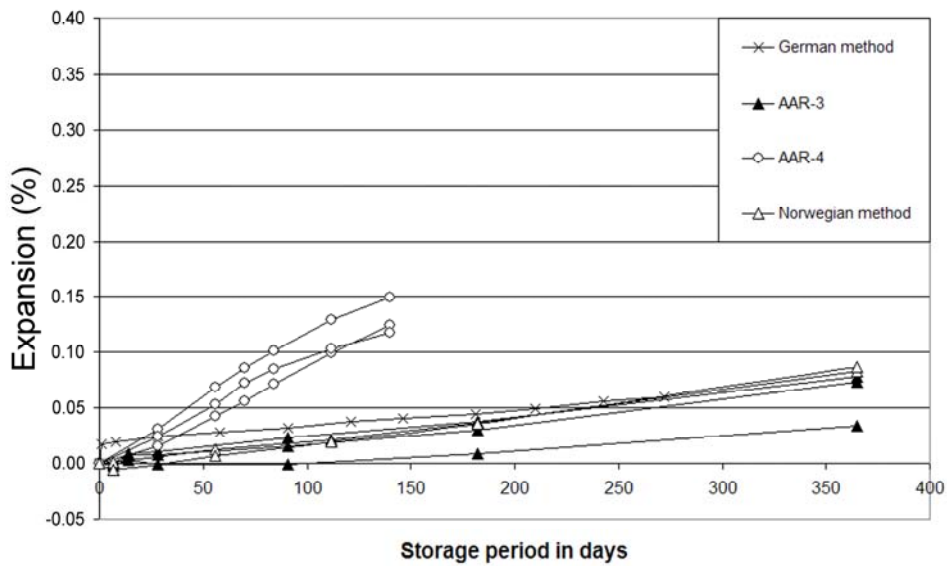


Figure 5: Expansion of the “slowly” reactive aggregate N5 (fine/coarse gravel with the reactive rock types rhyolite and fine grained quartzite) in the various concrete prism methods.

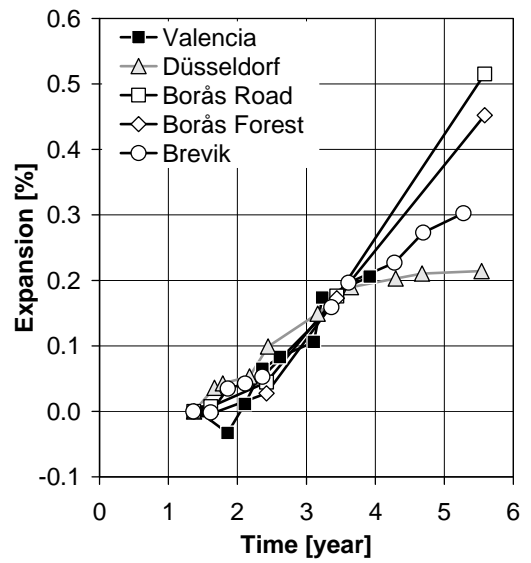
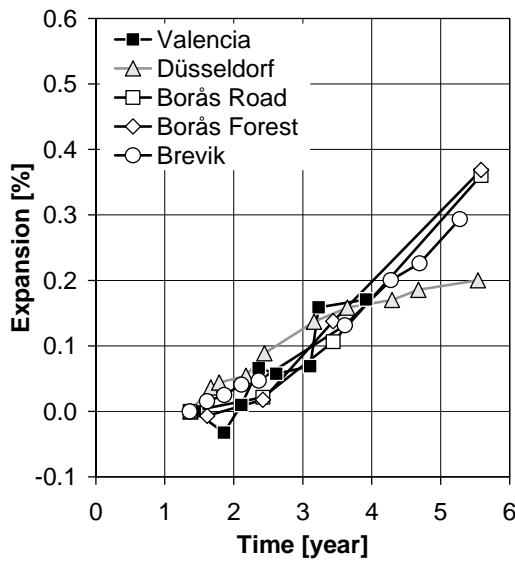


Figure 6: Mean expansion of concrete cubes with aggregate combination B1(C+F); left: stored partly immersed in water; right: only exposed to ambient rainfall

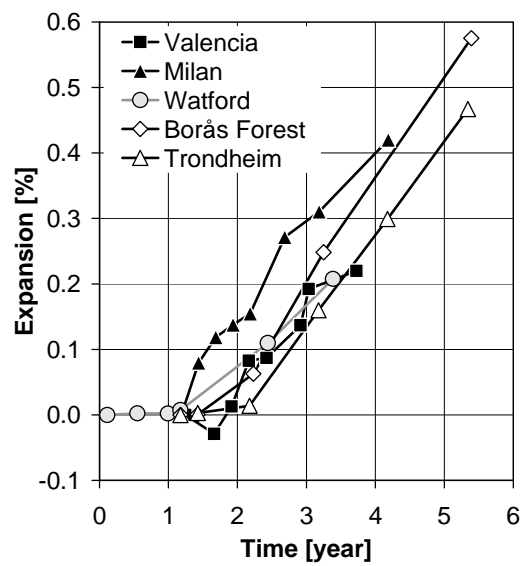
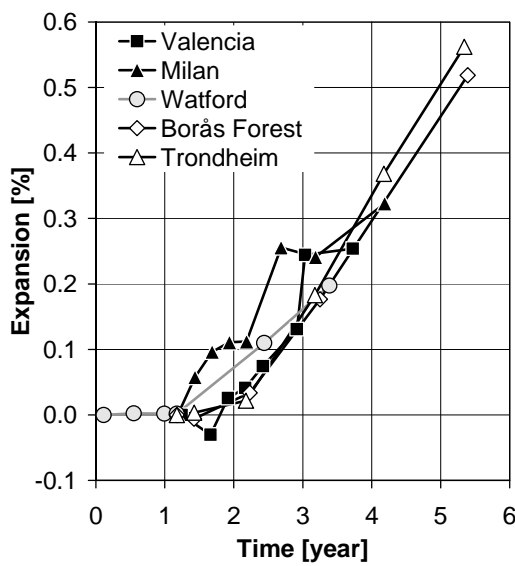


Figure 7: Mean expansion of concrete cubes with aggregate combination B1(C+NRF); left: stored partly immersed in water; right: only exposed to ambient rainfall

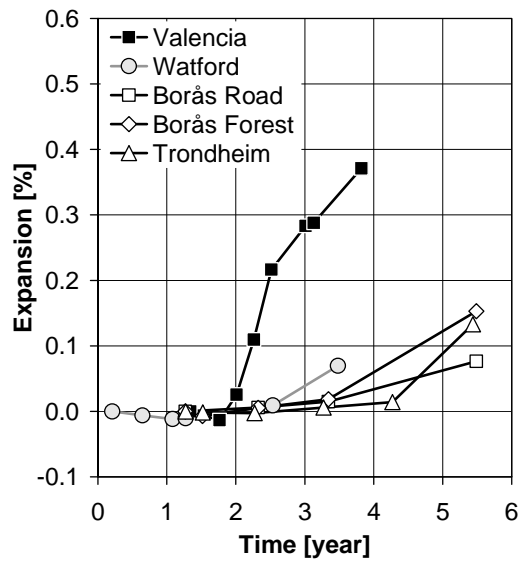
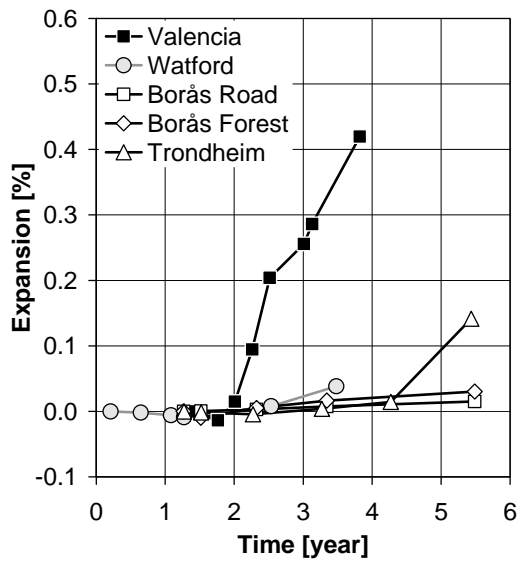


Figure 8: Mean expansion of concrete cube with aggregate combination D2(F+NRC); left: stored partly immersed in water; right: only exposed to ambient rainfall

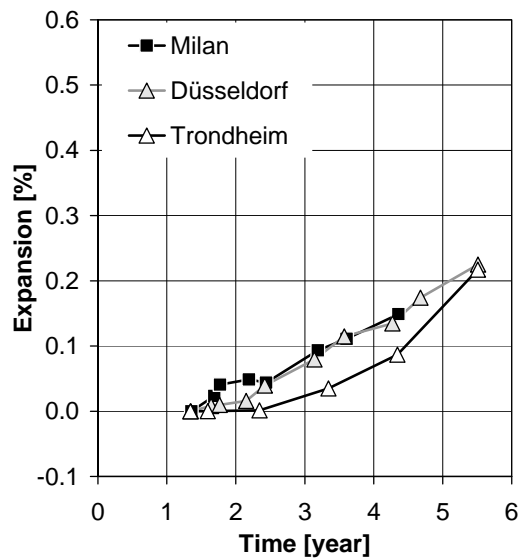
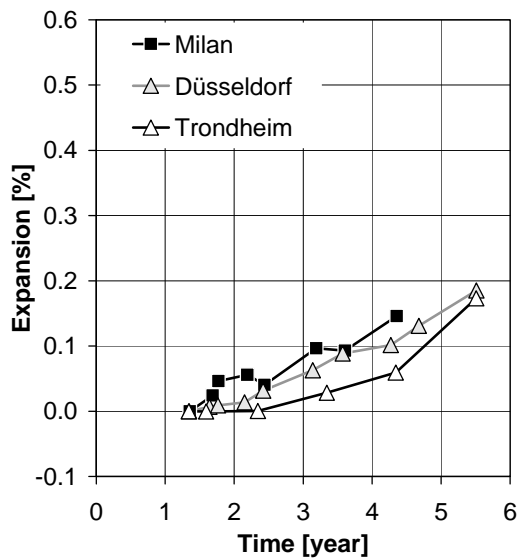


Figure 9: Mean expansion of concrete cube with aggregate combination G1(C+NRFF); left: stored partly immersed in water; right: only exposed to ambient rainfall

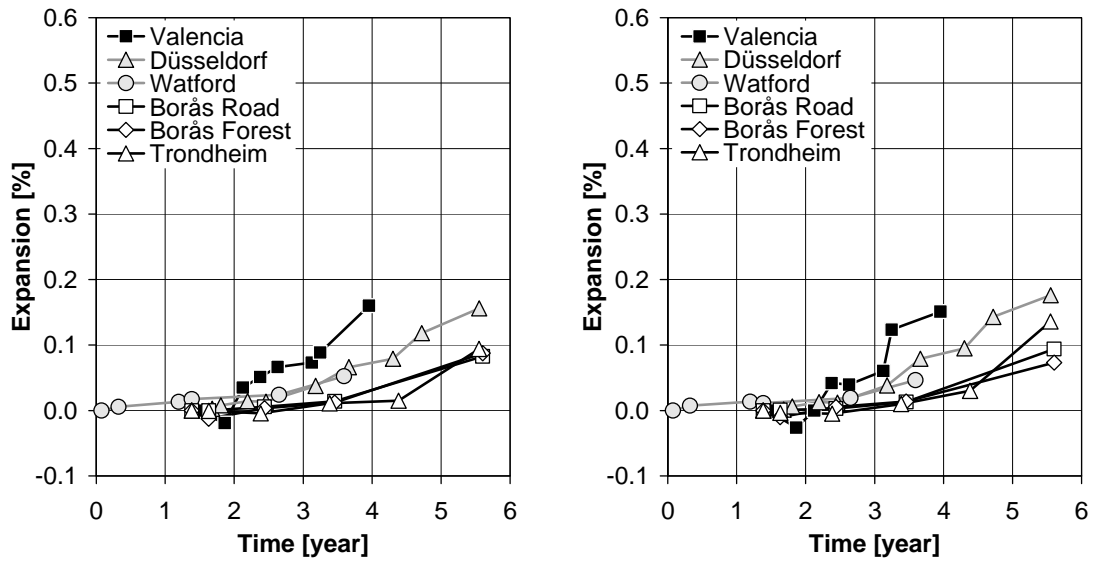


Figure 10: Mean expansion of concrete cube with aggregate combination N1(C+NRf); left: stored partly immersed in water; right: only exposed to ambient rainfall

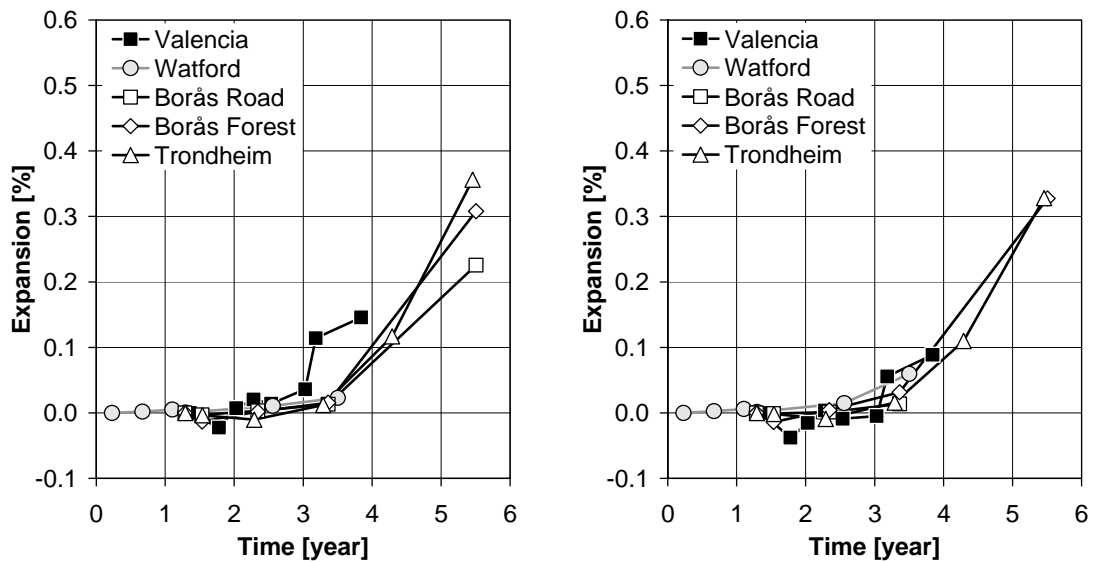


Figure 11: Mean expansion of concrete cube with aggregate combination UK1(C+F); left: stored partly immersed in water; right: only exposed to ambient rainfall

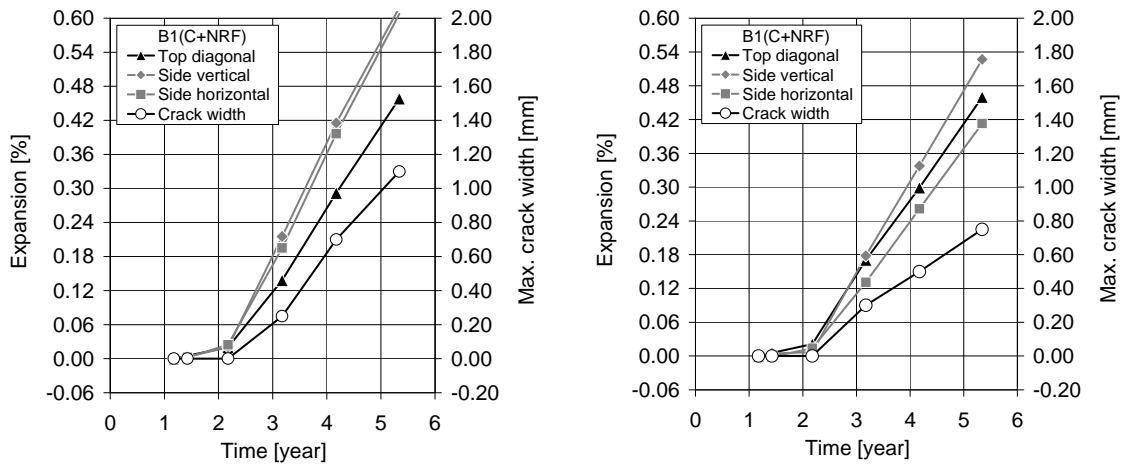


Figure 12: Expansion of and max. crack width at concrete cubes with aggregate combination B1(C+NRF); field site Trondheim, Norway; left: stored partly immersed in water; right: only exposed to ambient rainfall

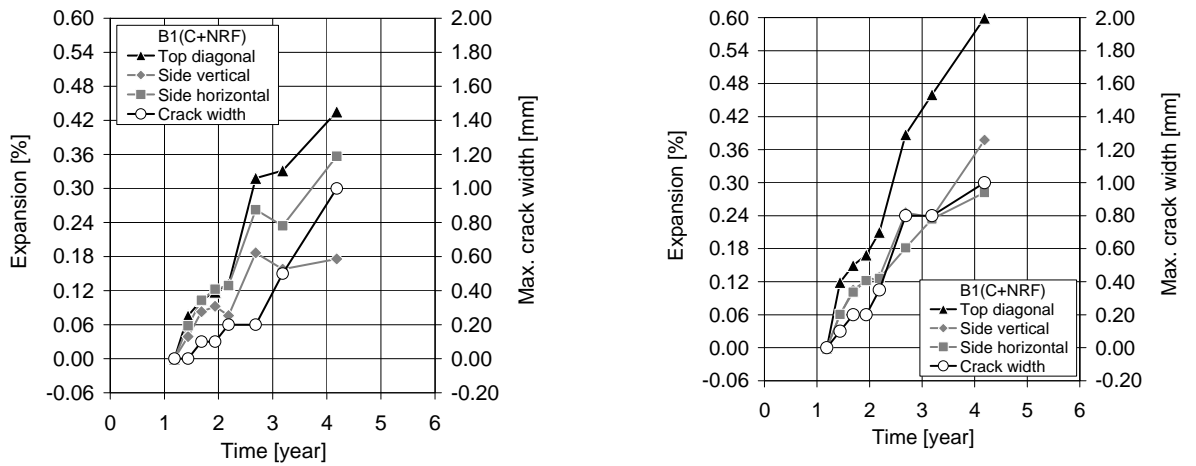


Figure 13: Expansion of and max. crack width at concrete cubes with aggregate combination B1(C+NRF); field site Milan, Italy; left: stored partly immersed in water; right: only exposed to ambient rainfall

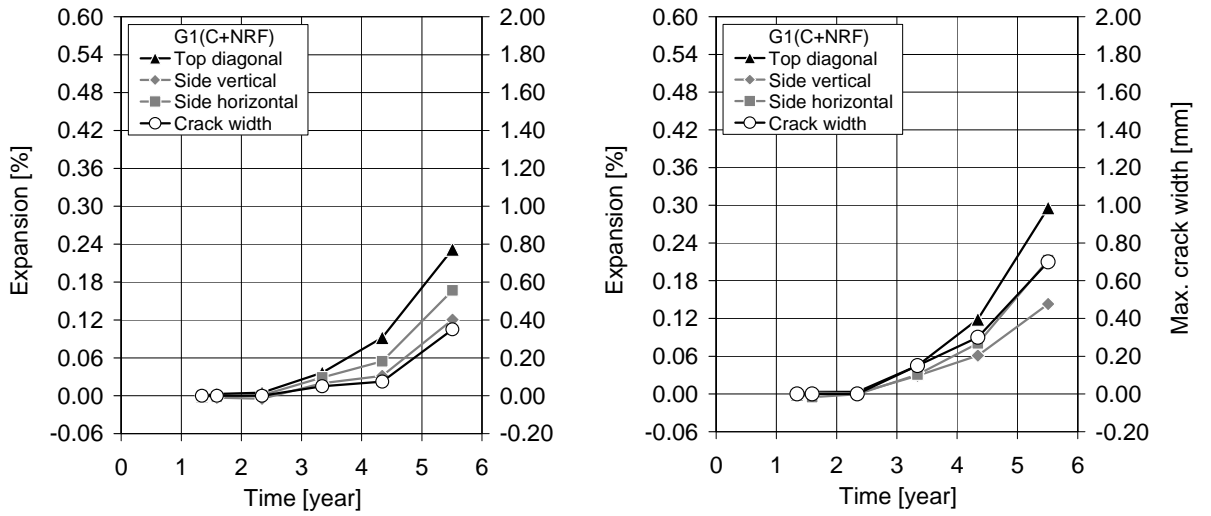


Figure 14: Expansion of and max. crack width at concrete cubes with aggregate combination G1(C+NRF); field site Trondheim, Norway; left: stored partly immersed in water; right: only exposed to ambient rainfall

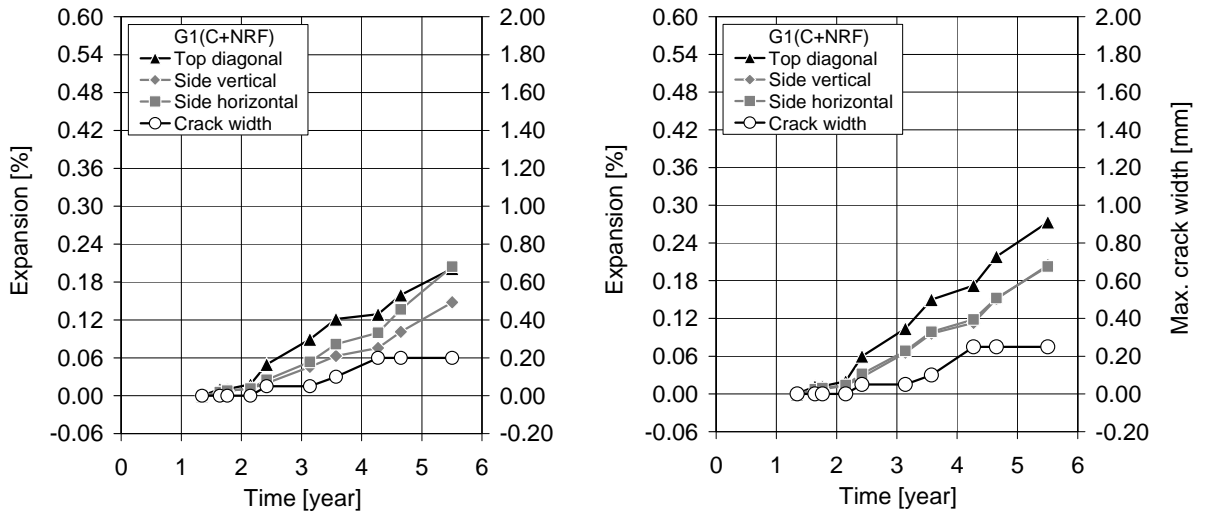


Figure 15: Expansion of and max. crack width at concrete cubes with aggregate combination G1(C+NRF); field site Düsseldorf, Germany; left: stored partly immersed in water; right: only exposed to ambient rainfall

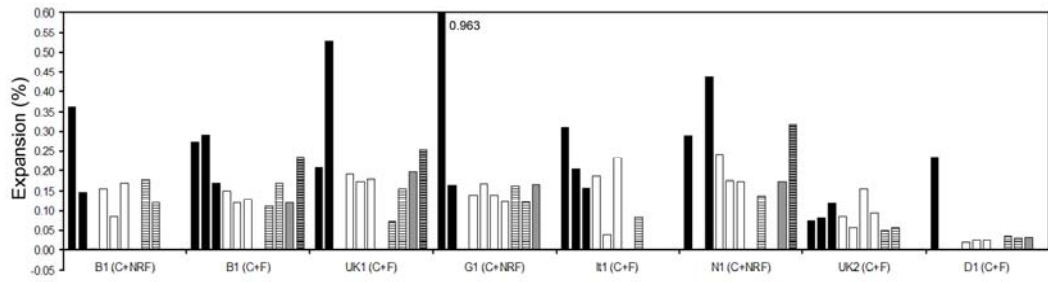


Figure 16: “Normally” reactive aggregate combinations: % expansion at the end of the test period – all concrete prism methods. Order in chart is RILEM AAR-3 (black), RILEM AAR-4 (white), RILEM AAR-4 Alt. (white with stripes), German (grey), Norwegian (grey with stripes).

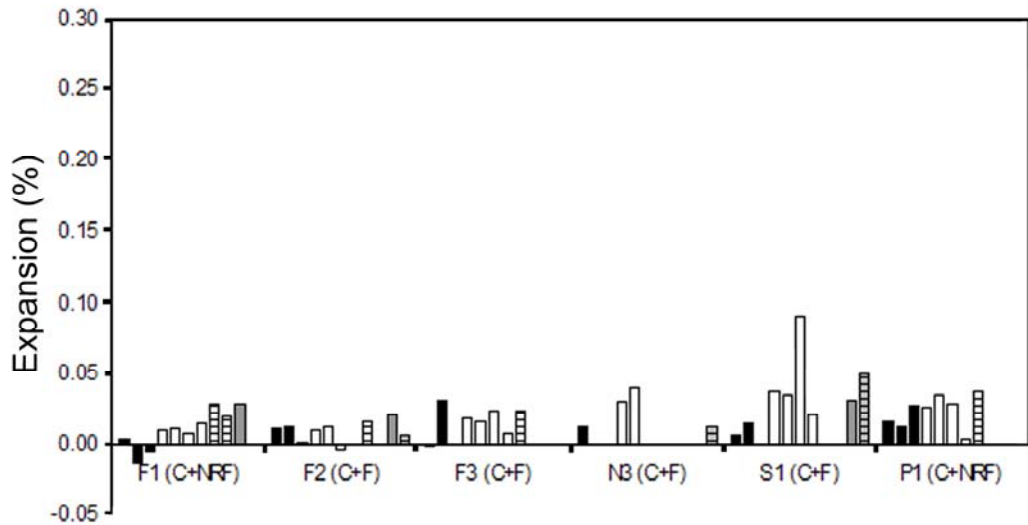


Figure 17: Non-reactive aggregate combinations: % expansion at the end of the test period – all concrete prism methods. Order in chart is RILEM AAR-3 (black), RILEM AAR-4 (white), RILEM AAR-4 Alt. (white with stripes), German (grey), Norwegian (grey with stripes).

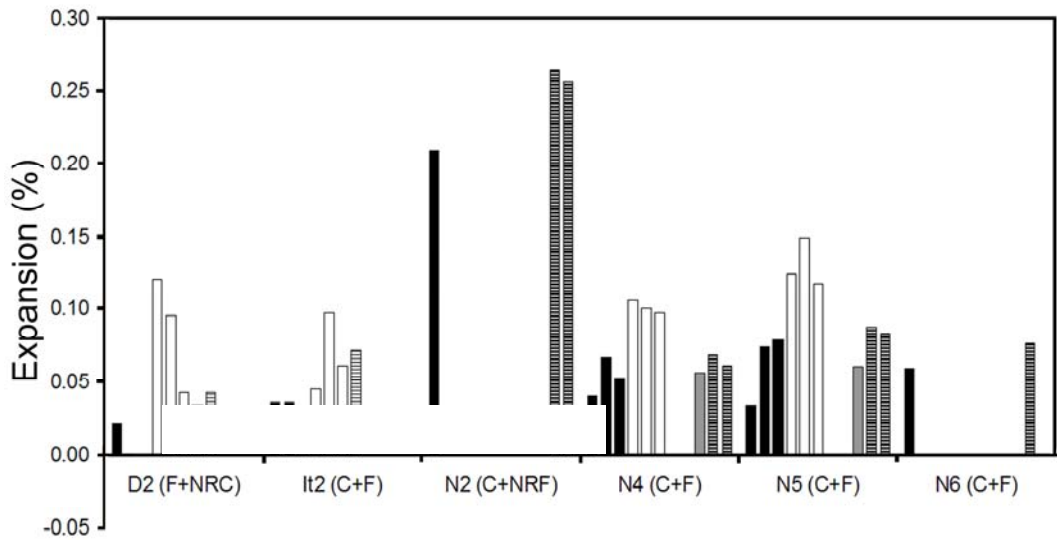


Figure 18: “Slowly” reactive aggregate combinations: % expansion at the end of the test period – all concrete prism methods. Order in chart is RILEM AAR-3 (black), RILEM AAR-4 (white), RILEM AAR-4 Alt. (white with stripes), German (grey), Norwegian (grey with stripes).



Figure 19: Fractional shovelling, in accordance with EN 932-2.

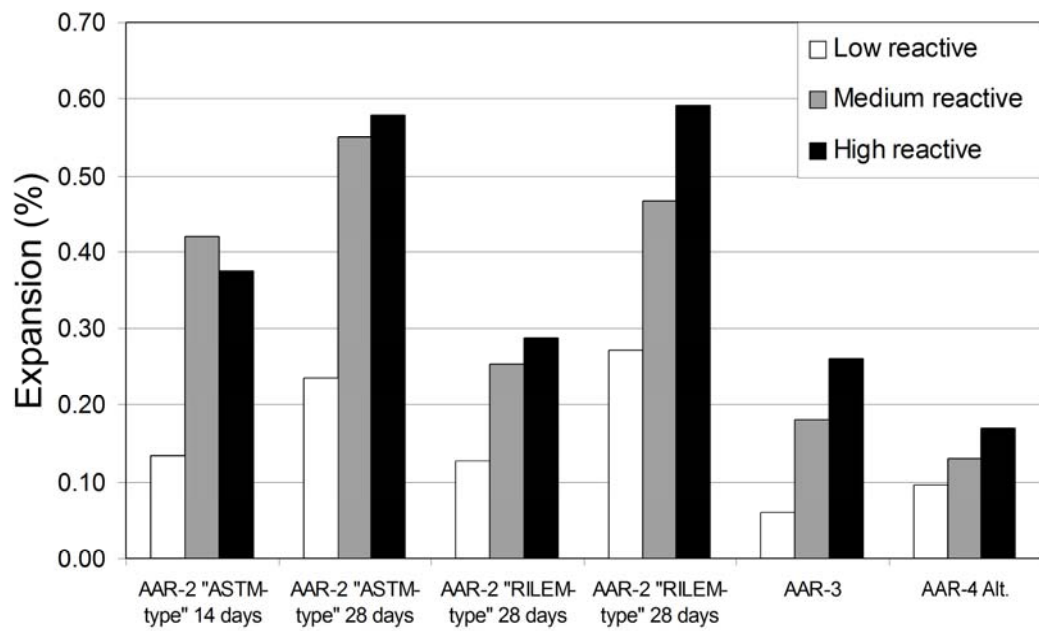


Figure 20: Classification of the three test materials according to the RILEM methods evaluated in the precision trial. The white coloured columns indicate the results of the least expansive material combinations.