EVALUATION OF TEST METHODS FOR THE ASSESSMENT OF THE ALKALI-REACIVITY OF AGGREGATES AND CONCRETE COMPOSITIONS

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Abstract

This report describes the results of investigations divided into three different subjects. Firstly, the results of two different accelerated mortar bar tests that can be used for the assessment of the alkali-reactivity of aggregates according to the German Alkali Guidelines were compared. Secondly, the reliability of the 60 °C concrete prism test compared to the concrete prism test with 40 °C fog chamber storage for aggregate assessment was investigated. Furthermore, the results from the concrete prism test with the 40 °C fog chamber were compared with the current state of the corresponding concrete cubes and prisms which were stored at an outdoor exposure site. Thirdly, the suitability of the 60 °C concrete prism test as a performance test for the assessment of the alkali-reactive potential of specific concrete compositions that were made with different w/c ratios, cement contents, $Na_2O_{eq.}$ of cements, cement types and fly ashes was examined.

Keywords: alkali-silica reaction, test methods, outdoor exposure site, aggregate assessment, performance testing

1 INTRODUCTION

In practice a deleterious alkali-silica reaction (ASR) can occur relatively rapidly. In fact it can occur within one to three years with very reactive aggregates (in Germany these are generally gravels that contain porous opaline sandstone and flint), high alkali content in the concrete and moist ambient conditions – possibly with external supply of alkalis. However, with dense, slow-reacting, aggregates without pessimal behaviour (in Germany, for example, these are rhyolites, greywackes and crushed Upper Rhine gravel) it may only lead to visible damage after 10 to 30 years. Laboratory tests for a deleterious ASR are therefore particularly difficult. The tests should provide information within two to six months as to whether any damage will occur in practice after 10 to 30 years. The development of a test method is therefore only possible if there have been long-term investigations with test specimens stored outdoor at an exposure site and if investigations on structures with known concrete composition can be used for comparison.

Some cases of damage to concrete pavements have occurred in Germany in recent years that were attributable to reactive aggregates that had not yet been included in the German Alkali Guidelines. Therefore the Alkali Guidelines were revised in 2007 [1]. Accelerated mortar bar tests have been included for the first time. Furthermore, it is permissible for the suitability of specific concrete compositions to be assessed by an expert on the basis of performance tests. Figure 1 shows the strategy for aggregate testing according to Part 3 of the German Alkali Guidelines [1]. The specific points that should be taken into account are described below.

After the petrographic investigation of the aggregate an accelerated mortar bar test is carried out as part of an initial test on three samples per aggregate. For crushed rock it is sufficient to test the 8/16 mm fraction. For crushed gravel the 2/8 and 8/16 fractions are tested together by crushing a mixture of the two fractions. The samples have to be taken by the testing institute or by the third-party inspector at intervals of about four weeks.

If the accelerated mortar bar test is passed then no further tests or measures will be necessary. If the accelerated mortar bar test is not passed then a concrete prism test shall be carried out. If the aggregate passes the concrete prism test, no further tests or measures will be required, not even if alkali is supplied from outside. In case of failure, the measures mentioned in Part 3 of the Guidelines have to be taken.

If no expert is involved and no performance test is carried out then the following general rule will apply: for concretes that are exposed to a moist environment with external supply of alkalis the aggregate must be replaced. If the concrete is exposed to a moist environment without external supply of alkalis then the aggregate can be used in the concrete in combination with a low-alkali cement. These measures mean that a number of aggregates or cements cannot be used in specific areas so it is

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advisable to have the concrete composition to be used specially assessed by an expert report using a performance test. Performance tests are essential if aggregates or cements are not to be unnecessarily excluded from use but to guarantee the safety of the concrete construction.

2 METHODS AND MATERIALS

2.1 General

Numerous test methods have been developed for assessing the reactivity of aggregates on the one hand and for assessing concrete with respect to the risk of the occurrence of a deleterious alkali silica reaction on the other hand. Accurate modelling of the conditions actually present in an individual instance is not possible with a single test method. However, a suitable model should reflect the practical behaviour. It should also lead to the smallest possible variance. In principle, any such test method is a convention. Test methods for aggregates should make it possible to classify an aggregate as non-reactive, potentially reactive or very reactive. The tests for characterizing the reactivity of an aggregate are divided into accelerated mortar bar test methods and concrete prism tests. Performance test methods should make it possible to assess whether or not the concrete to be used in a particular instance would in practice show any deleterious ASR, even in the long term.

2.2 Aggregate assessment

During the testing of the alkali reactivity of an aggregate it is necessary to differentiate between porous aggregates such as gravel with opaline sandstone or flint, possibly with pessimum behaviour, and dense aggregates. The test methods described below can only be used for dense aggregates without pessimum behaviour. Special framework conditions must be considered for porous aggregates.

2.2.1 Accelerated mortar bar tests

Two methods are used in Germany – the accelerated mortar bar test at 80 °C [2], which originated from Oberholster and Davies [3] as well as from RILEM [4], and the accelerated mortar bar test at 70 °C that was developed by Philipp [5]. Both have been adopted in slightly modified form as reference and alternative method in the German Alkali Guidelines [1].

Various fractions of 16 different aggregates were investigated using the accelerated mortar bar test at 80 °C (80 °C method) and the accelerated mortar bar test (70 °C method with measurement at 70 °C).

Accelerated mortar bar test (Reference method)

The aggregate is ground down to 0.125 mm to 4 mm and the comminuted material is used to produce mortar (three 40 mm x 40 mm x 160 mm mortar prisms). The expansion of the prisms is measured after storage for 13 days (formerly 14 days) in 1 molar NaOH solution at 80 °C. The limit value for the expansion of the mortar bars is 1.0 mm/m. The lengths of the bars are measured at 80 °C [1].

Accelerated mortar bar test (Alternative method)

The aggregate is ground down to 0.5 mm to 2 mm. For production of the mortar the alkali content is raised to an Na_2O equivalent of 2.5 wt% relative to the cement by addition of NaOH solution. The test is carried out on three mortar bars (40 mm x 40 mm x 160 mm) that are stored for 28 days at 70 °C above water in closed containers. The limit value for the expansion after 28 days is 1.5 mm/m. The lengths of the bars are measured at 20 °C [1]. Previously, the measurements were carried out at 70 °C, whereas the limit value was 2.0 mm/m after 21 days [5].

2.2.2 Concrete prism tests

The 40 °C fog chamber storage used to be the only method for assessing the alkali-reactivity of aggregates in Germany. This method was included in the former German Alkali Guidelines [6] and corresponds almost to the RILEM AAR-3 method [7]. The disadvantage of this method is its long duration of nine months. The 60 °C concrete prism test is to be applied as an alternative method permitting faster testing in the future.

Comparative tests with various aggregates were carried out with the 40 °C fog chamber storage and with the 60 °C concrete prism test. The concrete composition was in accordance with part 3 of the Alkali Guidelines [1]. In some cases the concrete composition for the 60 °C concrete prism test was in accordance with AAR-4 [9].

40 °C fog chamber storage

The 2/16 mm or 2/22 mm fraction is tested using three concrete prisms (100 mm x 100 mm x 500 mm) and one cube (300 mm), which are stored in a fog chamber for nine months at 40 °C and about 100 % r.h. The aggregate can be classified as non-reactive if the expansion of the prisms does not exceed 0.6 mm/m and the maximum crack width on the cube is less than 0.2 mm. It should be borne in mind that the expansion includes the temperature expansion and the moisture expansion.

60 °C concrete prism test

The 60 °C concrete prism test was defined on the basis of the procedures in the French standard NF P 18-454 [8] and the RILEM AAR-4 method [9]. The 2/16 mm or 2/22 mm coarse fraction of the aggregate is used to produce three 75 mm x 75 mm x 280 mm prisms, which, after removal from the mould, are stored in a testing cabinet at 60 °C and a minimum of 98% r.h. above water in tightly sealed containers in a test reactor. The expansion is determined by measuring the lengths of the prisms at 20 °C at 0, 4, 8, 12, 16 and 20 weeks after production of the test specimens. Based on [10] the limit value is provisionally set at 0.3 mm/m after twelve weeks for aggregate testing [11].

2.3 Performance testing

If an aggregate is classified as reactive (E III) in accordance with the German Alkali Guidelines then, depending on the moisture class of the structural component and the cement content of the concrete, the aggregate has to be replaced or cements with a low effective alkali content (low-alkali cements) have to be used. Performance tests are essential if aggregates or cements are not to be unnecessarily excluded from use and also, if necessary, for simulating an external supply of alkalis. The performance method should provide information about whether an intended concrete composition with a particular aggregate and particular cement can be used for a specific moisture class. The 60 °C concrete prism test and the cyclic climate storage [12] are currently being refined in Germany for this purpose. These methods are to be included in a future Part 4 of the German Alkali Guidelines. If the 60 °C concrete prism is used as a performance test a limit value of 0.2 mm/m after twelve weeks based on [13] will be applicable at present [11].

2.4 Outdoor storage

Long-term outdoor storage is essential in order to establish the limit values for ASR test methods. This outdoor storage provides a good indication for the suitability of a test method. By using the outdoor storage it was established that aggregates that in practice lead to damage can be detected with the 40 °C fog chamber storage (as a test for aggregate assessment) but that the 40 °C fog chamber storage is not suitable as a performance test [14], [15]. Two prisms (100 mm x 100 mm x 500 mm) and one cube (300 mm) are used for the outdoor storage.

Eleven aggregates were tested as described in section 2.2.2 in accordance with part 3 of the Alkali Guidelines [1] within the 40 °C fog chamber storage. At the same time test specimens have been stored on an outdoor exposure site on the roof of the Research Institute of the Cement Industry, Düsseldorf, Germany, and observed for six to eleven years up to now.

2.5 Materials

Different starting materials and concrete compositions were used for comparing different test methods and for the comparison between test methods and outdoor storage or the behaviour of structures. The following coarse aggregates, among others, were used:

crushed gravel from the Upper Rhine
greywacke
rhyolite
gravel with rhyolite
Rhine gravel (Düsseldorf)

A Rhine sand (Düsseldorf) was used as the fine aggregate. The cements used were:

Portland cements with alkali contents between 0.6 and 1.3 wt% (Na_2O equivalent)
CEM II/B-S and CEM II/B-M (S-LL) Portland composite cements

The cement content of the concrete lay between 300 kg/m³ and 500 kg/m³. The above mentioned test methods are used.

3 RESULTS

3.1 Aggregate assessment

3.1.1 Accelerated mortar bar test

The results of the accelerated mortar bar tests show that there is no strict correlation between the results obtained by the two methods. In most cases, however, the reference method and the alternative method lead to at the same classification as far as the alkali-reactivity of aggregates is concerned (Figure 2). Deviating classifications were obtained in three cases only. As a tendency, the reference method is somewhat more stringent than the alternative method.

3.1.2 Concrete prism test Error! Reference source not found. shows the results of the aggregate assessment within the 40 °C fog chamber and the 60 °C concrete prism test in accordance with Part 3 of the Alkali Guidelines. The figure shows the expansions after nine months of fog chamber storage and after twelve weeks within the 60 °C concrete test. If cracks being ≥ 0.2 mm occurred on the 300 mm cube during the 40 °C fog chamber storage the point is marked in black within the diagram. The aggregate is considered to be non-reactive in the case of the 40 °C fog chamber storage in the event that the expansion of the bars do not exceed 0.6 mm/m and the maximum crack width of the cube is lower than 0.2 mm. The results show that the 60 °C concrete prism test after a period of time of three months, in general, provides the same information regarding the alkali reactivity as the 40 °C fog chamber storage after nine months. Up to now only two of eighteen aggregates have been assessed differently.

3.1.3 Outdoor storage

Figure 4 shows the expansions of the bars as well as the maximum crack width on the cube after nine months of fog chamber storage. In the event that significant expansions or cracks of a minimum size of 0.2 mm occurred on the specimens in the outdoor storage, these specimens were classified as damaged and are marked in grey in the diagram. The aggregates that were used were considered to be reactive because with one exception they had to be checked in accordance with Part 3 of the Alkali Guidelines. The exception was one sort of gravel. The concrete with gravel (see marked point No. 1) showed neither in the fog chamber nor in the outdoor storage signs of a deleterious ASR. Nine aggregates, which showed damages in the outdoor storage, were classified as being alkali reactive in the case of the 40 °C fog chamber storage within a period of time of nine months. In the case of one aggregate (see marked point No. 2) the test with the fog chamber storage has been passed after a period of nine months, although the specimens had to be classified as damaged in the outdoor storage. As after nine months there were cracks on the cube with a width of 0.10 mm and a further increase of expansions could have been observed, the testing continued. Approximately, after twelve months cracks of a size of 0.2 mm occurred on the cube in the fog chamber. Therefore, the aggregate was classified as being alkali reactive.

3.2 Performance test

The 60 °C concrete prism test is used in France [8] and Switzerland [16] as a performance test method. Extensive investigations into this performance test method for assessing concrete compositions have been carried out in Germany as part of the AiF (Federation of Industrial Research Associations) research project No.: 14013 N. Figure 5 shows how the expansion of concrete containing a reactive aggregate depends on the cement content. The higher the cement content the higher is the expansion.

The influence of the effective alkali content of the cement used can be deduced clearly from the results of the test method. With a low-alkali cement the expansion of concrete containing a reactive aggregate remains below the limit value of 0.2 mm/m (Figure 6), even for a cement content of 400 kg/m³.

The use of a CEM II/B-S or a CEM II/B-M (S-LL) cement led to results that were equally as good as those with the low-alkali Portland cement (Figure 7). The reactive aggregate used – crushed Upper Rhine gravel – can be used with a CEM I-NA (low alkali) cement or with CEM II/B-S or CEM II/B-M (S-LL) cement, e.g. for concrete in a moist environment, without causing any damage. This is supported by the results with comparable concrete compositions that had been produced with a CEM II/B-S cement and a CEM I-NA (low alkali) and have been stored at the outdoor exposure site for seven years (**Error! Reference source not found.**). So far no major expansion or cracking has occurred. As expected, the reference concrete, which was also produced with reactive, double-crushed, Upper Rhine gravel showed serious expansion and cracks ≥ 0.2 mm in the outdoor exposure site.

The influence of the w/c ratio is also reflected by the 60 °C concrete prism test (Figure 9). The alkali concentration in the pore solution increases with decreasing w/c ratio, while at the same time there is an increase in the density of the cement mortar. These two opposing tendencies cause the worst situation at a w/c ratio of 0.45.

The extent to which concretes that contain pozzolanic additions, or cements with pozzolanic main constituents, can be tested by this method has not yet been adequately clarified. To deal with this situation in Switzerland the test has been extended to a year with a simultaneous increase in the limit value to 0.3 mm/m [16]. The increase in the limit value is necessary because of the longer test duration and the associated higher moisture expansion. Figure 10 shows investigations with 20 wt% and 30 wt% of fly ash FA1 or fly ash FA2. Fly ash FA1 has an alkali content of 3.1 wt% $Na_2O_{eq.}$ and fly ash FA2 has a value of 1.6 wt% Na_2O_{eq}. Both fly ashes significantly reduced the expansion caused by ASR – fly ash FA2 somewhat more than fly ash FA1.

After one year the expansion of the concrete that contained 20 wt% of fly ash FA2 was below the limit value of 0.3 mm/m and, this was classified as innocuous. The concrete that contained fly ash FA1, however, exceeded the limit value within the test period and was classified as critical. If 30 wt% of cement were replaced by fly ash FA1 and FA2 the expansions were reduced further compared to 20 wt% fly ash and were below the limit of 0.3 mm/m after 12 months. Interim results from tests in the outdoor exposure site with two concretes with comparable compositions with fly ash FA1 and without fly ash confirm the expansion reducing effect of fly ash (Figure 11).

It is not yet known whether the substitution of 20 wt% of cement by fly ash is sufficient to prevent a deleterious ASR in concrete containing reactive aggregates and cement with high alkali content. A comparable concrete composition which was made with fly ash FA1 from the same plant was stored at the outdoor exposure site. After seven years of storage the development of a deleterious ASR has been indicated by a slight increase in expansion since the 4th year. The chosen dosage for the fly ash has possibly only delayed a deleterious ASR, and not prevented it. The investigations are being continued and will also show if 30 wt% of fly ash will be enough to prevent a deleterious ASR.

4 CONCLUSIONS

ASR test methods must provide information within two to six months as to whether any deleterious ASR will occur in a concrete, including in the long term. In some cases this damage only occurs after 10 to 30 years so it is absolutely essential that the limit values for the test methods are calibrated against outdoor exposure tests and investigations are carried out on structures.

The investigations are subdivided into tests on aggregates, in which the reactivity of the aggregates is determined, and performance tests that assess the suitability of the concrete for a specific application.

The two accelerated mortar bar tests (reference method at 80 °C immersed in NaOH solution and alternative method at 70 °C above water) that are included in the German Alkali Guidelines arrive at the same classification as far as the alkali-reactivity of aggregates is concerned. A strict correlation between the results obtained by the two methods was not found.

The 60 °C concrete prism test provides the same information after a period of time of three months regarding the alkali reactivity in most cases as the 40 °C fog chamber storage after nine months if it is applied for aggregate assessment. The 40 °C fog chamber method takes a long time and is therefore to be replaced in the next years by the 60 °C concrete prism test.

Aggregates which have caused damage in concretes that were stored at an outdoor exposure site were indentified as alkali-reactive with the 40 °C fog chamber storage according to the German Alkali Guidelines. With the 40 °C fog chamber method aggregates can be classified reliably. This method is available in Germany for aggregates without pessimum behaviour.

The 60 °C concrete prism test as a performance test is a suitable method to assess the alkali-reactive potential of specific concrete compositions. It displays the influences from different w/c ratio, cement contents, $Na_2O_{eq.}$ of cements, cement types, fly ashes on the ASR potential. To what extent these laboratory results can be transferred to practice is still unclear. Further investigations with outdoor storage will have to be done. Limit values are stipulated on the basis of the practical experience available at the Research Institute of the Cement Industry.

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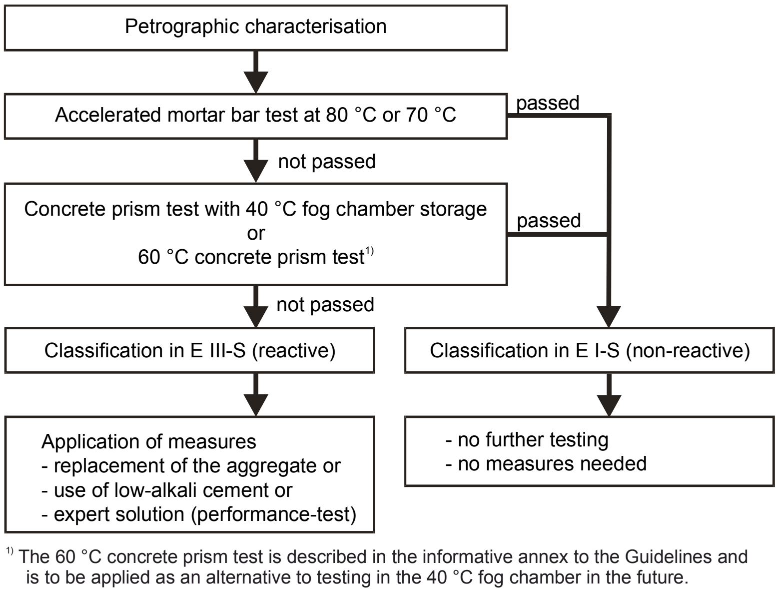

Figure 1: Flow chart of aggregate testing in accordance with Part 3 of the Alkali Guidelines [1].

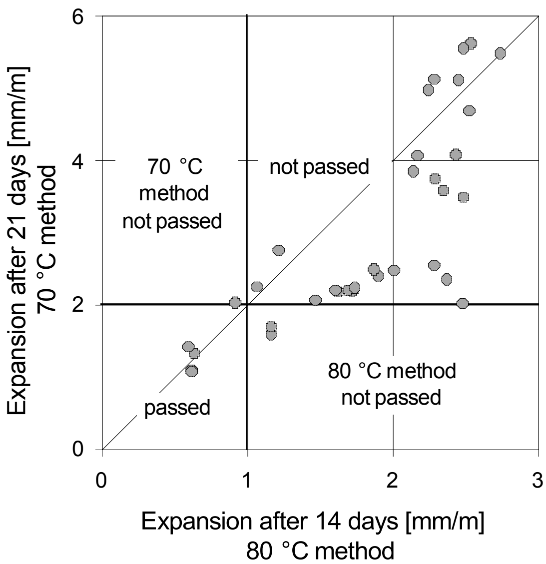

Figure 2: Expansion of mortar bars made with a selection of aggregates at the time of testing in accelerated mortar bar tests; 80 °C method: testing according to [6] and measurement after 14 days; 70 °C method: testing according to [5] and measurement after 21 days (limit value 2,0 mm/m); both methods were integrated as modified versions as reference and alternative method in the Alkali Guidelines [1].

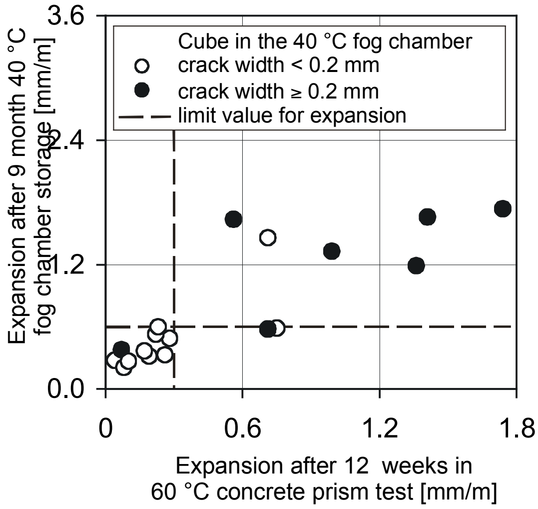

Figure 3: Expansion of concretes made with various aggregates in the 40 °C fog chamber (c = 400 kg/m³, w/c ratio = 0.45, $Na_2O_{eq.}$ = 1.3 wt%) and the 60 °C concrete prism test (c = 400 kg/m³, w/c ratio = 0.45, $Na_2O_{eq.}$ = 1.3 wt%) respectively RILEM AAR-4 (c = 440 kg/m³, w/c ratio = 0.50, $Na_2O_{eq.}$ = 1.26 wt%) as well as cracks = 0.2 mm (black point) and cracks < 0.2 mm of 300-mm-cubes in the 40 °C fog chamber.

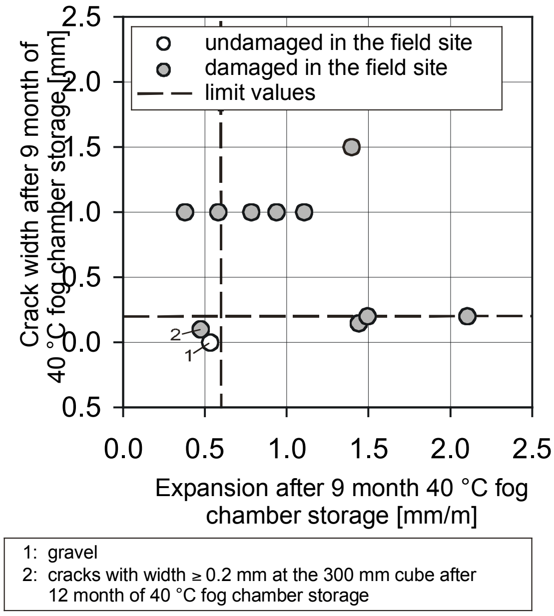

Figure 4: Expansion of concretes with different cement contents in the 60 °C concrete prism test with 70 % crushed Upper Rhine gravel, CEM I 32,5 R cement with $Na_2O_{eq.}$ = 1.3 wt%, w/c ratio = 0.45.

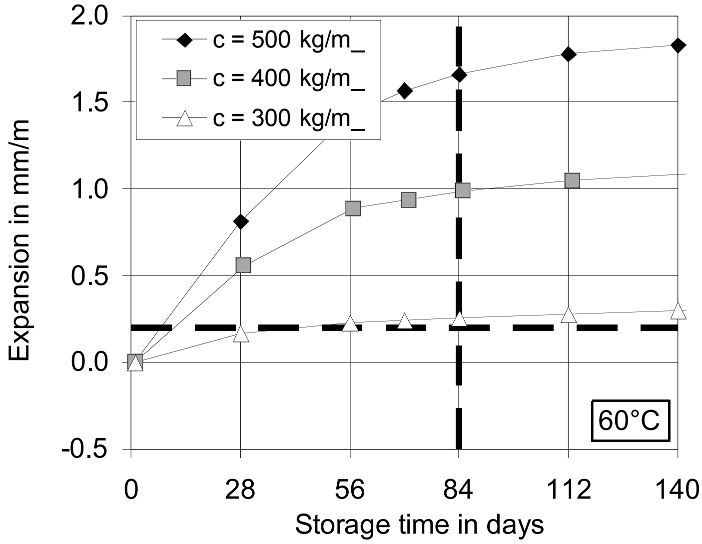

Figure 5: Expansion of concrete prisms and maximum crack width of concrete cubes made with various aggregates tested in the 40 °C fog chamber (c = 400 kg/m³, w/c ratio = 0.45, $Na_2O_{eq.}$ = 1.3 wt%) as well as the performance of the concretes in an outdoor exposure site.

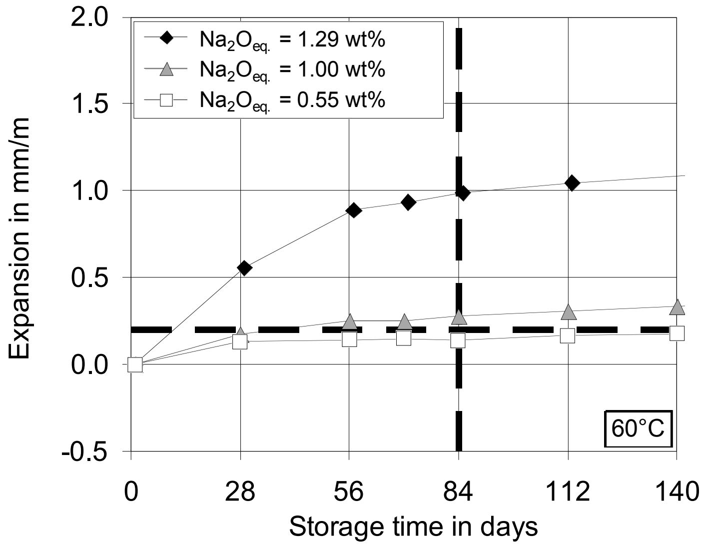

Figure 6: Expansion of concretes made with various Portland cements and with different total alkali contents ($Na_2O_{eq.}$) in the 60 °C concrete prism test with 70 % crushed Upper Rhine gravel, c = 400 kg/m³, w/c ratio = 0.45.

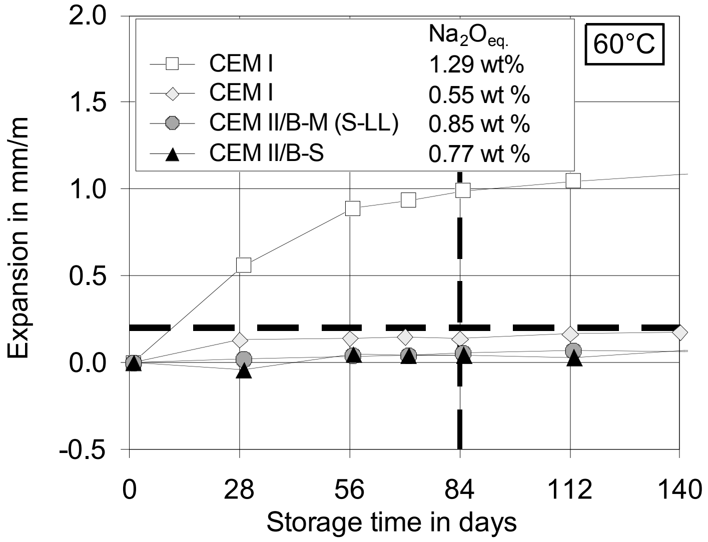

Figure 7: Expansion of concretes made with different cements and with different total alkali contents ($Na_2O_{eq.}$) in the 60 °C concrete prism test with 70 % crushed Upper Rhine gravel, c = 400 kg/m³, w/c ratio = 0.45.

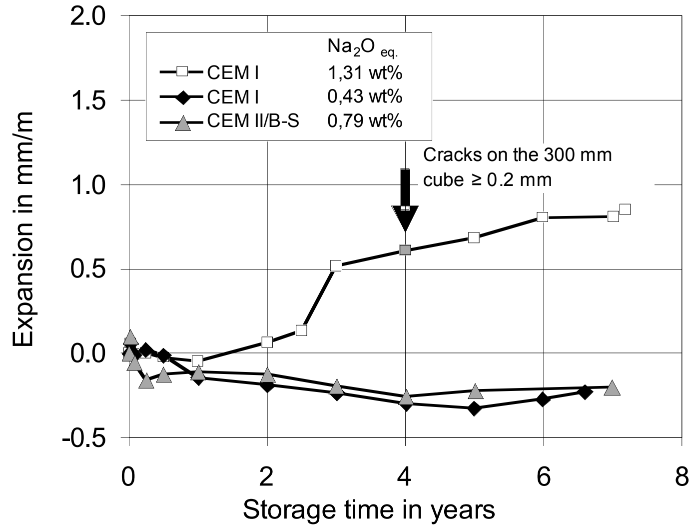

Figure 8: Expansion of concretes made with different cements and stored at the outdoor exposure site with 70% crushed Upper Rhine gravel, c = 400 kg/m³, w/c ratio = 0.45.

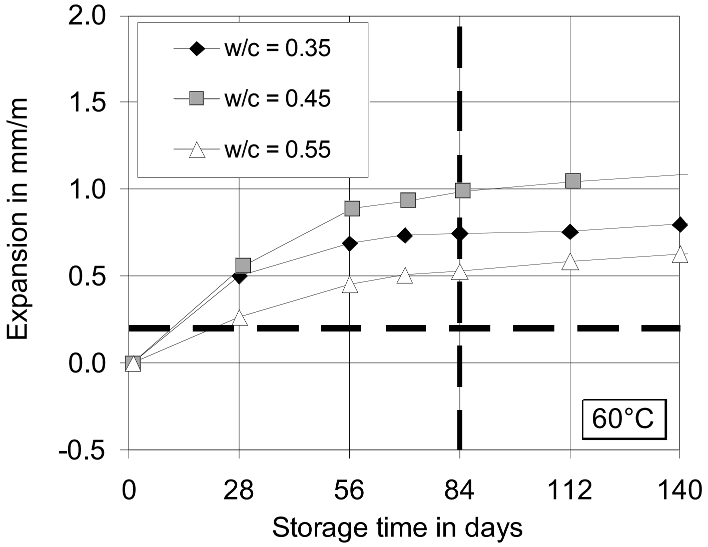

Figure 9: Expansion of concretes with different w/c ratios in the 60 °C concrete prism test with 70 % crushed Upper Rhine gravel, c = 400 kg/m³, CEM I 32,5 R cement with $Na_2O_{eq.}$ = 1.3 wt%.

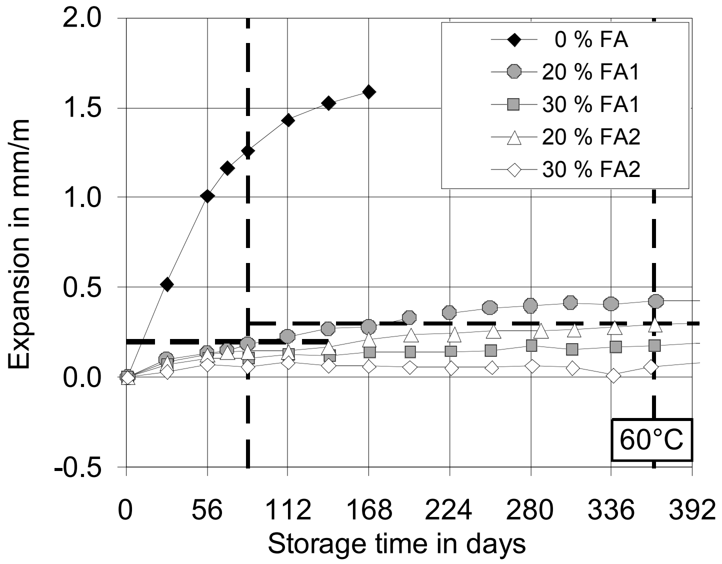

Figure 10: Expansion of concretes with and without fly ash in the 60 °C concrete test with 70 % crushed Upper Rhine gravel, CEM I 32,5 R cement with $Na_2O_{eq.}$ = 1.3 wt%, w/(c+f) = 0.55, c + f = 500 kg/m³

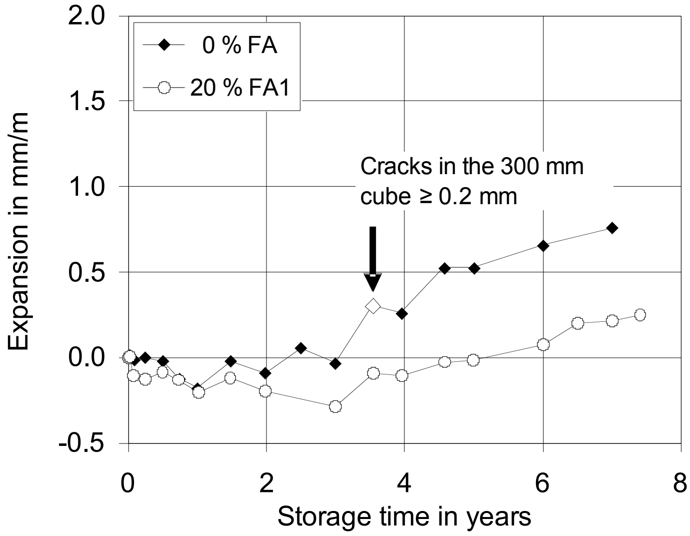

Figure 11: Expansion of concrete prisms and crack width on concrete cubes with and without fly ash stored on the outdoor exposure site with 70 % crushed Upper Rhine gravel, CEM I 32,5 R cement with Na_2O eq. = 1.3 wt%, w/(c+f) = 0.55, c + f = 500 kg/m³