Investigations on the influence of sand and testing conditions on the expansion behaviour of concretes in ASR tests

Wibke Hermerschmidt [(1)], Christoph Müller [(1)], Matthias Böhm [(1)]

(1) VDZ gGmbH, Düsseldorf, Germany, bte@vdz-online.de

Abstract

In concrete road pavements there is a high risk of a deleterious alkali silica reaction (ASR) due to the dynamic loads and the external alkali supply if the concrete contains alkali reactive aggregates. In order to avoid damage caused by ASR in concrete pavements of federal highways in Germany, there are regulations for the assessment of the ASR resistance of concretes and the alkali reactivity of the aggregates. These regulations are based on the results of concrete prism tests under conditions accelerating ASR (increased temperature and external alkali supply). Due to the large variety of aggregates to be assessed and other parameters that influence ASR, it has not yet been completely clarified whether the ASR test methods and the associated assessment criteria currently in use provide a consistent assessment of the ASR resistance of the tested concretes or the alkali sensitivity of the aggregates.

Against this background, this contribution presents an investigation to characterize the effects of various test parameters on the expansion behaviour of concretes in accelerated ASR tests.

The focus was on investigations into the behaviour of different coarse aggregates in combination with different sands in a standardized concrete composition. As test method the 60ºC concrete prism test with varying external alkali supply was applied. Upon completion of the concrete tests all concretes were investigated with polarized light microscopy on thin sections with regard to possible microstructural damages and products of ASR.

***Keywords**: alkali supply; concrete prism test; road pavements; sand; test methods*

1. INTRODUCTION

In concrete road pavements there is a high risk of a deleterious alkali silica reaction (ASR) due to the dynamic loads and the external alkali supply, when the concrete contains alkali reactive aggregates. To assess ASR resistance of concrete for road pavements prior to its use in practice, there are several test methods, most of which are based on measuring the expansion under conditions that accelerate ASR. Due to significant geological differences in aggregates and aggregate types used in different countries or even regions, as well as due to differences in climate and consequently in the exposure conditions for concrete, regulations for the assessment of ASR resistance of concrete are normally based on national rules.

The German regulations for aggregates and concretes for road pavements in the moisture class WS (combination of high moisture of the concrete, alkali supply from the outside and dynamic loading) published by the Federal Ministry of Transport and Digital Infrastructure differentiate between two test concepts: WS basic tests for coarse aggregates and ASR performance tests for concretes with a defined composition. In WS basic tests, the alkali reactivity of coarse aggregates is assessed using a concrete test with a predefined concrete composition and supplementary petrographic and mineralogical examinations. The concrete specimens for the test are prepared using a defined WS testing cement and a defined WS testing sand in combination with the aggregate to be tested. After passing a WS basic test, the coarse aggregates can be used in concretes for the tested field of application (top or bottom layer concrete) without further restrictions with regard to the choice of cement and sand, as long as the general requirements for concrete pavements are adhered to. In contrast to ASR performance tests, the validity of which is limited to the tested concrete composition, coarse aggregates can be used more flexibly after passing a WS basic test.

In the procedure of WS basic tests it is assumed that a deleterious ASR is essentially caused by the coarse aggregate and not by the sand. This assumption is based on the fact that in Germany there were no damages in structural concretes or concretes for road pavements publically reported caused solely or decisively by the sand. In international publications it was shown that the sand used in the concrete may certainly have a potential for an alkali-silica reaction, see e.g. [1, 2]. Results from WS basic tests and ASR performance tests on concretes with similar compositions except for the sand have also shown that the use of different sands influences the test results.

This raises the question of whether the current procedure and the associated assessment criteria for WS basic tests and ASR performance tests achieve a consistent assessment of alkali reactivity of aggregates or ASR resistance of concretes in all cases. Against this background, this paper presents an experimental program to characterize the effects of sand and the test solution on the expansion behaviour of concretes in accelerated ASR tests.

2. MATERIALS AND METHODS

2.1 Raw materials and concrete compositions

The selection of coarse aggregates included a crushed rhyolite (R), a crushed granite (G), two crushed basalts (B1, B2) and a crushed limestone (L). The coarse aggregates were delivered by the producer in the grain fraction 2/8 mm which is the common coarse fraction for top layer concretes for road pavements in Germany.

Three natural sands (S1, S2, S3) and a crushed limestone sand (S4) were selected as fine aggregates (grain fraction 0/2 mm). The sand S1 is the testing sand for WS basic tests in Germany. The particle size distributions of the sands determined by sieving according to EN 933-1 are given in Table 2.1.

The crushed limestone aggregates (0/2 mm and 2/8 mm) were considered inert with respect to ASR.

Table 2.1: Particle size distribution of the sands S1, S2, S3 (natural sands) and S4 (crushed limestone sand)

	Cumulative percentage of the mass of material passing the sieve					
sieve size	0.063 mm	0.125 mm	0.25 mm	0.5 mm	1 mm	2 mm
S1	0.8	2	11	41	74	97
S2	0.7	2	7	36	60	88
S3	0.3	1	9	54	84	96
S4	2.7	7	24	52	78	94

Various combinations of the coarse and fine aggregates and a Portland cement CEM I 42.5 N (testing cement for WS basic tests) were used to prepare a total of 12 concretes with the composition shown in Table 2.2. When using the testing sand for WS basic tests (S1), the concrete composition in Table 2.2 corresponds to the specified concrete composition for WS basic tests for top layer concrete.

Table 2.2: Concrete composition

Cement	430 kg/m³ CEM I 42.5 N (Na_2O-equ. = 0.76 %)
Aggregates	30 vol.-% sand 0/2 mm (S1, S2, S3 or S4) 70 vol.-% crushed stone 2/8 mm (R, G, B1, B2 or L)
Water-cement ratio	0.45
Air content	5.5 to 6.5 vol.-%

2.2 Test methods

The coarse and fine aggregates were tested with the accelerated mortar bar test according to the German guidelines on preventive measures against deleterious ASR in concrete. The test method is comparable to RILEM AAR-2.2 [3] and is based on measuring the expansion of mortar prisms with the dimensions (40 x 40 x 160) mm³ that were prepared with the aggregate to be tested. Coarse aggregates were crushed to ≤ 4 mm. The crushed material was sieved and washed to a set of fractions between 0.125 and 4 mm, which were mixed acc. to prescribed ratios prior to the mixing of the mortar. Defined test cement with a sodium equivalent of 1.3 wt. % was used. The water-cement ratio of the mortar was 0.47 and the weight ratio of aggregates to cement was 2.25:1. The prisms were stored in the formworks at (20 ± 2) °C over water for the first (24 ± 2) hours. After demolding, they were stored under water in a cabinet at (80 ± 2) °C for (24 ± 2) hours. After this preliminary storage, the specimens were stored in a (1.00 ± 0.01) molar sodium hydroxide solution at (80 ± 2) °C for 13 days. For expansion measurements the lengths of the prisms were measured before (zero measurement), during and after the storage in NaOH solution.

The concretes were tested with the 60 °C concrete prism test with alkali supply. The test method is comparable to RILEM AAR-12 [4] except for the concrete mix design. For each concrete, six specimens with the dimensions (75 x 75 x 280) mm³ and embedded measuring marks at the end faces were prepared. The specimens were stored in the formworks at (20 ± 1) °C and > 98 % relative humidity (RH) for one day. After demolding they were stored until the age of 28 days according to the following procedure: 6 days at (20 ± 1) °C and > 98 % RH, 14 days at (20 ± 1) °C and (65 ± 5) % RH, 6 days at (60 ± 2) °C and > 98 % RH and one day at (20 ± 1) °C and > 98 % RH. At the age of 28 days the expansion was measured for the first time (zero measurement). Subsequently the cyclic testing of the prisms started. The test comprised 14 test cycles according to the following procedure:

1. Five days at (60 ± 2) °C in a drying cabinet
2. Two days submerged in the test solution (3 prisms in a 3 % NaCl solution and 3 prisms in a 10 % NaCl solution) at (20 ± 1) °C
3. Six days at (60 ± 2) °C and > 98 % RH
4. One day at (20 ± 1) °C and > 98 % RH with subsequent measurement of expansion

The temperature of 60 °C and the external alkali supply through the test solution accelerate ASR so that an assessment of the resistance to ASR is usually possible within 20 weeks (10 test cycles). The test method can be seen as a modification of the 60 °C concrete prism test at 100 % RH acc. to RILEM AAR-4.1 [3]. It was developed in Germany for evaluating the potential for deleterious ASR in concrete proposed for use in road pavements. This development was based on the experience that the assessment of the reactivity of aggregates by concrete prism tests at 38 °C or 60 °C did not in all cases agree with the behaviour of these aggregates in concrete road pavements. The alkali supply through NaCl solution was therefore chosen to account for the impact of de-icing salts during the service life of road pavements. In tests for road pavements according to the German specifications, the expansion after 10 test cycles (140 days test duration) is normally used as an assessment criterion. For a sufficient resistance against ASR, the expansion after 10 test cycles in the 60 °C concrete test with alkali supply should not exceed 0.30 mm/m when using a 3 % NaCl solution and 0.50 mm/m when using a 10 % NaCl solution [5].

After the completion of the 60 °C concrete prism tests with alkali supply, thin sections were prepared from selected concrete prisms and examined microscopically for signs of a deleterious ASR, i.e. typical reaction products (alkali silica gel) in air voids and cracks as well as cracks that ran through cement paste and aggregate grains or that originated from aggregate grains. The concrete specimens were impregnated with a resin containing a UV fluorescent dye before thin section preparation. This facilitated the quick and easy identification of cracks in the concrete samples when the thin sections were evaluated under UV light.

3. RESULTS AND DISCUSSION

The results of the accelerated mortar bar tests are shown in Figure 3.1. For the basalt B1, the granite and the rhyolite, the expansion was at a very similar level of around 0.8 mm/m after 13 days of testing. The test results for the basalt B2 showed a significantly lower expansion. A similar low expansion was determined for the limestone and the crushed limestone sand (S4). The behaviour of the limestone and crushed limestone sand met the expectations for the selection of these aggregates as inert reference materials with regard to ASR. The tests with the three natural sands showed the highest expansion for the sand S3, a slightly lower expansion for the sand S1 and the lowest expansion for the sand S2.

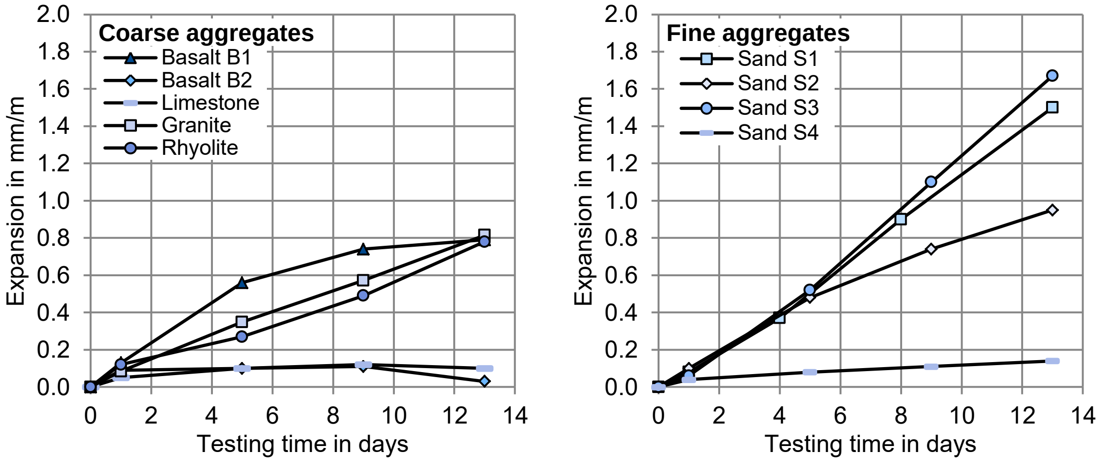

Figure 3.1: Results of the accelerated mortar bar tests

Figure 3.2 shows the expansion of the concretes with different coarse aggregates and testing sand for WS basic tests (S1) or crushed limestone sand (S4) in the 60 °C concrete prism test with alkali supply. The compositions of the respective concretes, whose expansion curves are shown in the same diagram, are identical except for the sand. The direct comparison of the expansion curves shows a reduction of the expansion when the testing sand for WS basic tests (S1) is substituted with the crushed limestone sand (S4). This indicates that a part of the expansion in the concretes with sand S1 results from a reaction of the sand.

After 10 test cycles (140 days test duration), the expansion of the concretes with crushed limestone sand (S4) was around 15 % to 40 % lower than the expansion of the corresponding concretes with sand S1. In all tests, the expansion curves for the respective concrete with sand S1 were approximately proportional to the respective concrete with crushed limestone sand (S4), i.e. the reduction of the expansion due to the exchange of S1 for S4 was nearly linear during the testing time. This relationship is illustrated in Figure 3.3. In the case of the crushed basalt and the crushed rhyolite, the sand used would not be decisive for the assessment of ASR resistance of the concrete if the above mentioned expansion criteria ($\varepsilon \leq 0.30$ mm/m for 3 % NaCl and $\varepsilon \leq 0.50$ mm/m for 10 % NaCl) are used for assessment. In the case of the crushed granite, on the other hand, the assessment would be influenced by the choice of the sand.

Comparable observations in concrete prism tests at 60 °C and 100 % RH have been made by Ideker et al. [6]. Data investigating a reactive coarse aggregate combined with different “non-reactive” sands showed a significant effect of the sand on the overall expansion of the concrete prisms. The sands in the study were classified as “non-reactive” based on the expansion in the accelerated mortar bar test according to ASTM C 1260 ($\varepsilon < 0.10$ % at 14 days) or CSA A23.2-25A ($\varepsilon < 0.15$ % at 14 days) respectively. The concrete prisms showed a higher expansion when natural sand was used compared to the cases where crushed limestone sand was used. There was also a measurable effect on the expansion when using crushed limestone sands from different sources. Ideker et al. showed that the contribution of alkalis from the “non-reactive” sands to the pore solution has an influence on the expansion behaviour in the concrete prism test. It cannot be ruled out that this effect might also be part of an explanation for the test results shown in Figure 3.2. However, as signs for a reaction of the natural sand S1 were found in the microscopic analyses of thin sections it is assumed that this is the main reason for the higher expansion in the tests with S1 compared to S4. Additionally, chemical analyses, the results of which are not presented in this contribution, showed relatively low total alkali contents (≤ 1.32 mass % Na_2O-equ.) in all sands. The alkali release behaviour of the sands was not investigated.

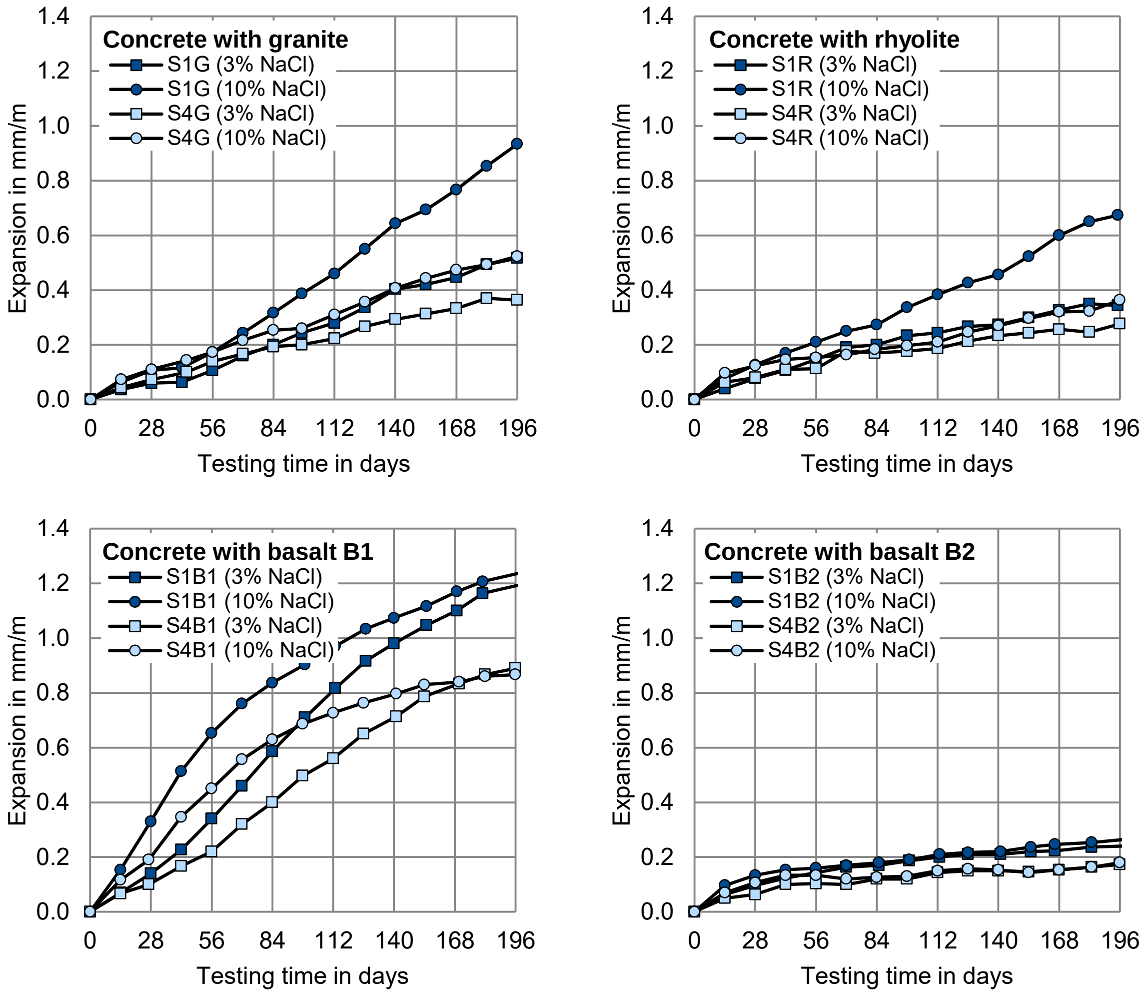

Figure 3.2: Results of the 60 °C concrete prism tests with external alkali supply

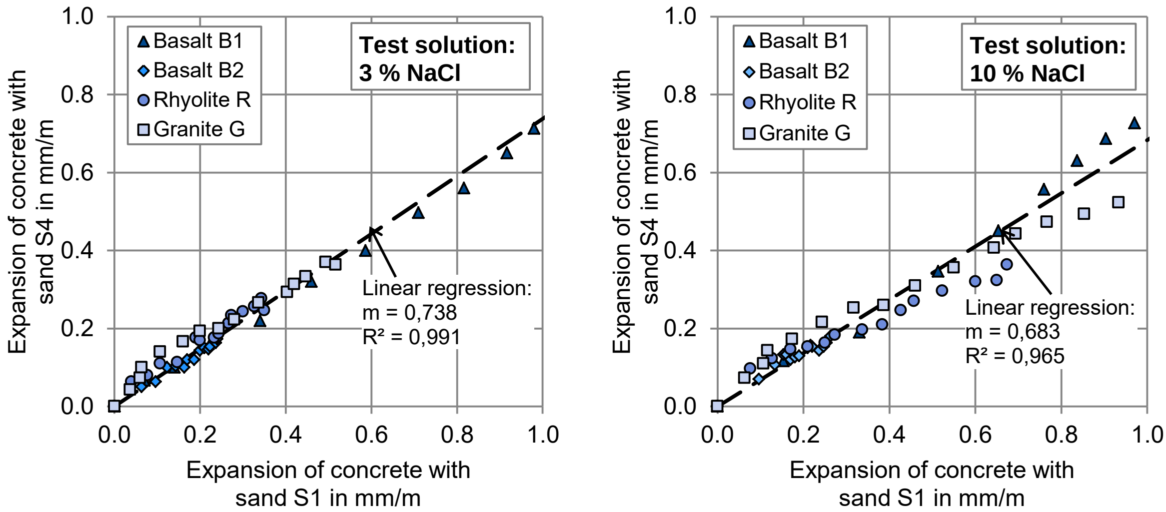

Figure 3.3: Comparison of expansion of concretes with sand S1 and sand S4 in the 60 °C concrete prism tests with external alkali supply

A clear connection between the results of the concrete tests and those of the accelerated mortar bar tests could not be determined, neither for the concretes with testing sand for WS basic tests (S1) nor for the concretes with crushed limestone sand (S4). Only for the basalt B2 the low expansion in the accelerated mortar bar test correlated with the results of the corresponding concrete tests. The basalt B1, the granite and the rhyolite showed similar expansion after a test period of 13 days in the accelerated mortar bar test, while the expansion curves of the corresponding concretes differed significantly. In particular, the high expansion of the concretes with basalt B1 compared to the other concretes could not be predicted based on the results of the accelerated mortar bar tests.

In most cases, the observations made when examining selected thin sections of the concretes corresponded to the respective expansion curves and confirmed the influence of the sand. For example, some indications of a reaction of the crushed rhyolite were observed in the concrete with crushed rhyolite (R) and crushed limestone sand (S4), while in the concrete with crushed rhyolite and the sand for WS basic tests (S1) there were additional indications of a reaction of the sand, see Figure 3.4. In the concretes with crushed basalt B2 and sands S1 and S4, there were no clear indications of ASR.

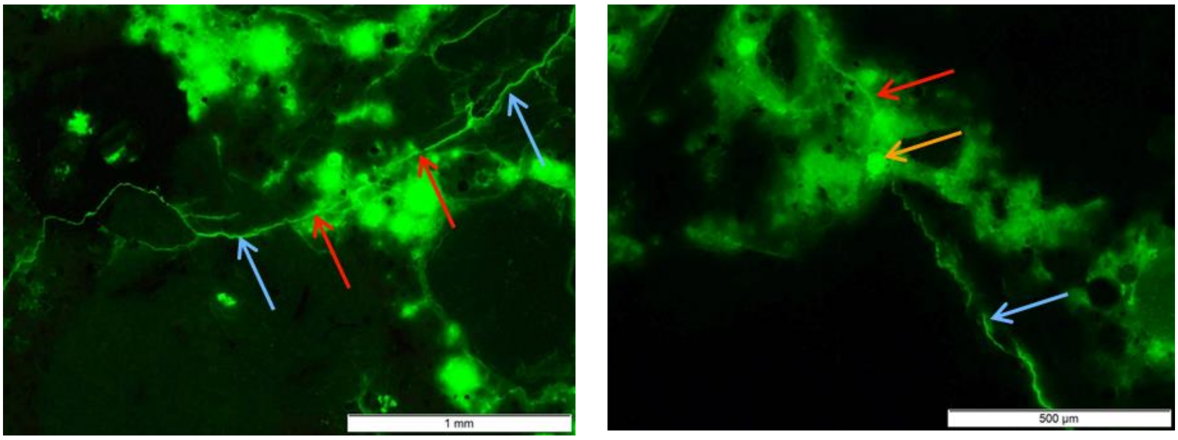

Figure 3.4: Thin sections under UV light; left: concrete S1R, cracks through sand grain (right blue arrow), rhyolite grain (left blue arrow) and cement paste (red arrows); right: concrete S4R, crack through rhyolite grain (blue arrow) and cement paste (red arrow), air void with ASR gel (orange arrow)

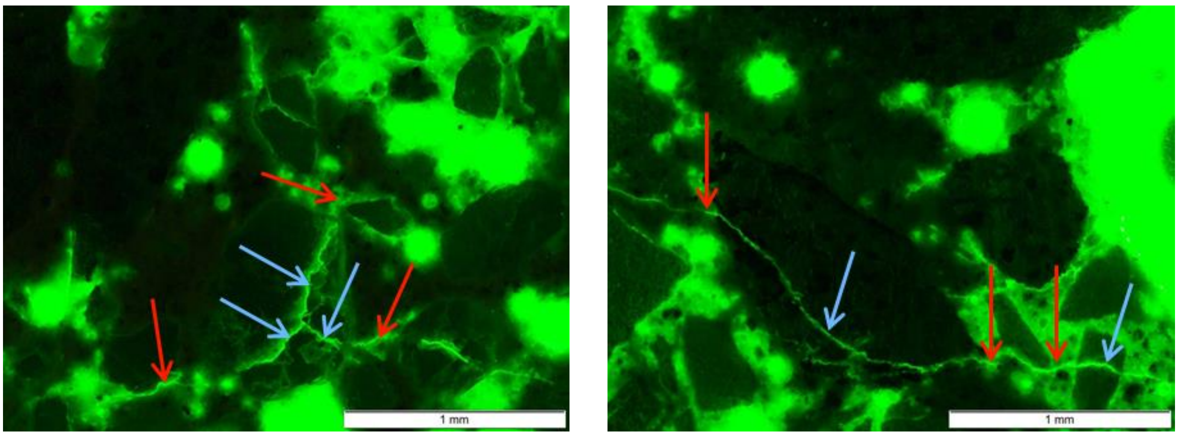

Figure 3.5: Thin sections under UV light; left: concrete S1B1, cracks through sand grain (blue arrows) and cement paste (red arrows); right: concrete S4B1, cracks through sand grain (right blue arrow), basalt grain (left blue arrow) and cement paste (red arrows)

In the concretes with crushed basalt B1 and the sands S1 and S4, indications of ASR were observed with the participation of the crushed basalt and in the case of the concrete with S1 also with the participation of the sand (S1), see Figure 3.5. The quantity of the visible signs of ASR in the concretes with crushed basalt B1 was significantly lower than experience has shown in concretes of comparable composition and with comparable expansion curves in a 60 °C concrete prism test with alkali supply. The reason for this is not clear yet and will be investigated further.

The expansion of the concretes with the natural sands (S1, S2, S3) or with crushed limestone sand (S4) in combination with crushed limestone as coarse aggregates in a 60 °C concrete prism test with alkali supply are shown in Figure 3.6.

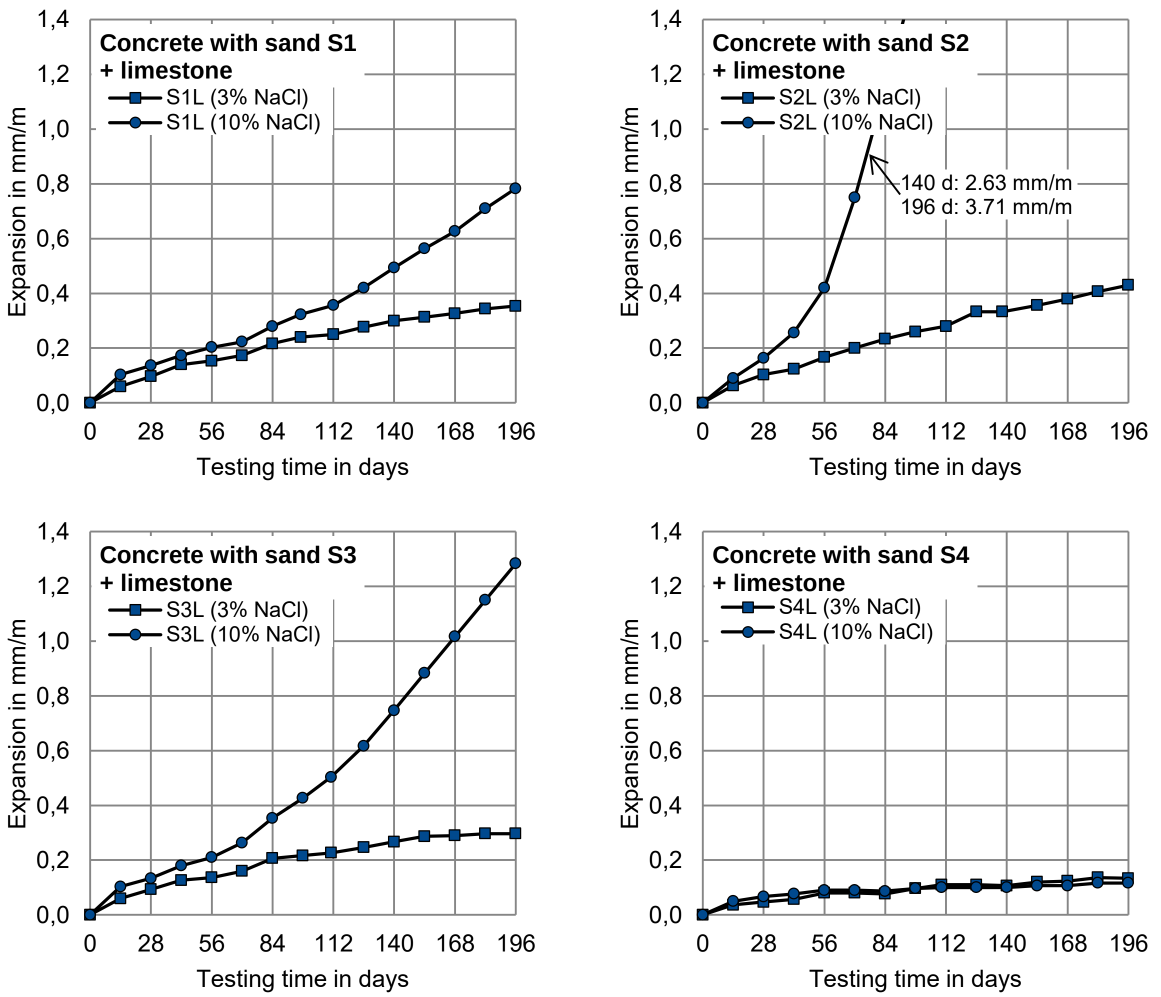

Figure 3.6: Expansion of the concretes with different natural sands (S1, S2, S3) or with crushed limestone sand (S4) in combination with crushed limestone in a 60 °C concrete prism test with alkali supply

The concrete S4L with limestone both in the fine and coarse aggregate fraction showed, as expected, small expansion due to the inert behaviour of the limestone with respect to ASR. The concretes S1L, S2L and S3L with the natural sands S1, S2 and S3 in combination with crushed limestone showed expansion values close to the assessment criterion of 0.3 mm/m after 140 days of testing (10 testing cycles) in the tests with a 3 % NaCl solution. The tests with a 3 % NaCl solution also showed a very similar behaviour of the concretes S1L, S2L and S3L when considering the development of the expansion over time. In the tests with a 10 % NaCl solution, these concretes showed a more differentiated behaviour. In the case of concrete S1L with sand S1 for WS basic tests, the expansion after 140 days of testing corresponded to the assessment criterion of 0.50 mm/m used for WS basic tests or ASR performance tests for road pavements. The concretes S2L and S3L showed a higher expansion. In the case of the S2L concrete with the natural sand S2, macroscopically visible cracks with a maximum crack width of 0.4 mm were found after a test period of 196 days on the test specimens tested with a 10 % NaCl solution, while the other concretes showed no macroscopically visible damage characteristics. A relation between the results of the accelerated mortar bar tests for natural sands S1, S2 and S3 and the corresponding concrete prism tests could only be determined to a limited extent. For the natural sand S2, the accelerated mortar bar test showed a lower expansion than for S1 and S3, but in the concrete tests with a 10% NaCl solution, the concrete S2L showed by far the highest expansion. For the remaining sands (S1, S3 and S4), the less expansion was found in the corresponding concrete tests, the lower the expansion in the accelerated mortar bar test, so that there was a qualitative relationship between the results.

The results for the concretes S1L, S2L and S3L indicate that in the 60 °C concrete prism tests with alkali supply for these concrete compositions ASR of the sands takes place. It is currently assumed that due to the inert coarse aggregate (limestone), the alkalis present in or supplied into the system are almost completely available to the sand as a reaction partner.

The observations in the corresponding thin section examinations correlated well with the expansion of the respective concretes. There were signs of ASR in which the respective natural sands, as expected, but not the inert crushed limestone, were involved. Figure 3.7, Figure 3.8 and Figure 3.9 show examples for observations of cracked sand grains and alkali silica gel in air voids in thin sections under the light microscope. In principle, a higher extent of visible signs of ASR correlated with higher expansion of the concrete.

The expansion behaviour of concretes with crushed limestone as coarse aggregates in combination with different natural sands was also investigated by Pierkes et al. [7]. The effects of different quartzitic sands were investigated with concrete prism tests at 60 °C and 100 % RH. The use of different natural quartzitic sands led to only slightly higher expansions than the inert reference with crushed limestone sand. The comparison of those findings and the results shown in Figure 3.6 indicates that the external alkali supply through the test solution intensifies the effect of the sand on the overall expansion. Accordingly, a higher NaCl concentration (10 %) leads to a stronger effect and a wider range of expansion values than a lower NaCl concentration (3 %)

The test setup of the 60 °C concrete prism test with alkali supply and the corresponding assessment criteria were developed with reference to the field performance of concrete road pavements made with raw materials from different sources. It is assumed that it allows for a safe assessment of the ASR resistance of a concrete mix or coarse aggregates respectively. Due to the broad variety of aggregates in Germany there might still be cases with misleading results. The further application of the test concept should therefore be combined with investigations of the long-term field performance of concrete road pavements to get further insights.

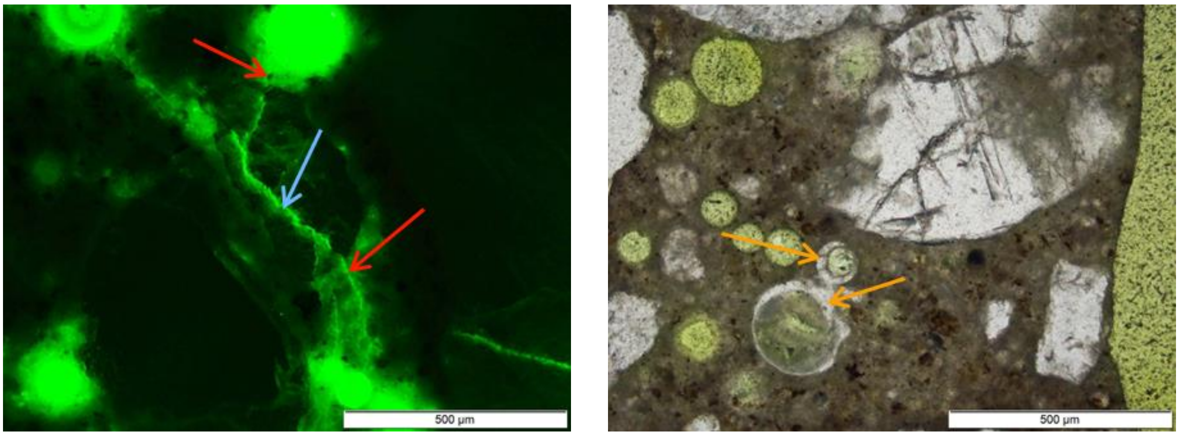

Figure 3.7: Thin section of concrete S1L: Microscopic picture under UV light (left) and with parallel polarizers (right); crack through sand grain (blue arrow) and cement paste (red arrows), ASR gel in air voids (orange arrows)

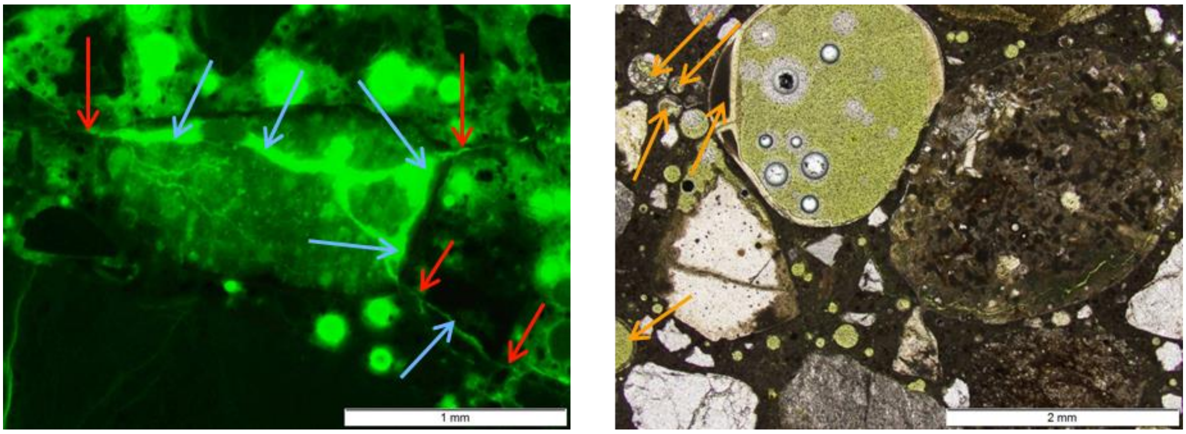

Figure 3.8: Thin section of concrete S2L: Microscopic picture under UV light (left) and with parallel polarizers (right); cracks through sand grain (blue arrows) and cement paste (red arrows), ASR gel in air voids (orange arrows)

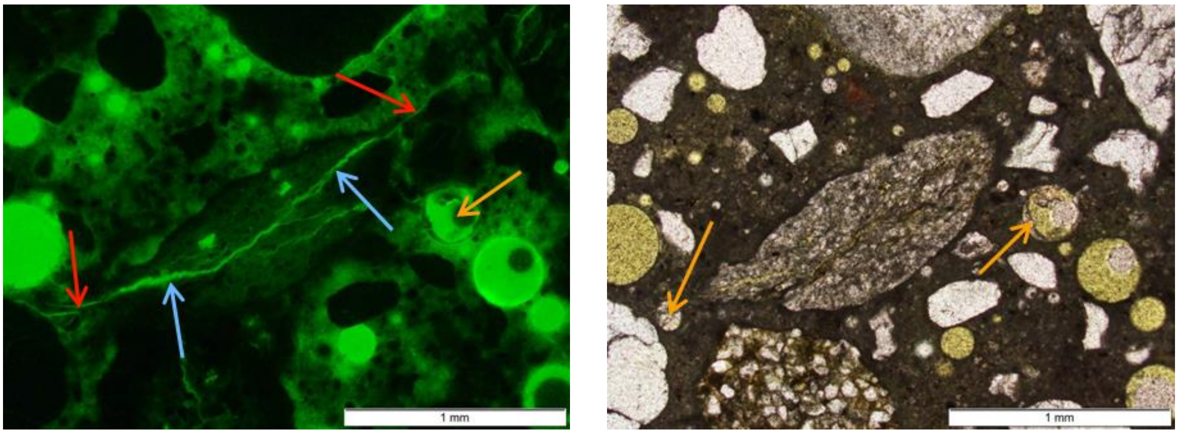

Figure 3.9: Thin section of concrete S3L: Microscopic picture under UV light (left) and with parallel polarizers (right); crack through sand grain (blue arrows) and cement paste (red arrows), ASR gel in air voids (orange arrows); same picture detail left and right

4. CONCLUSIONS

In the context of this article, an investigation program for the characterization of the influences of the sand and the test solution on the expansion of concrete under accelerating conditions in ASR test methods was presented. The aggregates used were examined using the accelerated mortar bar test (similar to RILEM AAR-2.2 [4]) in accordance with the German guidelines on preventive measures against deleterious ASR in concrete. The expansion curves of 12 concretes under ASR accelerating conditions were determined with the 60 °C concrete prism test with alkali supply [4] through a 3 % and a 10 % NaCl solution. After completion of the concrete tests, selected concrete specimens were examined for signs of a deleterious ASR using thin section microscopy.

In the case of the concretes that were prepared with the natural sand S1 (German testing sand for WS basic tests), a reduction of the expansion in the 60 °C concrete prism test with alkali supply was observed if the sand was replaced with crushed limestone sand that was classified as inert with regard to ASR. This indicates that a part of the expansion in the concretes with the natural sand S1 are due to a reaction of the sand. In the thin section investigations, characteristics of ASR were found in the concretes with sand S1, which also showed a reaction of the sand.

The concretes with different natural sands in combination with crushed limestone showed in the 60 °C concrete prism test with alkali supply expansion values in the range of or above the assessment criteria usually used in Germany for the assessment of ASR resistance of concretes for road pavements. In the subsequent thin section investigations, characteristics of ASR could be determined in the respective concretes, which showed a reaction of the respective sands. The results show that ASR of the sands takes place under the selected test conditions. This does not necessarily mean that these sands in practice would solely or significantly lead to a deleterious ASR. So far, the authors are not aware of such cases from Germany for construction concrete or concrete road pavements.

The test results have shown that the choice of sand can influence the test results of the 60 °C concrete prism test with alkali supply. The contribution of the sand can vary and is influenced by the coarse aggregates contained in the concrete, as well as by other test parameters such as the sodium chloride concentration of the test solution. In certain cases, it is advisable to investigate the influences of the sand more precisely, e.g. by comparative tests on a concrete with sand that is inert with respect to ASR.

5. ACKNOLEDGEMENTS

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