CORRELATION OF ASR PERFORMANCE TESTING FOR HIGHWAY PAVEMENT CONCRETES WITH FIELD PERFORMANCE AND INVESTIGATIONS INTO BOOSTING THE ALKALI LEVEL

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Abstract

The use of a performance test has become a usual procedure over the last couple of years in Germany to evaluate the ASR potential of concrete mixtures for highway and airfield pavements. Major demands on a performance test are to evaluate specific concrete compositions in a timely manner and to provide results that correlate with field performance. Within this study, the field performance of two highway pavement concretes could be correlated successfully with the results of the cyclic climate storage, a performance test developed at the Finger-Institute (FIB). Furthermore, first investigations into boosting the alkali level indicate that performance testing of pavement concretes with the cyclic climate storage does not require an augmentation of the alkali level to consider fluctuations in the cement alkali content over the production period. However, the origin of the cement and boosting in case of an exposure to water only seems to influence the expansions and needs further research.

Keywords: performance testing, pavement concrete, laboratory/field correlation, boosting

1 INTRODUCTION

In Germany, about 10-15 % of all concrete highway pavements are either ASR-affected or at least ASR-suspected. Owed to the problem of an exacerbating ASR for concretes exposed to alkali-containing deicers it was evident that the standardized procedures in Germany were often unable to detect the ASR-potential of aggregates correctly for the use in pavement concretes [1, 2, 3]. Since 2004, the performance test method developed at the FIB, the cyclic climate storage, has been used to evaluate project specific concretes for highway and airfield pavements and revealed as successful in considering the influence of externally supplied alkalis [4, 5, 6, 7]. Up to now, more than 250 concrete compositions, mainly for pavements but also for concrete pipes, tunnel tubbings, railway sleepers and offshore structures were tested. A major demand for a performance test is a reasonable correlation with field performance. Since it was inappropriate to correlate the performance test against the German fog chamber test that proved as unable to evaluate aggregates for pavements reliably, it was calibrated against two investigated pavement concretes that showed ASR damage in the field after 8-12 years in service.

Ordinary concrete prism tests, i.e. aggregate tests, require an augmentation of the alkali level ("boosting") by either using high-alkali cements (e.g. German fog chamber test) or by adding NaOH to the mixing water (e.g. RILEM AAR-3/-4, ASTM C 1293) up to around 5 kg Na_2O_{eq}/m^3. This has been proven as necessary to compensate leaching effects on laboratory samples and consequently to improve the correlation between field performance and laboratory test results [8]. Such tests, however, neither allow testing specific binder-aggregate combinations nor do they allow determining the threshold alkali level below

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a deleterious ASR will not occur for a certain aggregate. Both are major requirements for a performance test as well. Furthermore, adding of NaOH influences the solubility of $Ca(OH)_2$ and changes the original Na/K ratio which both can affect the composition of ASR-gels and consequently their swelling capacity [9, 10]. Also, the release of alkalis from certain aggregates, i.e. feldspar minerals, might be different in a boosted mixture than under field conditions [11]. Moreover and most important for pavement concretes, deicers (especially alkali-acetates and -formates) trigger mechanisms that are highly able to exacerbate ASR in concretes with reactive aggregates and that cannot be considered adequately with boosting [12, 13]. Also, expansion data (unpublished) from the German 70 °C-AMBT indicated that despite of boosting ordinary portland cements from different plants with different alkali contents to the same level (2.5 wt.% Na_2O_{eq}), significantly different expansions emerged for the very same aggregate (Figure 1). Since performance tests were introduced only recently in Germany, no studies regarding the influence of boosting in performance testing are available. Finally, also the RILEM TC 219-ACS concluded that it has to be looked further into the issue of boosting for performance testing [14]. There is a major concern that usual fluctuations in the cement alkali content during the cement production could influence the testing results. This would require at least limited boosting to set the highest possible alkali content for a certain cement to meet the worst case alkali level in the performance test. To provide a first insight into this issue, four pavement concretes with different boosting options were investigated with the cyclic climate storage as performance test.

2 MATERIALS AND METHODS

2.1 Materials and mixture proportions

For the correlation of the cyclic climate storage with field performance, two ASR damaged German highway pavement concretes with first signs of damage after 8-12 years in service were used as a reference. For concrete C-1, detailed information about the original composition were available and new batches of the cement and all the aggregates were collected from the same plant and deposits respectively that delivered the material for the construction (Table 1). The alkali content of the new cement batch was slightly (0.06 wt.% Na_2O_{eq}) lower, the aggregate fractions and the air content were set to meet the requirements for pavements in Germany. To compare the reactivity of the coarse rhyolite aggregates used at the time of construction with the today's situation, coarse rhyolite grains were extracted from the cores of the damaged pavement by means of shock-wave crushing [15] and were tested with the 70 °C-AMBT. For concrete C-2, however, no details about the original composition were available but the quarry of the coarse granodiorite aggregates which were affected by ASR could be identified by thin section analysis. A new batch of that granodiorite aggregates were used with a non-reactive sand and the mixture was set to meet the latest requirements for pavements in Germany (Table 1). From both of these recreated and unboosted concrete mixtures, prisms were cast and tested with the cyclic climate storage under exposure of NaCl-solution and water as the control respectively.

The influence of boosting was investigated on a field representative concrete mixture for pavements by using granodiorite aggregates from another quarry and a non-reactive sand (Table 2). Overall, four mixtures with different boosting options were tested. The reference mixture B-1 contained an ordinary portland cement for pavements (OPC-A1) with an alkali content of 0.81 wt.% Na_2O_{eq}. Mixture B-2 contained a cement (OPC-A2) that came from the same plant as OPC-A1, but was produced about 2 years later and exhibits an lower alkali content of 0.67 wt.% Na_2O_{eq}. Mixture B-3 contained OPC-A2 as well but the level of alkali was boosted by adding K_2SO_4 to balance the difference of 0.13 wt.% Na_2O_{eq} between cement OPC-A1 and OPC-A2. Mixture B-4 contained a cement (OPC-B) that came from a different plant than OPC-A1/2 with an alkali content of 0.65 wt.% Na_2O_{eq} and was boosted by adding K_2SO_4 to balance the difference of 0.15 wt.% Na_2O_{eq} compared to OPC-A1. All four mixtures were tested under exposure of NaCl-solution, HCOOK (potassium formate) deicer solution and water as the control with the cyclic climate storage.

2.2 Methods for assessment and analysis

German accelerated mortar-bar test at 70 °C (70 °C-AMBT)

All aggregates were tested with the accelerated mortar-bar test at 70 °C according to the German alkali-guideline [16]. The aggregate is crushed and sieved to obtain 450 g of the grain size fraction 0.5-1 mm and 1-2 mm respectively. Both fractions are mixed and 450 g of non-reactive quartz sand (0.1-0.5 mm) is added. The mortar bars (40×40×160 mm) are prepared according to DIN EN 196-1 using a high-alkali portland cement (1.3±0.1 wt.-% Na_2O_{eq}) and a w/c ratio of 0.50. A certain amount of NaOH is added to the mixing water to set the Na_2O_{eq} to 2.5 wt.-%. After 1 day of curing at 20 °C and > 95 % relative humidity (RH), the mortar bars were demolded and initial length and mass were measured. Afterwards, the bars were stored at 70 °C above a water bath until the 28th day after casting. The expansion limits and classifications for pavements are defined as ≤ 1.5 mm/m (sufficiently non-reactive), 1.5-2.0 mm/m (potentially alkali-reactive) and > 2.0 mm/m (highly alkali-reactive).

ASR performance testing with the FIB cyclic climate storage

Concrete prisms (100×100×400 mm) were cast from each mixture with embedded stainless steel studs cast in each end for expansion measurements. After 24 hours, the prisms were demolded, airtight protected in sheets of polyethylene and stored for 5 days at 20 °C. Subsequently, a flexible foam rubber tape was glued around the upper edges of the prisms to form a guard that will retain the later applied test solution. The cyclic climate storage started 7 days after casting. A NaCl-solution and a commercial HCOOK deicer solution respectively were placed on top of three prisms from each mixture. The deicer test solutions were prepared to have a concentration of 0.6 mol/l prior to the application of 400 g on each of the three prisms. Concentration and application amount were chosen based on preliminary studies to ensure conditions near to the field. With some assumptions, the amount of NaCl applied in 8 cycles (360 g/m² per cycle) corresponds nearly to the average amount of NaCl that is applied during one winter period in the field on German highway pavements. The amount of the commercial HCOOK deicer that is applied with every cycle (920 g/m²) corresponds nearly to the average amount of the deicer that is applied during one winter period in the field on runways of German international airports. Additionally, a set of three prisms from each mixture were treated with distilled water as the control.

The prepared concrete prisms were stored under a defined cycle of alternating temperature and moisture conditions in a walk-in climate simulation chamber (Feutron, Type 3705/04). One cycle lasts 21 days and consists of 4 days of drying at 60 °C and ≤ 10 % RH, 14 days of wetting at 45 °C and 100 % RH and 3 days of freeze-thaw cycling between +/–20 °C [1-7]. After the very first drying phase the initial length and mass are measured and 400 g of the test solution (deicer or water) is applied to every prism for the first time and remains on the prisms until the end of the cycle. After the cycle, the prisms are brought to 20 °C and the test solution is removed to measure length change and mass of the prisms and is replaced again once the readings were taken. During the second drying phase, the water of the test solution evaporates, leaving behind minor solid residues from the deicer as well as leached substances from the concrete, e.g. some alkalis. After the second drying phase, new test solution is applied and the cycle starts all over again.

For pavement concretes exposed to deicers, the ASR potential is assessed after 8 cycles (6 months). The expansion limits were defined as 0.5 mm/m for application of deicer solutions and as 0.4 mm/m for application of water. Additionally, the slope of the expansion curve between cycle 6 and 8 is evaluated. After 12 cycles, microscopic examinations will be performed to evaluate the condition of the concrete microstructure and to identify the cause of expansion (Table 3). Concretes for other purposes, e.g. for offshore structures as well as concretes incorporating SCMs are tested up to 16 cycles owed to the longer expected service life and to account for temperature effects on the hydration of SCMs respectively [17].

German fog chamber test

For the German fog chamber test, a standardized mixture with an high-alkali (1.3±0.1 wt.% Na_2O_{eq}) portland cement (400 kg/m^3), a w/c ratio of 0.45 and gradations of 30 vol.% 0-2 mm, 40 vol.% 2-8 mm and 30 vol.% 8-16 mm or 30 vol.% 0-2 mm, 20 vol.% 2-8 mm, 20 vol.% 8-16 and 30 vol.% 16-22 mm is used. The sand 0-2 mm has to be non-reactive. After casting three prisms (100×100×500 mm) with stainless steel studs at two opposite sides of each prism for expansion measurement and one block (300×300×300 mm) for crack monitoring, the samples were demolded after 24 hours and all the initial readings were taken. Shortly after, the samples were placed in the fog chamber at 40 °C and ≥ 99 % RH for 9 months [16]. Length change and mass change were measured periodically. The acceptance criteria are expansion ≤ 0.6 mm/m and crack widths < 0.2 mm on the block.

Thin section analysis

Thin sections (60×100 mm) were prepared after the cyclic climate storage by taking samples from the middle of the prisms. The longer side (100 mm) represents the full height of the prism. Pores and cracks were filled by vacuum impregnation with a yellow colored resin. The thin sections with a thickness of approx. 22-25 µm were investigated under a polarizing microscope (Zeiss, Jenalab).

3 RESULTS

The new batches (8-16 mm, 16-22 mm) of the rhyolite for the laboratory/field correlation testing of concrete C-1 show a slightly higher expansion in the 70 °C-AMBT as the original material extracted form the pavement cores, but both are highly alkali-reactive. The gravel 2-8 mm and the sand A 0-2 mm are alkali-reactive too (Figure 2). Contrary, the German fog chamber test classifies the rhyolite as non-reactive (Figure 3). The expansions for the granodiorite from quarry A (2-8 mm, 8-16 mm, 16-22 mm) for concrete C-2 are below the limits for both, the 70 °C-AMBT and the German fog chamber test. Sand B 0-2 mm is classified as non-reactive as well (Figure 2, Figure 3). For concrete C-1 with the rhyolite and exposed to NaCl-solution, the expansion exceeds the limit of 0.5 mm/m after 7 cycles of the cyclic climate storage and the slope limit between cycle 6 and 8 is exceeded as well (2.4 > 1). Also, the thin section analysis after 12 cycles provided clear evidence for ASR (Figure 4). Even if exposed to water, deleterious expansion (> 0.4 mm/m) occurs after 12 cycles. Concrete C-2 with the granodiorite from quarry A exposed to NaCl-solution shows critical expansion (> 0.5 mm/m) after 8 cycles, a critical slope of the expansion curve between cycle 6 and 8 (1.7 > 1) and clear evidence for ASR after 12 cycles (Figure 5). Exposed to water only, no deleterious expansion (> 0.4 mm/m) occurred until the end of the performance test.

For the boosting experiments, the granodiorite from quarry B (2-8 mm, 8-16 mm, 16-22 mm) is classified as sufficiently non-reactive based on the 70 °C-AMBT (Figure 2). During the cyclic climate storage and under exposure of the deicer solutions, however, the expansions increased continuously for all four mixtures, regardless of the boosting option (Figure 6). After 8 cycles, the expansion limit of 0.5 mm/m is exceeded for all four mixtures exposed to the deicer solutions and all the slopes between cycle 6 and 8 are critical (> 1). Finally, the thin section analysis showed evidence for ASR after 12 cycles in all four mixtures exposed to the deicer solutions. For mixture B-4, there is a slower increase in expansion under exposure of the NaCl-solution from cycle 6 onwards which results in a significant lower expansion after 12 cycles compared to the other mixtures. Under exposure of the HCOOK deicer solution, there is a faster increase in expansion for mixture B-4, but the expansion after 12 cycles is nearly the same as for the other mixtures. Exposed to water, as expected, the increase of the expansions is much slower for all four mixtures compared to the exposure of the deicer solutions. But deleterious expansion (> 0.4 mm/m) occurs for mixture B-3 after 10 cycles (Figure 7).

4 DISCUSSION

For concrete C-1, all the aggregates are alkali-reactive based on the expansion data of the 70 °C-AMBT. In the German fog chamber test, however, the rhyolite was found to be non-reactive. The cyclic climate storage proved that deleterious ASR occurred in concrete C-1 under exposure of NaCl-solution. This corresponds very well to the field performance of this concrete that showed ASR damages in a pavement after about 12 years in service. Hence, the cyclic climate storage as performance test predicted the ASR potential for concrete C-1 correctly compared to field performance. In this case, also the 70 °C-AMBT was able to classify the reactivity of the aggregates correctly. The regulations at the time of construction (1991/93), however, do not include any of these tests. For concrete C-2, the granodiorite from quarry A was supposed to be non-reactive based on the 70 °C-AMBT as well as on the German fog chamber test. However, these results do neither correspond to the cyclic climate storage nor to the field performance of that granodiorite which triggered deleterious ASR in a pavement concrete after about 8 years in service. In this case, only the results of the cyclic climate storage correspond to field performance. Moreover, concrete C-2 meets all the latest requirements for pavement concretes in Germany, i.e. (1) the granodiorite passed the 70 °C-AMBT and (2) the cement alkali content is ≤ 0.80 wt.% Na_2O_{eq}. Hence, it is evident that the latest regulations for pavement concretes in Germany cannot reliably prevent ASR damages. This is due to a possible underestimation of the reactivity of some aggregates in the 70 °C-AMBT but especially in the German fog chamber test for the use in pavements [7, 18, 19]. In addition to granodiorite aggregates, also the reactivity of some recently tested granite, granulite and gneiss aggregates was underestimated with the 70 °C-AMBT compared to the results of the cyclic climate storage (unpublished). In the field, first signs of ASR on pavements usually occur after about 10 years in service, suggesting that 8 cycles are sufficient to identify a deleterious ASR potential for pavement concrete mixtures. Nevertheless, the cyclic climate storage is always run for 12 cycles to ensure that deleterious ASR is prevented for about 20-30 years, i.e. within the intended service life for concrete pavements.

Since NaOH influences among others the solubility of $Ca(OH)_2$ (Figure 7) and usually potassium is predominant in most cements, K_2SO_4 was used for the boosting within this study. Again, the 70 °C-AMBT clearly underestimated the reactivity of the granodiorite aggregates from quarry B since deleterious expansion occurs for all four mixtures in the cyclic climate storage under exposure of the deicer solutions. More important, all four mixtures exposed to the deicer solutions fail the performance test regardless of the boosting option. The unboosted mixture B-1 (reference) shows the same increase in expansion than mixture B-2 (unboosted, lower alkali level as B-1) and mixture B-3 (boosted, same alkali level as B-1), all with cement from the very same plant. This indicates that differences of around 0.1 wt.% Na_2O_{eq} for a cement, caused by fluctuations during the cement production, can be neglected for the cyclic climate storage for mixtures under exposure of deicer solutions regarding the final test result. Mixture B-4, however, with cement from a different plant shows different expansion rates although it was boosted to the same alkali level as mixture B-1 and B-3. Hence it seems that the origin of the cement, i.e. its specific composition, has some influence on the expansion caused by ASR, at least under exposure of deicer solutions. This corresponds to the expansion data from the 70 °C-AMBTs with the different cements (Figure 1) even though to a lesser extent and without changing the final performance test results. Correspondingly, another study with ASTM C 1260 tests also found varying expansions for different cements, with and without added NaOH, that could not be linked to the alkali content of the cements [20]. The situation is somewhat different under exposure of water. On the one hand, there is no significant difference in expansion for the mixtures B-1, B-2 and B4, indicating that the origin of the cement does not has an influence on the final test results in this case. On the other hand, for the boosted mixture B-3 (same alkali level as B-1), the expansion beyond cycle 6 distinguishes clearly from the unboosted mixture B-1, indicating a possible influence of the boosting on the final test result. Again, in another study with ASTM C 1260 tests it was concluded too that the addition of NaOH to bring the total alkali content of different mortars to the same level may not result in similar expansions [20]. Based on results in [9, 10], the change of the Na/K ratio due to the boosting could be a possible reason for this. Finally, the results from this study confirm essentially that an external alkali supply is highly able to drive the ASR predominantly [1-7, 12, 13, 18, 19]. In addition it is evident that (1) sufficiently small fluctuations (~0.1 wt.% Na_2O_{eq}) in the alkali content of a cement from one particular plant that may occur during the production can be neglected for the cyclic climate storage at least under exposure of deicer solutions, (2) the origin of the cement, i.e. its specific composition, can have some influence on the expansion caused by ASR, at least under exposure of deicer solutions and (3) boosting a concrete mixture to the same alkali level as in a comparable unboosted mixture do not necessarily result in equal expansion under exposure of water. Especially the latter two findings require further research with respect to reliable performance testing since only a limited number of cements and only one type of aggregate could be tested within this study. But the results support the view that performance testing, by definition, should be done with the project-specific materials (cement, aggregates etc.) to consider as much of the individual material interactions as possible and that careful attention should be paid to boosting the alkali level.

5 CONCLUSIONS

It could be proved that the cyclic climate storage is able to assess the ASR potential of concrete pavement mixtures correctly compared to their field performance. Two concrete compositions that showed ASR damages after 8-12 years in service failed in the cyclic climate storage correspondingly. While some of the investigated aggregates (gravel, rhyolite) could already be classified correctly as alkali-reactive by the 70 °C-AMBT, the reactivity of the granodiorite aggregates could neither be classified correctly by the 70 °C-AMBT nor by the German fog chamber test for use in pavements. Based on these results and with a background of another 250 performance tests it can be concluded that the cyclic climate storage is an appropriate ASR performance test for pavement concretes, predicting a service life of 20-30 years.

First investigations into boosting the alkali level in mixtures for performance testing showed that (1) sufficiently small fluctuations (~0.1 wt.% Na_2O_{eq}) in the alkali content of a cement from one plant that may occur during the production can be neglected for the cyclic climate storage at least under exposure of deicer solutions, (2) the origin of the cement, i.e. its specific composition, can have some influence on the expansion caused by ASR under exposure of deicer solutions and (3) boosting a concrete mixture to the same alkali level as in a comparable unboosted mixture do not necessarily result in equal expansion under exposure of water. Especially for the latter two findings further research is needed with respect to reliable performance testing.

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TABLE 1: Concrete mixtures used for the laboratory/field correlation

Mixture	C-1	
	Used in the field for construction (1991/93)	Used for the ASR performance test
Cement	PZ 35 F (now CEM I 32.5 R) 360 kg/m^3 Na_2O_{eq} = 0.96 wt.%	CEM I 32.5 R 360 kg/m^3 Na_2O_{eq} = 0.90 wt.%
w/c	0.44	0.44
Air content	4-5 vol.%	4.9 vol.%
Alkali level	3.46 kg Na_2O_{eq}/m^3	3.24 kg Na_2O_{eq}/m^3
Aggregates	approx. 40 vol.% Sand and gravel* (0-8 mm) approx. 60 vol.% Rhyolite (8-22 mm)	28 vol.% Sand A 0-2 mm 15 vol.% Gravel* 2-8 mm 23 vol.% Rhyolite 8-16 mm 34 vol.% Rhyolite 16-22 mm
Mixture	C-2	
	Used in the field for construction (1991/93)	Used for the ASR performance test
Cement	PZ 35 F (now CEM I 32.5 R) approx. 360 kg/m^3 $Na_2O_{eq} \leq 0.90$ wt.%	CEM I 32.5 R 360 kg/m^3 Na_2O_{eq} = 0.76 wt.%
w/c	≤ 0.45	0.38
Air content	4-5 vol.%	4.9 vol.%
Alkali level	≤ 3.24 kg Na_2O_{eq}/m^3	2.74 kg Na_2O_{eq}/m^3
Aggregates	approx. 40 vol.% Sand and gravel* (0-8 mm) approx. 60 vol.% Granodiorite (8-22 mm)	28 vol.% Sand B 0-2 mm 18 vol.% Granodiorite A 2-8 mm 25 vol.% Granodiorite A 8-16 mm 28 vol.% Granodiorite A 16-22 mm

* glacial gravel with strained quartz, flint, chert, siliceous limestone, greywacke and rhyolite

TABLE 2: Concrete mixtures for testing different boosting options with the cyclic climate storage

Mixture	B-1	B-2	B-3	B-4
Cement	CEM I 42.5 R (OPC-A1) Plant A, batch 1 Na_2O_{eq} = 0.81 wt.% 360 kg/m^3	CEM I 42.5 R (OPC-A2) Plant A, batch 2 Na_2O_{eq} = 0.67 wt.% 360 kg/m^3	CEM I 42.5 R (OPC-A2) Plant A, batch 2 Na_2O_{eq} = 0.67 wt.% 360 kg/m^3	CEM I 42.5 R (OPC-B) Plant B Na_2O_{eq} = 0.65 wt.% 360 kg/m^3
Air content	4.3 vol.%	4.1 vol.%	4.2 vol.%	4.2 vol.%
K_2SO_4	---	---	3.79 g/kg cement	4.36 g/kg cement
Alkali level	2.92 kg Na_2O_{eq}/m^3	2.41 kg Na_2O_{eq}/m^3	2.92 kg Na_2O_{eq}/m^3	2.92 kg Na_2O_{eq}/m^3
w/c	0.42			
Aggregates	29 vol.% Sand B 0-2 mm 15 vol.% Granodiorite B 2-8 mm 27 vol.% Granodiorite B 8-16 mm 29 vol.% Granodiorite B 16-22 mm			

TABLE 3: Acceptance criteria for pavement concretes tested with the cyclic climate storage

Expansion after cycle 8	$\varepsilon_8 \leq 0.5$ mm/m
Slope between cycle 6 and 8	$(3\,\varepsilon_8 - 2\,\varepsilon_6)/0.45 \leq 1$
Thin section analysis	after 12 cycles

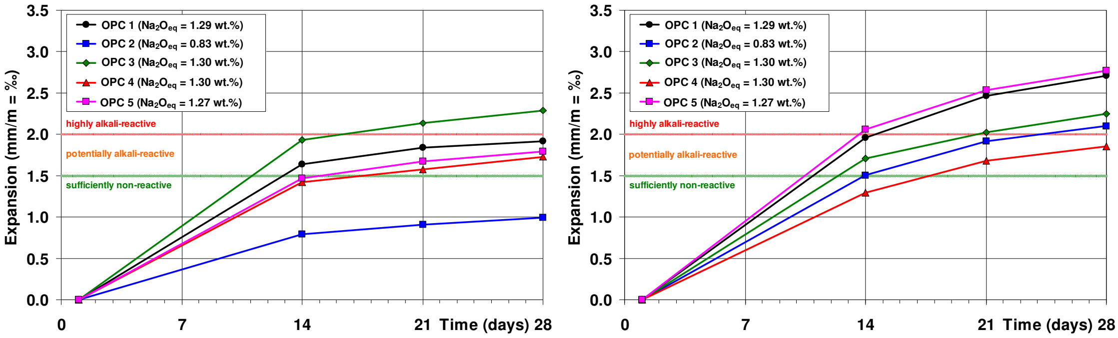

FIGURE 1: 70 °C-AMBT expansions for a gravel (left) and an andesite (right) from the same batch each with OPCs from different plants and with different alkali contents boosted with NaOH to 2.5 wt.% Na_2O_{eq}.

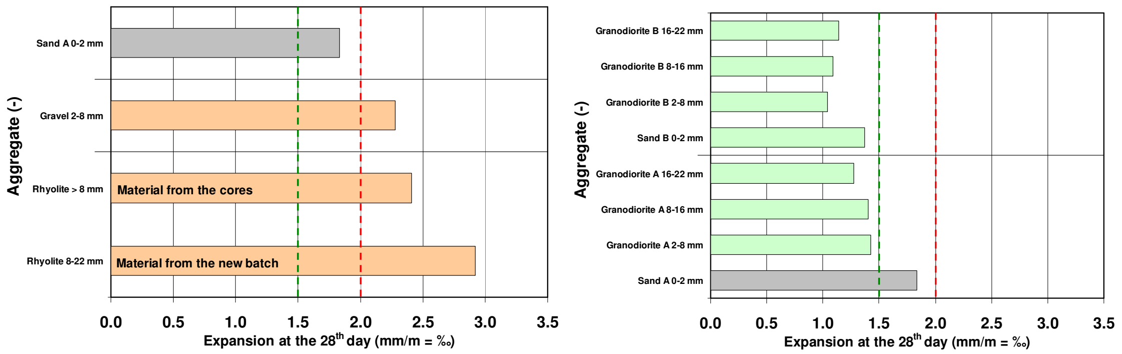

FIGURE 2: 70 °C-AMBT expansions for the aggregates used in concrete C-1 (left) and C-2 (right) as well as in the mixtures B-1, B-2, B-3 and B-4 respectively (right).

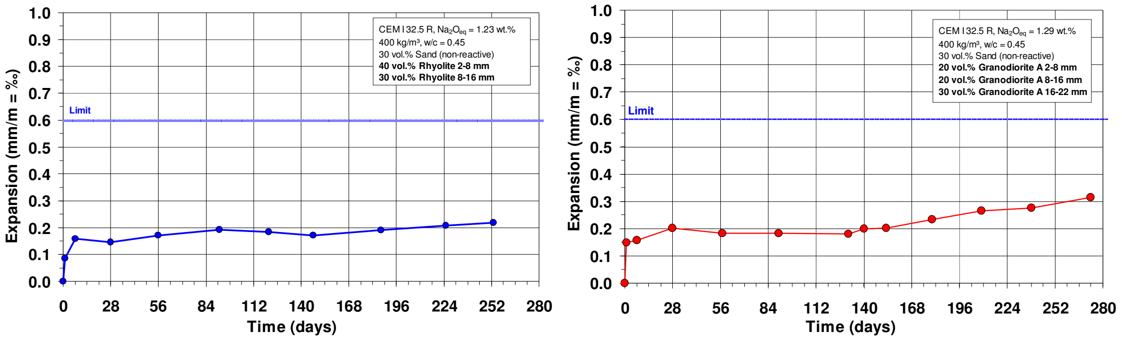

FIGURE 3: German fog chamber test expansions for the rhyolite used in concrete C-1 (left) and the granodiorite A used in concrete C-2 (right). In both cases, no critical crack widths (< 0.2 mm) were found on the blocks.

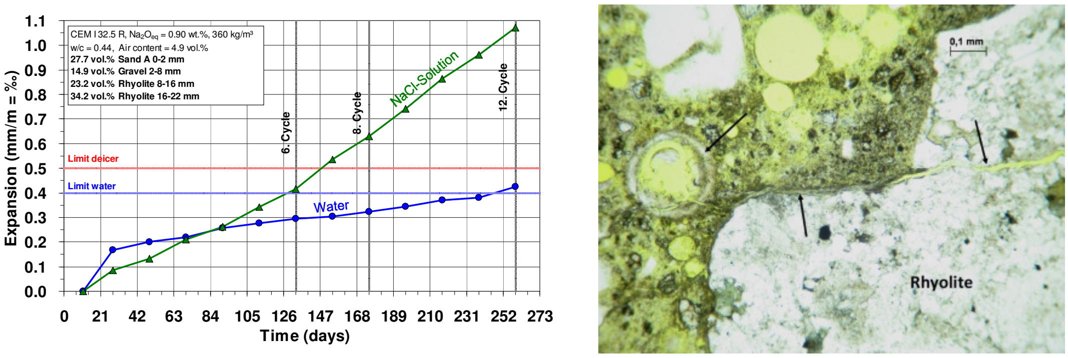

FIGURE 4: Cyclic climate storage expansions for concrete C-1 (left) and a thin section image after 12 cycles for a prism exposed to NaCl-solution with evidence for ASR (right). This concrete composition showed ASR damages in the field after 12 years in service.

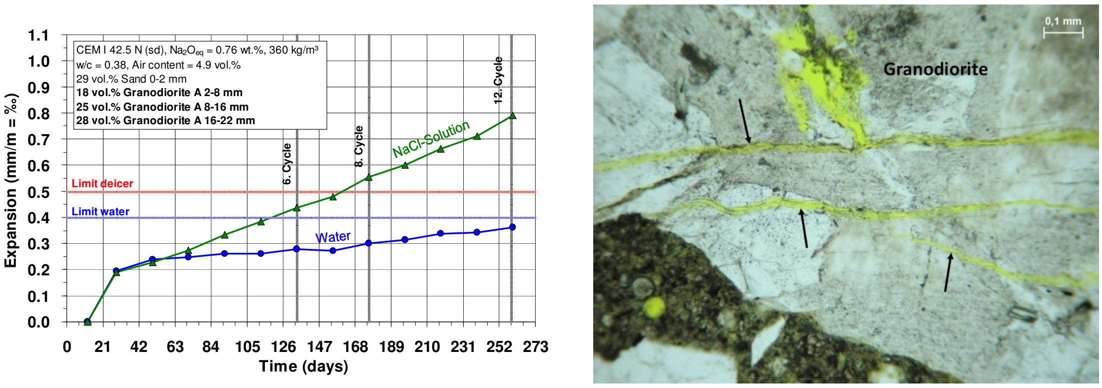

FIGURE 5: Cyclic climate storage expansions for concrete C-2 (left) and a thin section image after 12 cycles for a prism exposed to NaCl-solution with evidence for ASR (right). A similar concrete composition with granodiorite from the same quarry showed ASR damages in the field after about 8 years in service.

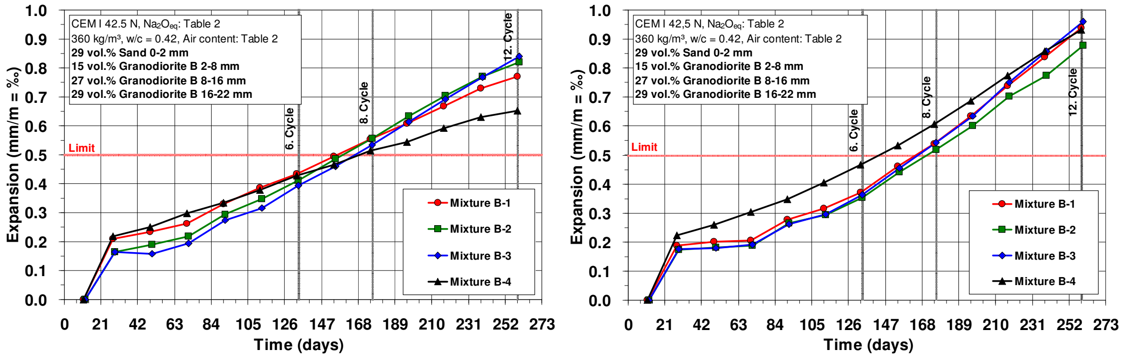

FIGURE 6: Cyclic climate storage expansions for mixture B-1, B-2, B-3 and B-4 exposed to NaCl-solution (left) and HCOOK deicer solution (right).

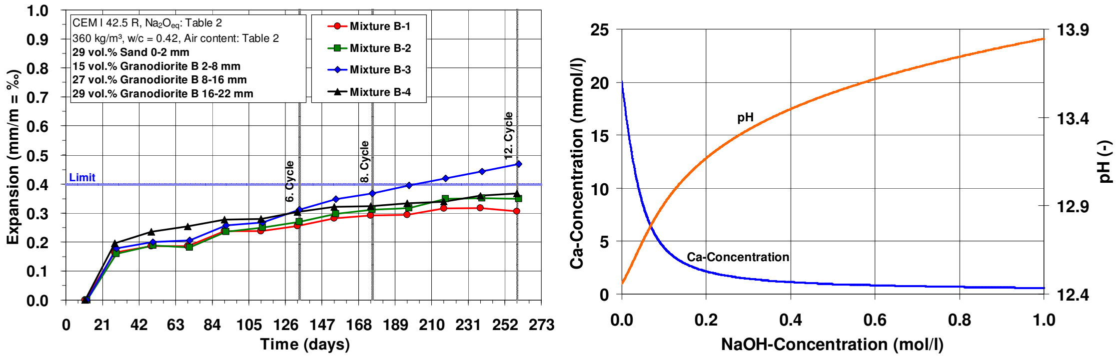

FIGURE 7: Cyclic climate storage expansions for mixture B-1, B-2, B-3 and B-4 exposed to water (left) and the influence (calculated) of NaOH on the solubility of $Ca(OH)_2$ in a saturated $Ca(OH)_2$-solution with solid $Ca(OH)_2$ in excess under addition of NaOH (right).