Creep and strength of pavement concretes containing alkali sensitive aggregates after climate simulating test

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Abstract

Four pavement concretes were subjected to the climate simulating test which has been developed at F.A. Finger Institute of University of Weimar, Germany. The so-called FIB climate test method comprises cycles of wet and dry environment, salt spraying and frost action. Tests have shown that pavement concrete which has passed the test successfully can sustain in natural environment in Germany. During and after the test, strains, compressive strength, elastic modulus, creep and shrinkage have been measured. The results show that the alkali-silica reaction (ASR) induced damage process manifests itself as follows. While micro cracking in the matrix is rather negligible for compressive strength it affects the static elastic modulus considerably which is due to dissolution processes and aggregate cracking. The cracks in slow reacting aggregates emanate from the grains and proceed into the matrix. Larger matrix volume causes more cracks and larger creep. Salt solution increases creep.

Keywords: *pavement concrete; alkali-silica reaction; slow reacting aggregates; cyclic climate test; compressive strength; modulus of elasticity; creep*

1. INTRODUCTION

Concrete construction promises high load-bearing capacity and deformation stability, even at very high temperatures. In addition, concrete pavement is also judged to have a long service life - a service life of 30 years is usually assumed. Approximately 28% of the 13,009 km network of German federal motorways is constructed in concrete. However, a problem has currently arisen regarding this network of German federal highways which makes that the planned 30-year service life of concrete pavements constructed before 2005/2006 will not be achieved. Aggregates with ASR sensitivity were used in part for these concrete road pavements. In a nationwide analysis of the German federal motorway network, it appeared that in 2012, approximately 1,500 km of directional lanes were suspected of ASR (alkali-silica reaction). The findings and experiences gathered over the last years were transferred into everyday operations through introduction of the advisory circular ARS 04/2013 [1]. Hence, new regulations and testing methods are already available to reduce the potential for damage due to ASR in concrete pavements [2].

In general, under the influence of an external supply of alkalis and in combination with cyclic loading, the ASR-related damage process is intensified [2-4]. Visual damage characteristics of ASR in concrete pavements are often discoloration in the area of joints which is subsequently accompanied by an increased crack formation. The cracks spread around the perimeter of the slabs and there is often little or no cracking in the center of the slab. The reason that the region around the joints is more prone to cracking is because there is often more moisture available, there is less restraint to expansion, and mechanical stresses due to vehicular loading are higher. ASR advances, there is additional loss of substance due to corner fractures. The cause of corner fractures can be found in a horizontal crack in the concrete slab [5].

Within the material there are micro cracks either in the cement matrix or in the aggregate grains which can lead to a reduction of strength and stiffness. Beside the mentioned surface cracks in concrete pavements, also severe cracking in the interior of the slabs can occur. Tests have shown that stiffness is far more affected than compressive strength [6-8] and deformations under load of ASR damaged concrete can be threefold of unaffected concrete [9]. Compressive stresses can suppress the expansion due to ASR in the direction of the load, but deformations transverse to the load are magnified [10].

The long time behavior of structural elements has been investigated [11-13], however, pavement concrete did not get appropriate attention although cracking is a severe problem when alkali sensitive aggregates have been used. The present investigation deals with four concrete compositions which are typical for pavements. The results are part of the project in [7, 14].

2. MATERIALS AND METHODS

2.1 General

The experimental program was designed such that the concrete could suffer from alkali-silica reaction. This reaction takes place if aggregates contain particles with distorted lattices and which are soluble in alkaline environment [15]. There are two types of relevant aggregates, one being fast reacting such as flint and opal and the other being slow reacting such as rhyolite. Slow reacting aggregate grains show internal cracks which continue in the cement matrix. The modulus of elasticity of the grain becomes smaller and, as a consequence, the modulus of elasticity of the concrete drops also. The compressive strength decreases not necessarily. The aggregates of the present investigation belong to slow reacting aggregates which cause distress after 10 to 20 years in ambient environment. These types of aggregate have been frequently used in German concrete pavements.

For the special case of concrete pavements where moisture and external alkali supply from deicing salt are important parameters, two ASR performance tests have been designed in Germany. The first method is the 60°C concrete test with external alkali supply. This method is developed at the German VDZ Institute [16] and is recently included in RILEM AAR-12 draft procedure. The second test method has been developed at the F.A. Finger-Institute in Weimar (FIB). This test method has been used for accelerated simulation of Central European climatic conditions. Significant effects from environment (wetting and drying, freezing and thawing and exposure to deicing chemicals) are simulated to observe degradation features of the concrete under test by alternating temperature and moisture conditions in a specially developed simulation chamber [17-19].

2.2 ASR performance test with external alkali supply

For the present investigations the FIB climate test method was used. One reason is, that on a real concrete pavement the deicing salt is applied on the top of the surface. This one-sided application of the deicing agent is best simulated by the FIB climate test method. In contrast to that, the samples in the 60°C concrete test with external alkali supply are submerged in the deicing agent solution.

For the used test method concrete prisms (100 x 100 x 400 mm³) were cast with embedded stainless steel studs in each end for expansion measurements. After 24 hours, the prisms were demolded and stored according to EN 12390-2:2009-08 (moist cabinet) for 5 days. Afterwards a flexible foam rubber tape was glued around the upper edges of the prisms to form a guard that will retain the testing fluid (Figure 2.1).

Figure 2.1: Prepared prism for the FIB climate test method (from [20])

The cyclic climate storage was initiated 7 days after casting. As testing fluids a 0.6 mol/l NaCl solution (400 g) and water (400 g) were placed on the top of every three prisms. Water was used as control. The cyclic climate storage was done for 12 cycles. One cycle takes 21 days and consists of 4 days of drying at 60°C and ≤10% relative humidity, 14 days of wetting at 45°C and 100% relative humidity and 3 days of freeze-thaw-cycling between +20°C and -20°C. The figure shows a sequence for one cycle of the FIB climate test method [21].

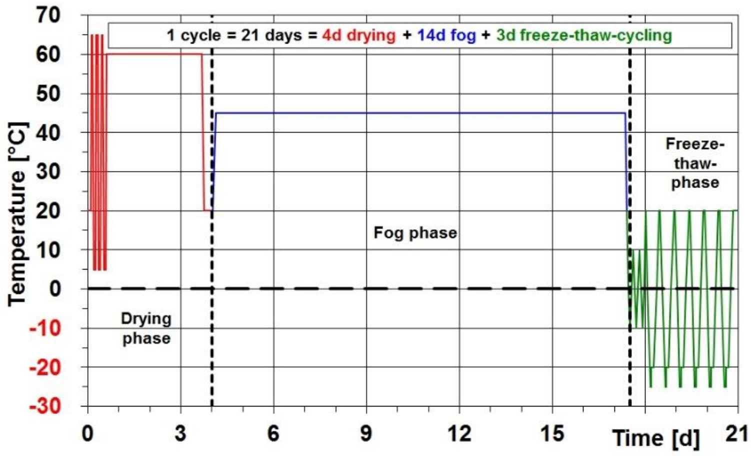

Figure 2.2: Temperature scheme for one cycle of the FIB climate test method [21]

After the first drying phase the initial length is measured and 400 g of the water and 400 g of the NaCl solution is applied to every prism. The testing fluids remain on the prisms until the end of the cycle. After 21 days (end of the cycle) the fluids are removed to measure length change. A Graf-Kaufmann measuring rack with dial gauge was used which is standard in Germany. After measurement, the fluids are again applied to the prisms. After the second drying phase water and NaCl solution are evaporated and new testing fluids are applied. For pavement concretes exposed to deicers, the ASR potential is assessed after 8 cycles [22]. The expansion limits for passing the test were defined as 0.5 mm/m for deicer solutions and as 0.4 mm/m for water. Additionally, the slope of the expansion curve between cycle 6 and 8 is evaluated according to [23] with equation (1). The strains (ε_6 and ε_8) are inserted in the equation with dimension mm/m. If a concrete has successfully passed the climate test method it is considered as appropriate for use in concrete pavements.

$$(3 \cdot \varepsilon_8 - 2 \cdot \varepsilon_6)/0.45 \leq 1 \tag{1}$$

2.3 Aggregates used

The aggregates are sand and crushed gravel. The sand 0/2 mm was non-reactive. The ASR sensitive coarse aggregates are rhyolite type A and type B both from two different quarries in Germany. The mineralogical compositions of type A is given as follows [20]: 28,3 % quartz, 31,0 potash feldspar (microcline and orthoclase), 29,3 plagioclase (albite and oligoclase), 4,6 % mica (biotite and muscovite), 3,1 % chlorite , 1,7 % enstatite, 1,0 % kaolinite, 0,6 % magnetite and 0,3 % hematite. The mineralogical compositions of type B consists of: 54,4 % quartz, 30,5 potash feldspar (microcline and orthoclase), 11,6 % mica (biotite and muscovite), 2,2 % kaolinite, 0,1 % magnetite and 1,3 % hematite.

2.4 Concrete composition

Four concrete compositions were selected (Table 2.1). In Germany, three types for concrete pavements are executed as follows: one concrete composition/single-layer constructed, one concrete composition/two-layer constructed, two concrete compositions/double layer constructed. In case of double layer constructed concrete pavements, one composition represents the upper layer and the other the lower layer. The upper layer contains a smaller 8 mm maximum grain size compared to the lower layer with 16, 22 or 32 mm grain size. However, the lower concrete could also be applied as upper concrete when the pavement was poured in once (A-0/16 and B-0/22).

The upper layer has to be frost and deicing salt resistant wherefore the air content is higher than for the lower layer. The $Na_2O_{equ.}$ of the cement was 0.65 % by mass which follows the German regulation TL Beton-Stb 07 [24] for concrete pavements, the water to cement ratio of all concretes was held constant at 0.45. In former investigations, the rhyolite A was more susceptible to ASR than rhyolite B. The surface of the specimens was either washed or brush stroke.

Table 2.1: Concrete compositions

	A-0/8	A-0/16	B-0/8	B-0/22
Cement [kg/m³]	CEM I 42,5 N 430 kg/m³	CEM I 42,5 N 360 kg/m³	CEM I 42,5 N 430 kg/m³	CEM I 42,5 N 360 kg/m³
$Na_2O_{equ.}$ [% by mass]	0.65	0.65	0.65	0.65
w/c ratio [-]	0.45	0.45	0.45	0.45
Air content [% by vol.]	5.5 – 6.5	4.0 – 5.0	5.5 – 6.5	4.0 – 5.0
Type of mix	upper layer	upper and lower layer	upper layer	upper and lower layer
Aggregate content [% by vol.]	sand: 30 2/8: 70	sand: 30 2/8: 40 8/16: 30	sand: 30 2/8: 70	Sand: 30 2/8: 15 8/16: 25 16/22: 30
Grain size [mm]	8	16	8	22

2.5 Mechanical testing

At the end of 12 cycles, specimens were manufactured from the beams by sawing the 400 mm beams in pieces of various lengths. For compression testing the specimen was a 100 mm cube, for creep testing the length was 200 mm and the width was 100 mm (Figure 2.3). Conventional testing devices have been used for the determination of compressive strength and modulus of elasticity.

Figure 2.3: Cut prism after FIB climate test method for testing compressive strength, modulus of elasticity, creep and shrinkage (from [20])

Before creep was measured, the static modulus of elasticity was determined on two samples according to the German standard DIN 1045-5:1991-06 which is similar to EN 12390-13:2014-06, procedure B. To determine the static modulus of elasticity the deformation was measured with two LVDTs (Linear Variable Differential Transformer). One LVDT was fixed on the surface which was exposed to water or NaCl, the other on the opposite side.

Creep tests were carried out with a load corresponding to one third of the characteristic 28 days cube strength. The specimens were loaded with the aid of a hand pump and remained under load for 364 days. The load was held constant by Belleville springs and checked in regular intervals. However, one must admit, that 364 day testing does not lead to the final state but gives a rather good indication for creep behaviour. The deformation on creep specimens was measured in the direction of load (longitudinally) by using dial gauge. The dial gauges were clamped in a metal frame which was fixed by screws pressing against the concrete surfaces. We used 2 different positions for our measurement:

Position 1 was on the surface which was exposed to water or NaCl solution, position 2 was the area on the opposite side.

The measuring distance in the direction of load was 100 mm, measured to an accuracy of 1/1000 mm. Shrinkage was measured on one specimen in axial direction without load. After 364 days, the specimens (creep test) have been unloaded and the static modulus of elasticity and elastic deformation respectively was determined again.

Figure 2.4: Example of the test rig for creep and shrinkage (from [14]) and an example for the positions of the dial gauges

3. TEST RESULTS

3.1 Expansion

The expansion has been measured after a certain time. The results for concrete compositions A-0/8 and A-0/16 are shown in Figure 3.1 and for concrete compositions B-0/8 and B-0/22 in Figure 3.2 as mean value of three prisms. One common feature is that the expansion is always larger for the specimens which were exposed to deicing solution than for specimens exposed to water. All concretes stayed under the expansion limit (≤ 0.4) when they were exposed to water.

After 8 cycles, the acceptable limit expansion of 0.5 mm/m has been exceeded for the concrete compositions A-0/8 and A-0/16 when they were exposed to NaCl solution. On contrast to that, the concrete composition B-0/8 is under the expansion limit of 0.5 mm/m after 8 cycles when it was exposed to NaCl solution. However, the slope between the 6th and 8th cycle is 1.3 and therefore greater than 1. By definition according equation (1), the concrete composition B-0/8 is sensitive against ASR. The concrete composition B-0/22 is ASR insensitive, because the expansion is under the limit when it was exposed to NaCl solution and the slope between the 6th and 8th cycle is smaller than 1 (0.8 < 1).

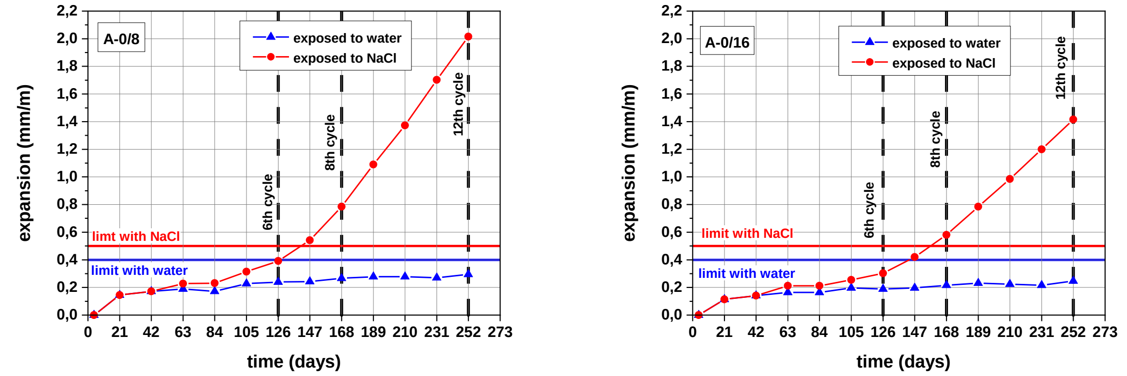

Figure 3.1: Results of expansion measurements, concrete compositions A-0/8 and A-0/16

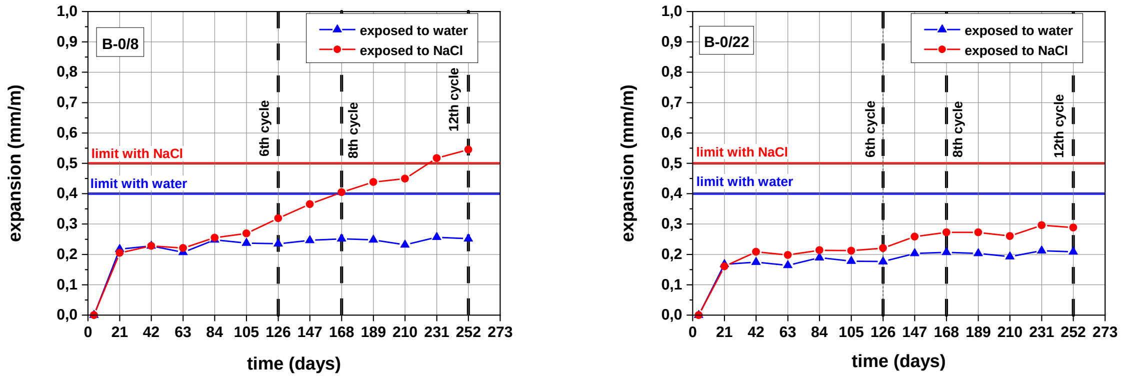

Figure 3.2: Results of expansion measurements, concrete compositions B-0/8 and B-0/22

3.2 Compressive strength

The compressive strength has been measured before the cyclic climate test and after 12 cycles (= 252 days). The results are given as mean value of three samples in Table 3.1.

Table 3.1: Compressive strength in MPa and % (in brackets) of 28 days strength before and after cyclic climate test

Concrete composition	After 28 d curing	After cyclic climate test 12 cycles (= 252 days)	
		H_2O	NaCl
A-0/8	50.2 (100)	75.5 (150)	64.5 (128)
A-0/16	59.8 (100)	82.6 (138)	77.4 (129)
B-0/8	58.3 (100)	87.1 (149)	84.0 (144)
B-0/22	59.7 (100)	85.6 (143)	86.8 (145)

The compressive strengths of three concretes are alike around 59 MPa after 28 days storage in the moist room acc. to EN 12390-2:2009-08. Only the concrete made with A-0/8 aggregate had a lower strength (the reason for the difference is not yet known). Exposure to water caused a considerable increase of the strength by 38 to 50 % whereas the exposure to deicing salt caused only an increase of 28 to 45 %. Obviously, there were two conflicting mechanisms: one is the continued hydration and the other is the degradation due to ASR (frost damage is excluded due to air entrainment). Only in case of deicing salt one could find a larger contribution of the second mechanism.

3.3 Modulus of elasticity

The results of the measurements of the modulus of elasticity are presented as mean value of two samples in Table 3.2. The values after 28 days storage in the moist room are between 25,410 and 39,070 MPa. The concretes with smaller aggregate (0/8) are always less stiff than the concretes with larger aggregate (0/16 and 0/22). The reason for the difference is the higher amount of cement (see Table 2.1), 430 kg/m^3 cement instead of 360 kg/m^3. After 12 cycles in the cyclic climate test and water as testing fluid, the elastic modulus increased by 11 to 38 %. The exposure to deicing salt caused a reduction by 37 to 23 % on concrete composition A-0/8 and A-0/16 compared to the original value. If one compares the influence of the fluid one can state a difference of 31 to 43 %. The influence of the fluid in case of B aggregates was considerably smaller (7 to 14 %).

Table 3.2: Modulus of elasticity in MPa and % (in brackets) of 28 days value before and after cyclic climate test

Concrete composition	After 28 d curing	After cyclic climate test 12 cycles (= 252 days)	
		H2O	NaCl
A-0/8	33,870 (100)	37,420 (111)	21,380 (63)
A-0/16	39,070 (100)	43,590 (112)	30,240 (77)
B-0/8	25,410 (100)	34,890 (137)	29,870 (118)
B-0/22	28,840 (100)	39,800 (138)	36,860 (128)

3.4 Creep

The specimens for the creep test were stored about half a year in a climate controlled room with 65 % RH and 20°C after the cyclic climate test, i.e. the concrete was about 430 days old when the creep test started. During the test in a climate chamber with 80 % RH and 23°C, the total deformation was measured which comprises the elastic (or initial) strain, creep and shrinkage.

For evaluation of creep, elastic and shrinkage strain are subtracted from the measured total strain. Further, since the compressive stress was one third of the 28 days cube strength and the strength was different for the four concretes the creep is related to the stress which yields the so-called specific creep. The results for concrete compositions A-0/8 and A-0/16 are shown in Figure 3.3 and for concrete compositions B-0/8 and B-0/22 in Figure 3.4. The figures show the increase of strain during the 364 days loading, and they show also that the specimens which were subjected to the deicing solution creep more than the specimens which were exposed to water. Creep of the concrete with A-0/8 had a specific creep of about 42 (µm/m)/MPa after 364 days with salt and about 12 (µm/m)/MPa with water. Concrete with A-0/16 showed a specific creep of 29 (µm/m)/MPa with salt and 12 (µm/m)/MPa with water. The specific creep of concrete with B-0/8 had a creep of 29 (µm/m)/MPa with salt and 15 (µm/m)/MPa with water. The concrete with B-0/22 showed a specific creep of 15 (µm/m)/MPa with salt and 10 (µm/m)/MPa with water.

With the creep factor φ after 364 days of loading, the Figure 3.3 and Figure 3.4 show a second feature. With creep (ε_{cc}), elastic strain (ε_{el}), stress (σ) and elastic modulus (E_{28}) the creep factor φ is calculated according to the following equation (2).

$$\varphi = \varepsilon_{cc}/\varepsilon_{el} = \varepsilon_{cc}/(\sigma/E_{28}) = \varepsilon_{cc,specific} \cdot E_{28} \quad (2)$$

Based on the creep factors φ as a function of the concrete compositions and the testing fluids (see Figure 3.3 and Figure 3.4), the following can be derived:

- A higher cement content and a simultaneous influence of NaCl solution (A-0/8, B-0/8) leads to greater creep
- Creep in ASR-sensitive concretes under influence of NaCl solution is always significantly higher than under water (A-0/8, A-0/16, B-0/8)
- Creep in ASR-insensitive concretes under the influence of water and NaCl solution differ only marginally (B-0/22)

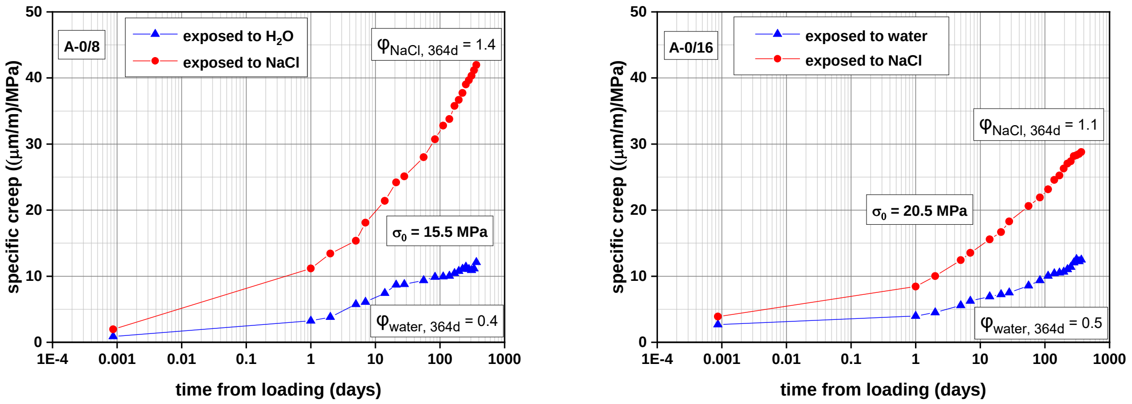

Figure 3.3: Specific creep, concrete compositions A-0/8 and A-0/16

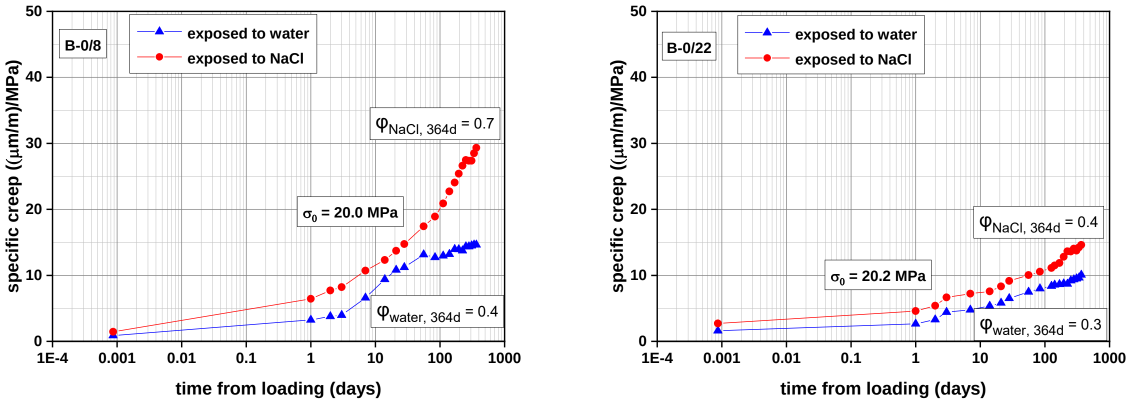

Figure 3.4: Specific creep, concrete compositions B-0/8 and B-0/22

3.5 Elastic deformation before and after creep

Table 3.3 shows the comparison of the elastic deformation before ($\varepsilon_{el/before\ creep}$) and after ($\varepsilon_{el/after\ creep}$) the creep test on the same specimen, depending on the concrete composition and the testing fluids. This means for the elastic deformation after creep that the specimen has already been loaded four times: Three times for the determination of the static modulus of elasticity (acc. DIN 1048-5:1991-06) and once for the creep test. The results in Table 3.3 show, that the elastic deformation is always smaller after creep than before creep. In the case of water as testing fluid, the values are 2% to 7% smaller. When NaCl solution was the testing fluid and the concrete composition is ASR sensitive (A-0/8, A-0/16 and B-0/8), the values are 7% to 19% smaller. For the ASR insensitive concrete composition and NaCl solution as testing fluid, the elastic deformation is 4% smaller after creep than before creep. The reduction of the elastic deformation means, that a non-reversible plastic-deformation in the test specimen has occurred due to the load.

Table 3.3: Comparison of the elastic deformation in mm/m with load (σ_0) during determination of static modulus of elasticity before ($\varepsilon_{el/before\ creep}$) and after ($\varepsilon_{el/after\ creep}$) the creep test depending on concrete composition and testing fluid.

	water		NaCl solution	
	$\varepsilon_{el/before\ creep}$	$\varepsilon_{el/after\ creep}$	$\varepsilon_{el/before\ creep}$	$\varepsilon_{el/after\ creep}$
A-0/8	σ_0 = 15,5 MPa		σ_0 = 15,5 MPa	
	0.41	0.39	0.73	0.59
A-0/16	σ_0 = 20,5 MPa		σ_0 = 20,5 MPa	
	0.47	0.46	0.68	0.63
B-0/8	σ_0 = 20,0 MPa		σ_0 = 20,0 MPa	
	0.57	0.53	0.67	0.58
B-0/22	σ_0 = 20,2 Mpa		σ_0 = 20,2 MPa	
	0.51	0.49	0.55	0.53

4. DISCUSSION

The results of expansion, compressive strength, modulus of elasticity and specific creep will be discussed. Figure 3.1 and Figure 3.2 revealed that all concretes didn't show signs of ASR damage when they were exposed to water. Contrary to that, when the specimens were exposed to deicing solution, three concrete pavements show signs of a damaging ASR, one didn't show signs of ASR damage. The usual observation that air-entraining agents can help to prevent ASR has not been confirmed. However, the damage pattern of concrete pavements in Germany is in close agreement with the experimental results. Investigations in [25] show too, that air entrained concrete exposed to external alkalis cannot prevent an ASR.

In general, the compressive strength of concrete is influenced by cement paste and not by aggregates, if the compressive strength of aggregates is high enough (> 100 MPa). Table 3.1 contained the values of compressive strength after storage in the moist room for 28 days. Three concretes were rather similar while concrete with A-0/8 aggregates was about 15 % less strong. After the cyclic climate test with water as testing fluid, all concretes showed a strength increase of 38 to 50 % which means that the alkali-silica reaction did not cause a decay of strength. This can be explained by two facts: Firstly, the strength increase is due to the good curing conditions (higher temperature and higher humidity) which leads to a continued hydration, and secondly, the cracks close during loading.

To detect the influence of ASR one has to compare the strength results of specimens exposed to deicing salt versus water. Except of concrete composition B-0/22 (without signs to deleterious ASR) the strength of those specimens is reduced by 5 to 22 %.

The modulus of elasticity shows an increase by 11 to 38 % when water is the testing fluid, however, this increase is lost when deicing salt is penetrating. Large influence is obvious for the concretes with concrete compositions A-0/8 and A-0/16 while the decay is minor in case of concrete compositions with B as aggregate.

In General, the elastic modulus of concrete is mainly influenced by the elastic modulus of aggregate. Normally the mechanical properties are fixed once and for all when concrete is cast. When the modulus of elasticity of aggregate in the concrete matrix decreases, the elastic modulus of concrete itself also decreases [26]. In this context it is noted that Copuroglu [27] studied three types of rock in warm alkaline solution and found a reduction of the elastic modulus which was supposedly due to silica dissolution. Ben Haha [28] found that alkaline solution leads to a reduction of fracture energy and the brittleness of reactive rocks. Reinhardt and Mielich [29] showed that the modulus of elasticity of alkali-sensitive aggregates decreased with the time of exposure in alkaline environment. According to Reinhardt and Mielich [29] this degradation feature is attributed to the solubility and mobilization of rock minerals which depends strongly on a high concentration of OH^-. All alkali-sensitive aggregates are unstable in high alkaline environment and undergo an alteration. This deterioration feature of alkali-sensitive aggregates is irreversible and affects mechanical properties of concrete which depend on elastic modulus of elasticity of aggregates.

But in contrast to that, external alkali supply such as penetrating of NaCl in concrete leads not to a high concentration of OH^- in pore solution [30]. In this case a $NaHSiO_3$ complex forms in the presence of sodium which increases the solubility of SiO_2 in the alkali-sensitive aggregates [31]. To detect the influence of this solution processes in aggregates one has to compare the elastic deformations after creep of specimens exposed to deicing salt versus water. The Table 3.3 shows an increase by 51%, 37% and 9% for the ASR sensitive concrete compositions A-0/8, A-0/16 and B-0/8. An increase of 8% for the ASR insensitive concrete composition B-0/22. The samples were 794 days old when the elastic deformation was determined. An equal degree of hydration of the samples under influence of the testing fluids is assumed. As mentioned before, when determining the elastic deformation after creep, the specimens has already been loaded four times: three times for the determination of the static modulus of elasticity and once for the creep test. At each unloading, there is no complete strain recovery and, at reloading, the cracks are initially open and get closed again. The stress-strain behaviour remains elastic. Two facts lead to an increase of the elastic deformations and reduction of stiffness respectively: Firstly, if cracks are compressed, the aggregates are more damaged at the crack tips, and secondly, the solution processes of SiO_2 and other rock building minerals.

As the specific creep is concerned, the results allow to compare the influence of the two fluids which were applied on the specimens during the cyclic climate test. At the end of loading (364 days), the specimens subjected to deicing solution showed more creep than the specimens subjected to water. The differences amount to 20 to 40 %. The largest difference can be seen for the concrete with A-0/8 and the smallest for A-0/16 which is a consequence of the paste volume.

The mechanism of deterioration can be sketched. The aggregates are cracked due to ASR and external alkali supply which causes a reduction of the modulus of elasticity but hardly affects the compressive strength of the concrete. The cracks could propagate into the matrix and this the more the larger the paste content. One must assume a certain chemical alteration of the matrix. An investigation of the influence of seawater on creep has shown a considerable increase of creep compared to lime saturated water [32, 33] which supports the findings.

5. CONCLUSION

Four concrete mixes were investigated in the cyclic climate test which has been invented at the F.A. Finger Institute of University of Weimar, Germany. The test simulates the situation of concrete pavements with one-sided application of de-icing agents. One cycle of 21 days consists of drying, wetting, and freezing and thawing. The composition of the concretes refers to usual mixes used for concrete pavements. The test is carried out with a fluid on the specimen, either water or deicing solution (0.6 mol/l NaCl). Two different rhyolites in type, origin and alkali sensitivity were used. The concretes differed in the maximum aggregate size according to usual application in two layer concrete pavements. The following conclusions can be drawn:

- Air entrained concrete exposed to external alkalis did not prevent ASR.
- With regard to the measured expansions, three road concretes showed signs of a damaging ASR, one concrete showed no signs.
- A medium alkali Portland cement ($Na_2O_{equ.}$ = 0.65 wt%) is not capable of permanently preventing a deleterious ASR, when external alkalis such as deicers are supplied and alkali-sensitive aggregates are used in the concrete.
- All concretes have increased in compressive strength during cyclic climate storage test. This is due to the good curing conditions while the cyclic climate storage test. The post-hardening of the concrete clearly outweighs the damage caused by ASR.
- From the measurements of the modulus of elasticity, it could be concluded that the exposure to deicing solution has damaged the concretes whereas exposure to water did hardly affect the material.
- Static modulus of elasticity was significantly more affected by alkali-silica reaction than compressive strength if the concrete is exposed to external alkalis. This means, that any loss of mechanical properties is mostly driven by the damage in aggregates and for a smaller part by the damage of cement paste.
- The supply of external alkalis from deicing solution has increased the creep strain by a factor of two or more. The reason for that increase is seen in two effects: Firstly, the aggregate grains

are damaged due to ASR and, secondly, the matrix has undergone chemical changes as has been reported from creep tests in seawater.

- The classification into ASR sensitive and ASR insensitive concrete compositions with the cyclic climate test, based on expansion limit after 8 cycles and the slope between 6^{th} and 8^{th} cycle, corresponds well with modulus of elasticity, elastic deformations and creep.
- It must be emphasized that the properties of rocks can vary strongly even though the rocks have been taken from the same quarry. Strictly speaking, the conclusions are only valid for this investigation, however, the trends are also true for similar aggregates.

6. ACKNOWLEDGEMENT

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