Development of an automated 60 °C Concrete Prism Test

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Abstract

In most of the ASR-test procedures, the expansion of concrete or mortar specimens is used as an indicator to assess the ASR-potential of an aggregate or a specific concrete mix. For these tests, the specimens are stored in an ASR-provoking environment, where the reaction is accelerated by elevated temperature and humidity. To measure the length change, the storage must be interrupted for at least a few minutes. During the 60 °C Concrete Prism Test (60 °C-CPT), the specimens are cooled down to 20 °C for 24 hours, to ensure the same hygrothermal conditions for every measurement. This limits the number of measurements during the test period and may lead to additional effects, that probably influence the expansion development.

With a recently developed device, it is possible to continuously monitor the expansion of prisms without interrupting the ASR-provoking storage. Due to the dense database of this automated test, the results can contribute to a better understanding of the ASR-process. This study compares results of the automated and conventional 60 °C-CPT. Tests of different aggregates showed, that the results of the automated and conventional test are consistent, but the expansions during the conventional test are generally higher. Preliminary results led to the conclusion, that the cooling for the measurements leads to additional expansions. Therefore, a modified threshold should be discussed for the automated 60 °C-CPT.

***Keywords**: 60 °C-CPT; ASR expansion monitoring; automated testing*

1. INTRODUCTION

Despite extensive research in the field of Alkali-Silica-Reaction (ASR) during the last 80 years, damage caused by ASR still occur in concrete structures. In Germany, especially concrete pavements of the motorway network are affected by ASR due to the intensifying effect of de-icing-agents used in wintertime. Building authorities regulate the use of ASR-reactive aggregate to prevent ASR-induced damage and thus depend on reliable ASR test methods to identify ASR-reactive aggregates.

The spectrum of test methods comprises solubility methods and petrographic characterisation of the aggregates, quick tests of mortars, and concrete tests which last usually a few months up to one year. Additionally, so called performance tests were developed in the last years, which are usually based on the concrete test methods and provide a possibility to test for example a specific concrete mixture. During the concrete and mortar tests, specimens cast using the aggregate to be tested and a cement with a high alkali-content are stored at elevated temperatures and high humidity to accelerate the reaction. After certain time periods, the expansion of the specimens is measured to evaluate the volume increase caused by ASR. If the mean expansion exceeds a defined threshold, the aggregate is classified as alkali-reactive. Concerning the concrete tests, two different methods are common worldwide. One of them schedules the storage of concrete specimens in sealed containers at 38 °C above a water reservoir to ensure a high humidity for one year. This test is described for example in the ASTM C 1239 [1] and the RILEM Recommendation AAR-3 [2]. During the other widespread test method, concrete specimens are also stored in containers above a water reservoir, but at a temperature of 60 °C. This method, usually referred to as the 60 °C Concrete Prism Test (60 °C-CPT), is based on the French standard NF P 18-454 [3] and is also described in the RILEM Recommendations AAR-4.1 [4].

Germany has a long history of ASR-damage and thus, authorities supervising construction with concrete established a mandatory set of regulations, including four different concrete tests to classify aggregates concerning ASR-reactivity. Two of them were developed especially for the classification of aggregates

used to produce concrete for pavements including an external supply of alkalis during the tests [5;6]. The other two are mandatory for aggregates used in any concrete structure. These two tests are described and regulated in the German guideline for prevention of ASR in concrete ("Alkali-Guideline") [7]. The first one, which is the reference method according to the guideline, is a test in a fog-chamber at 40 °C. This test indeed is carried out at a similar temperature as the concrete test at 38 °C according to ASTM C 1239 and RILEM AAR-3. However, humidity conditions are more severe when a water fog atmosphere is maintained during storage, compared to lower absolute humidity when storing above water. The second test of the German Alkali-Guideline is carried out at 60 °C and is, except for some minor differences, comparable to the RILEM Recommendation AAR-4.1. These differences concern the concrete mixture (cement type and content, grading curve), the length of the test specimens and the casting procedure. Furthermore, the periods between and the total number of the length measurements differ slightly.

As described above, these test methods are very time consuming with a minimum duration of a few months. To conduct the expansion measurements, the storage at elevated temperature and humidity must be interrupted. To ensure consistent measuring conditions during the 60 °C-CPT, the specimens are cooled down to 20 °C for 24 hours beforehand to make sure that the specimens have reached the reference temperature. These interruptions may influence the reaction, which is why the measurements are only conducted every four or five weeks, depending on the regulation. Despite this time and work consuming approach, the user only gets one datapoint every few weeks which is a very limited database for describing and understanding the complex ASR-expansion process. Additionally, the interruptions and manual measurements can be a source of errors, e.g. due to changing personnel and thus eventual variations in the workflows.

To reduce the effort and to minimize the possible sources of error, an approach of continuous, automated expansion measurement implemented to the 60 °C-CPT was pursued at the German Federal Institute of Materials Research and Testing (Bundesanstalt für Materialforschung und -prüfung BAM) in 2012 [8]. In this case, the expansions were measured using inductive displacement transducers, which were especially developed to resist the elevated temperature and high humidity. In this setup, the displacement transducers were implemented in the conventional container by enlarging the lid. The containers could remain in the ASR-provoking environment for the whole test period without interrupting it. The setup eliminates possible influences of the interruptions on the ASR-process. As the measurement rate can be set to nearly any requested value, detailed information about the expansion development result. Due to the quasi-continuous measurement, an exceedance of the expansion-threshold can be recognized earlier and because of the high amount of data one can be sure that such an exceedance is not just an outlier. Beside this approach, continuous measurement of the expansion of concrete specimens has also been deployed by other researchers to study the relationship of expansion mechanisms and ASR kinetics [9;10]. There, vibrating wire strain gauges or fibre-optic sensors were embedded in the concrete specimens. Another technical approach realised the continuous measurement of the expansion of concrete cylinders across their full length [11]. The authors pursued the development of an improved ASR test method, which avoids leaching and allows rapid comparative testing of concretes at different loadings of alkali and fly ash. Another research group developed a similar setup which circumvents leaching of alkalis and compared conventional results from manual measurements with continuous expansion data from embedded sensors [12]. There, continuously measured expansion of ASR-affected concrete cylinders was smaller than comparable conventional expansion results, both for storage at T=38 and 60 °C. This effect, which was also reported elsewhere [13], apparently cannot entirely be prevented by avoiding leaching of alkalis.

The approach pursued at BAM from 2012 was advanced further in a following cooperation project with the company Schleibinger Testing Systems. The aim was to develop a user-friendly measurement system for an automated 60 °C-CPT. The result of this project is a prototype of a mini reactor, which accommodates six concrete prisms for simultaneous testing. Further details of the mini reactor are described in section 2.2.

This contribution shows first results of the prototype in comparison to the conventional 60 °C-CPT according to the German Alkali-Guideline. Additionally, the aggregates were tested in the fog-chamber at 40 °C, the reference method according to the German Alkali-Guideline.

2. MATERIALS AND METHODS

This work aims to evaluate possible differences, benefits and challenges of the automated 60°C-CPT in comparison with the conventional test. For that, two different aggregates were tested in both tests. Besides the expansion, leaching of the concrete specimens during the tests was considered as well as the change of the dynamic elastic modulus. In addition, to verify the classification of the aggregates, the two types of aggregate were tested applying the fog-chamber at 40 °C. Also, in this case, the development of the dynamic elastic modulus was measured.

2.1 Materials

Two concrete mixtures with two different types of aggregate were studied. The mixtures correspond to the German Alkali-Guideline [7]. The usually required test of a mixture with a low alkali cement according to the guideline was omitted. The chosen aggregates, a greywacke and a quartz-gravel represent a relatively wide range of reactivity. While the quartz-gravel is considered as a low reactive aggregate, the greywacke is commonly regarded as a reactive aggregate of the type "slow/late". The two different concrete mixtures are given in Table 2.1.

Table 2.1: Concrete mixtures; densities: 2.61 kg/m³ (quartz, sand), 2.69 kg/m³ (greywacke)

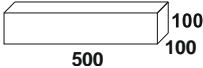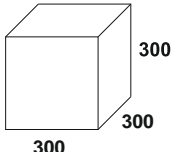| Component		GW	QG
Natural sand without mech. crushed parts 0/2	[vol.-%]	30	30
Greywacke, crushed 2/8	[vol.-%]	40	-
Greywacke, crushed 8/16	[vol.-%]	30	-
Quartz-gravel 2/8	[vol.-%]	-	40
Quartz-gravel 8/16	[vol.-%]	-	30
CEM I 32,5 R (Na_2O-equivalent: 1.3 wt.-%)	[kg/m³]	400	400
w/c-ratio		0.45	0.45

2.2 Methods

The geometry and quantity of the specimens produced for the concrete tests are given in Table 2.2. For both concrete mixtures, all specimens were cast in one batch to ensure a good comparability of the results. The prisms for both 60 °C-CPT and the fog-chamber were equipped with embedded stainless-steel studs at the end faces for the length measurements. After casting, the specimens remained in the moulds for 24 hours at 20 °C, covered with moist cloths.

For the fog-chamber test, the specimens were demoulded and clearly labelled after 24 hours. Then, the dimensions and masses of the prisms were precisely determined, and the initial measurements of the lengths and dynamic elastic moduli were conducted. These measurements were done at 20 °C. To calculate the dynamic elastic modulus, the eigenfrequency of the flexural vibration mode was measured using a GrindoSonic testing device of the type Mk5i. The vibration is excited using a small hammer, the eigenfrequency of the oscillation is measured with a piezoelectric detector as depicted in Figure 2.1. The dynamic elastic modulus is calculated according to Bunke [14]. A similar calculation is given in ASTM C215 [15].

After the initial measurements, the prisms and cube of each concrete mix were stored in the fog chamber at 40 °C. The following measurements were undertaken at a concrete age of 2, 7, and 28 days and then every 28 days until an age of 252 days. The last measurement was done at an age of 273 days. For each measurement, the specimens were separately withdrawn from the fog chamber to an environment of 20 °C. Then, the expansion, mass and eigenfrequency were measured rapidly to minimise shrinkage due to cooling and drying of the samples, according to the German Alkali-Guideline.

Table 2.2: Quantity and geometry of the cast specimens for each concrete mixture

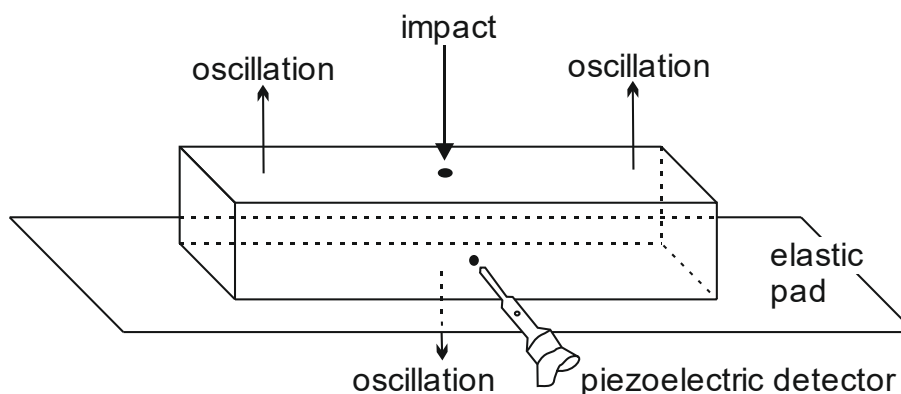| ASR-test method	Geometry [mm]	Quantity	Evaluation criterion (threshold)
60 °C-CPT conventional	280 / 75 75	3	Expansion (0.3 mm/m)
60 °C-CPT automated	280 / 75 75	3	Expansion (-)
40 °C fog-chamber test	100 / 100 / 500	3	Expansion (0.6 mm/m)
	300 / 300 / 300	1	Crack width (0.2 mm)

Figure 2.1: Measurement setup for the determination of the eigenfrequency to calculate the dynamic elastic modulus

Additionally, cracking at the surfaces of the cubes was assessed. If cracks had occurred, they were traced and documented photographically, and their width was measured, as shown in Figure 2.2. From these photos, crack maps of the cube faces were created to illustrate the crack development over the whole storage time. According to the guideline, the tested aggregate is classified as alkali-reactive, if the prism expansion exceeds a value of 0.6 mm/m or if the crack width at the cube exceeds a value of 0.2 mm.

Figure 2.2: Example of the documentation of the cubes during the ASR-provoking storage in the fog-chamber

The specimens for both, the conventional and the automated 60 °C-CPT, were also demoulded and clearly labelled after 24 hours. Then, the dimensions were precisely determined and the initial measurement of the length, mass and eigenfrequency were conducted. Afterwards, the specimens were stored under water at a temperature of 20 °C for 30 minutes before a control measurement of length and mass was done according to the Alkali-Guideline. For the conventional test, the procedure obeyed the guideline, with three prisms of each series being stored in a sealed stainless-steel container above a water-reservoir. These containers were then stored in a cabinet at 60 °C and a relative humidity above 98 %. For the following 140 days, length, mass and eigenfrequency were measured every 28 days. For that, the containers were withdrawn from the cabinet and cooled down to 20 °C for 24 hours. In addition, 20 ml of the water at the bottom of the containers were drawn at every measuring date to analyse the content of alkalis (Na and K), which leached from the concrete specimens into the water reservoir. The chemical analysis was done by means of inductively coupled plasma optical emission spectrometry (ICP-OES). After each measurement, the specimens were put back into the containers, at changed vertical orientation. Then, the containers were returned into the cabinet at 60 °C. If the mean expansion of the three specimens exceeds a value of 0.3 mm/m, the tested aggregate is classified as alkali-reactive according to the Alkali-Guideline.

For the automated 60 °C-CPT, the procedure differs slightly from the guideline. After the 30 minutes water bath and control measurement, the specimens were stored in the containers of the mini reactor. For the whole test period, the specimens were kept in the mini reactor at 60 °C and high humidity. In this case, the chemical analyses of the water reservoir of the containers were only done before and after the test to not interrupt it. Furthermore, length, mass and eigenfrequency of all specimens were manually measured before and after the automated test.

The mini reactor consists of a small test chamber, which has space for up to six containers (see Figure 2.3). To ease the handling, there is only one specimen per container. In this case, the containers have a cylindrical geometry, but the proportion of specimen to air volume is nearly the same as in the conventional test. The specimen is fixed in a rack, which is attached to the lid of the container as shown in Figure 2.3.

The non-contact expansion measurement is carried out by means of a calibrated temperature-compensated eddy current sensor from *micro-epsilon* of the type *eddyNCDT 3005* which is fixed in the lid and whose counterpart (stainless steel) is screwed in the upper stud of the specimen. Reliability, thermal stability and precision of the eddy current sensors were proven in preliminary studies [16]. The top of the specimen is held in position by two fixing pins which match in two holes of the counterpart of the sensor. The proper measuring distance between the sensor and the counterpart can be adjusted with screws on the bottom side of the fixing rack. Once the specimen is installed in the rack, the rack is inserted into the container, which also has a water reservoir with a level of 35 mm as in the conventional test. The container then is suspended into the mini reactor. After putting a second insulating lid on top, the system is ready to go. The mini reactor also contains a water reservoir, since an atmosphere of high relative humidity ensures stable and robust temperature control of the system.
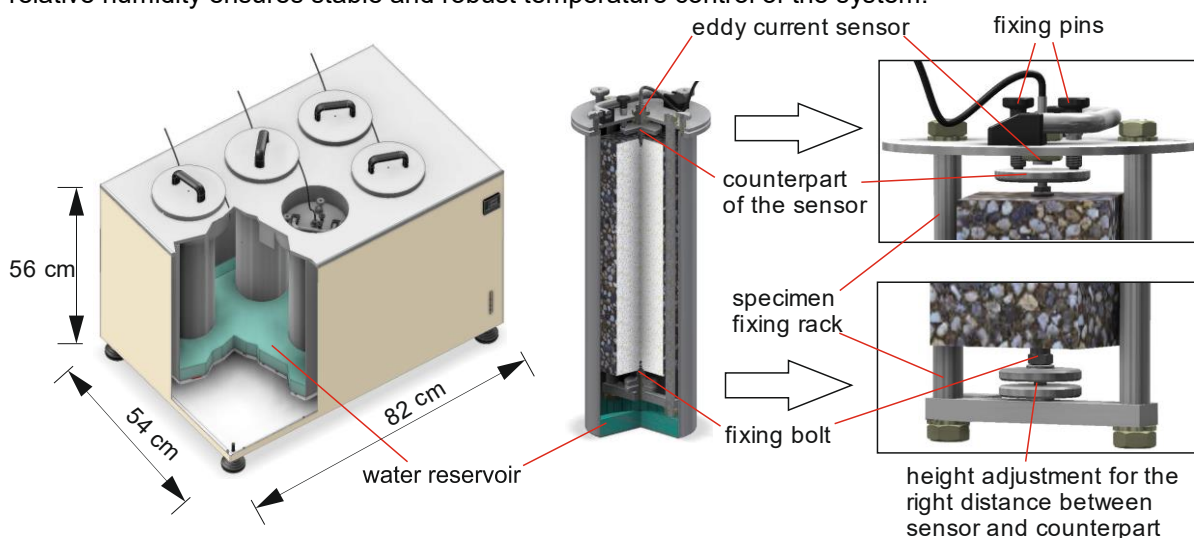

Figure 2.3: Schematic depiction of the mini reactor, the container and measuring system of the automated 60 °C-CPT

To exclude thermal expansion of the prisms in the beginning of the test, a reference time must be defined, at which the specimens and the whole system are in a thermal equilibrium and the displacement is set to zero. Former measurements have shown, that a thermal equilibrium is reached after six hours [16]. This same study revealed that omitting a change of the vertical orientation of the specimen, which is required according to the guideline but not possible in this setup, has no significant effect on the expansions.

3. RESULTS AND DISCUSSION

3.1 60 °C Concrete Prism Test

The results of the conventional and automated 60 °C-CPT are depicted in Figure 3.1. The threshold of 0.3 mm/m is already exceeded after the first 28 days. Therefore, both aggregates are classified as alkali-reactive according to the Alkali-Guideline. In the further course, the expansions continue to grow, while the gradients between two measurements decrease with a longer storage time. As expected, the greywacke (GW) shows higher expansions which is a sign for increased reactivity compared to the quartz-gravel (QG). The automatically measured prisms of both concrete mixtures exceed the threshold of the conventional test also within the first month of storage. The expansion development of conventionally and automatically measured prisms is basically comparable. There is a strong increase in the beginning and a following deceleration of the expansions, and GW-prisms expand more strongly than the QG-specimens. The extent of expansion, however, differs notably and systematically comparing both measurement techniques. The expansions of the continuously stored prisms are significantly lower which is confirmed by the manual expansion measurement of these specimens at the end of the test (see Figure 3.1 top) and was also observed in former studies [9;13;17].
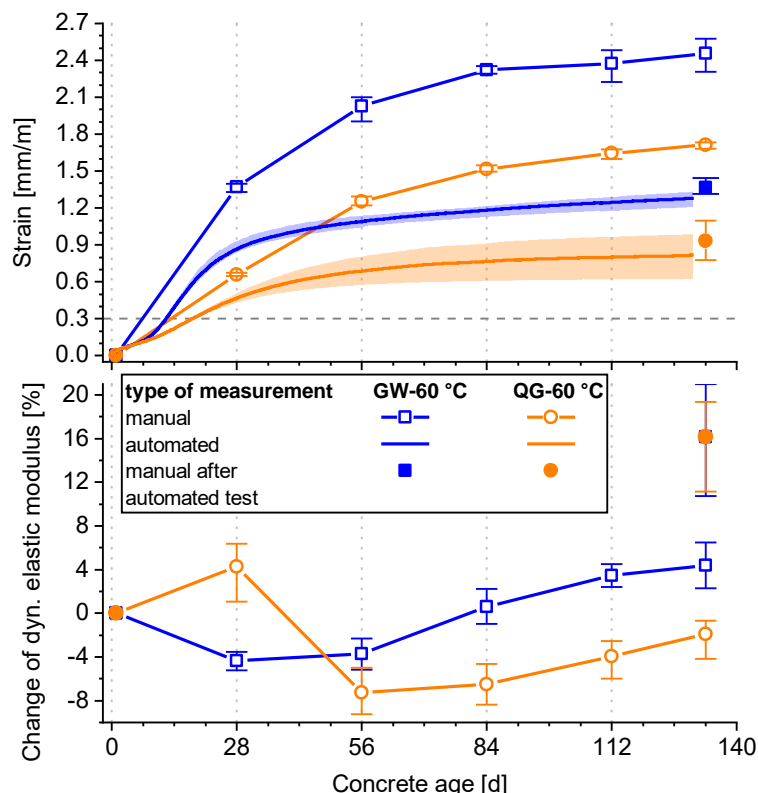

Figure 3.1: Expansion and development of the dynamic elastic modulus during the conventional and automated 60 °C-CPT

Due to the high amount of data during automated testing, the expansion development is described more detailed. Both expansion curves show an s-shaped development, which was also observed in the studies mentioned before and is typical for slower tests like the fog chamber test at 40 °C (see Section 3.2). Based on these detailed information, comprehensive interpretation of the expansion

development is possible. Both continuous expansion curves show a very similar increase during the first seven days of storage, which can be mainly attributed to moisture absorption. Afterwards, the expansions start to accelerate. In the case of the GW-specimens, the increase is more distinct, which results in a steeper gradient of the curve. By evaluating the derivative of the expansion curves, the maximum of the strain rate can be calculated. The time corresponding to the maximum characterises a phase of intense ASR-progress. Here, the maximum is reached after 15 days for the GW-specimens and after 17 days for the QG-specimen. In addition, the maximum strain rate of the QG is only 40 % of that of the GW-prisms. After the first 28 days, the expansions decelerate distinctly in both cases, which indicates a fading reaction. The deceleration of the QG-specimens is slightly delayed in comparison to the GW-prisms.

An advantage of the automated measurements is the quantity of measurement data. The detailed information about the expansion behaviour deduced above is based on the high-resolution expansion curves and cannot be obtained using the conventional test setup. Furthermore, the automated measurement provides a reliable database with a clear trend already after the first 28 days of the test, while there is only one datapoint per prism in the conventional test after the same duration.

Figure 3.1 also shows the development of the dynamic elastic modulus during the conventional 60 °C-CPT. In addition, the results of the automatically measured prisms after the test are depicted in the figure. The development is influenced by different mechanisms. While an increase is attributed to a densification of the concrete structure, a damage process like the formation of microcracks or any other structural defect is accompanied by a decrease of the dynamic elastic modulus. There are different possible mechanisms which lead to a densification of the concrete structure. One main reason, especially in the early age of the concrete is the hydration process. Other effects could be the filling of voids and cracks with ASR-products [18], a possible late hydration of unhydrated cement in fresh microcracks and also a filling of cracks by ettringite crystals [19]. Additionally, absorption of moisture in the concrete leads to an increase of the dynamic elastic modulus.

While the expansion behaviour of both concrete mixtures is qualitatively comparable, the developments of the dynamic elastic modulus differ. The QG-specimens show an increase after the first 28 days which indicates, that the hydration process and moisture absorption dominate. In the next 28 days, a strong decrease occurs, which is a sign for a distinct ASR-process. The following increase can be attributed to a filling of cracks with ASR-products and possibly to ettringite formation and late hydration as mentioned above. In the case of the GW-specimens, there is a decrease already after the first 28 days of storage which indicates, that the ASR-damage process has a bigger impact than the hydration process and the ASR starts earlier. This corresponds to the slightly faster approach of the maximum expansion rate of the GW-prisms. The following increase of the dynamic elastic modulus of all prisms can be attributed to the same reasons as mentioned above. The dynamic elastic moduli of the automatically measured specimens, which could be measured only before and after the test, show a more distinct overall increase. This corresponds to the lower expansions, and thus a less pronounced ASR-damage of these prisms.

Concerning the systematically lower expansions of the automatically measured prisms, a former study has shown, that the expansion process seems to be enhanced by the cooling and heating before and after the measurement events during the conventional test [13]. In this study, a container with a specimen, its expansion being measured automatically, was placed in a climate cabinet. After different periods of time, the temperature in the cabinet was lowered from 60 to 20 °C for 24 hours and raised again to 60 °C afterwards. As a result, the slope of the expansion was distinctly higher in the following few days after the simulated measurement event compared to the slope before. This effect could be observed especially in the phase of a high expansion rate in the beginning of the test.

Because leaching of alkalis from concrete specimens can also influence their expansion, the alkali concentration in the water reservoirs of the containers were analysed. As water in the reservoirs declined over the course of the test (by up to about 40 % of the initial mass), the absolute mass of leached alkalis was calculated. Figure 3.2 shows the mass of leached alkali per prism. The mass of alkali in the reservoirs of the conventional tests increase in the course of storage. Compared to the conventional test, the automatically measured prisms show elevated mass of alkali per specimen at the end of the test, which indicates an increased leaching of these prisms.
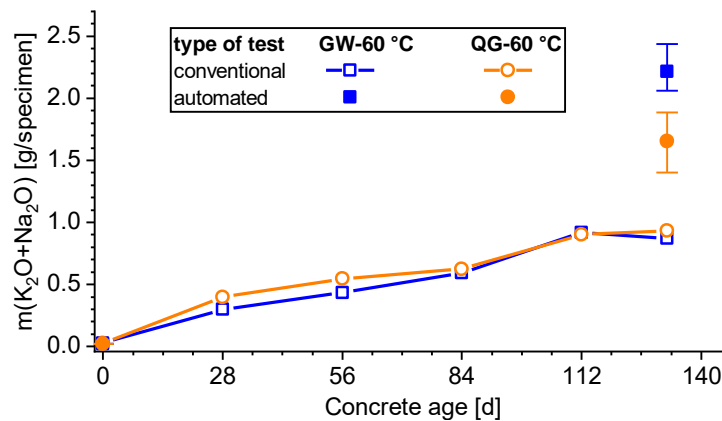
Figure 3.2: Mass of the alkali oxides per specimen in the container reservoirs

This seems to be another reason for the lower expansions of the automatically measured specimens. As the air to specimen volume of the automated and conventional test is nearly the same, this cannot be a cause of increased leaching. Temperatures, measured with thermocouples in the upper part of a container and the mini reactor, remain constant (60±1 °C) during storage. The water level in the containers, measured at the beginning and the end of the test, did not fall below 15 mm. Relative humidity thus can be assumed to be close to 100 %. However, the main reason of the enhanced leaching most likely is linked to the construction of the prototype of the mini reactor. Despite the insulation of the lid of the container, the temperature of the lid is ever so slightly lower than that of the lateral surface of the container. Consequently, water from the high humidity atmosphere condensates at the lid, drops onto the specimen and absorbs alkali before dripping back into the reservoir. This intensification of leaching can be prevented by a thermal optimisation of the mini reactor.

3.2 Fog Chamber

The results of the expansions and changes of the dynamic elastic moduli during the fog chamber test at 40 °C are depicted in Figure 3.3. The classification of both aggregates as alkali-reactive from the 60 °C-CPT results is confirmed by these results. Initially, the prisms expand strongly, which can be attributed to the temperature rise from 20 to 40 °C and swelling in consequence of water uptake due to the fog environment in the chamber. During the first 28 days of storage the expansions of both concrete mixtures resemble, which implies that these expansions are mostly caused by hygroscopic and temperature effects. In this period, the dynamic elastic moduli develop similarly, too. The strong increase is attributed to the hydration and hardening of the young concrete. After the first 56 days, the expansion of the GW prisms starts to increase strongly, which is accompanied by a distinct decrease of the dynamic elastic modulus. The threshold is exceeded after 84 d, which is also the first measurement, when cracks on the prism surfaces are observed.

This period, when the expansion increases strongly, and the dynamic elastic modulus decreases simultaneously, characterises the main phase of ASR-induced damage. This is also confirmed by the analysis of surface cracks on the GW-cube, also stored in the fog chamber. The crack pattern of the four lateral and the top faces of the cubes are depicted in Table 3.1. It can be seen, that the first cracks on the GW cube occur, when the expansion exceeds the threshold value. After 140 days, the main degradation process of the GW prisms is completed, and the length of the prisms remains nearly constant. This is accompanied by a slight increase of the dynamic elastic modulus. Compared to the GW prisms, the QG specimens show a different behaviour. The ASR damage process starts later and lasts longer. The threshold of expansion is exceeded after 140 days, which coincides with the first time when cracks are observed on the surfaces of the prism and the cube. The main degradation process with a constant slope of the expansion curve and a constant increase of the dynamic elastic modulus is not completed clearly at the end of the test.

In the case of both concrete mixtures, the expansions of the prisms and crack widths on the cubes exceed the threshold values. Hence, according to both independent criterions, the concrete mixtures are classified as alkali-reactive, which confirms the results of the 60 °C-CPT.
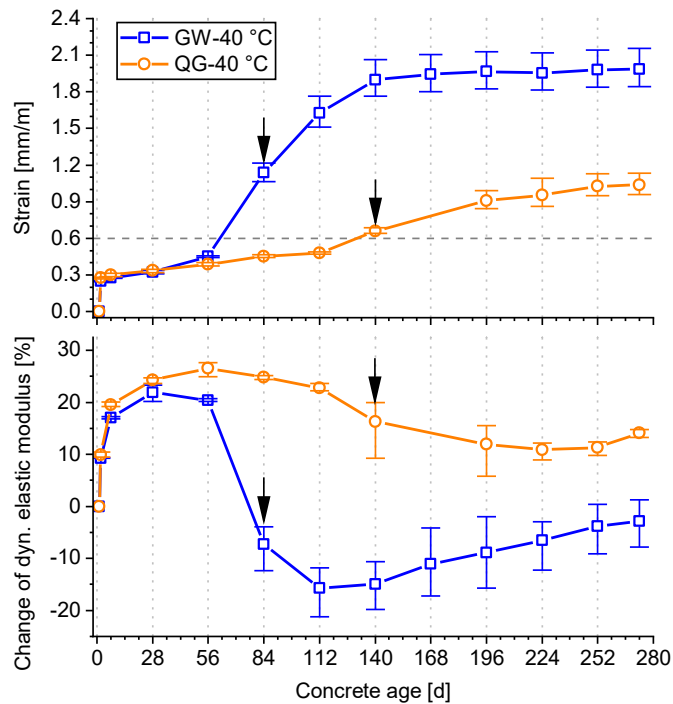
Figure 3.3: Expansion and development of the dynamic elastic modulus during the storage in the fog chamber at 40 °C, arrows mark first occurrence of cracks on the prism surface

Table 3.1: Crack development on the cubes during the storage in the fog chamber at 40 °C

crack width ≥ 0,2 mm

The typical s-shaped expansion curves, which could be observed in the automated but not in the conventional 60 °C-CPT, can also be observed during the fog chamber test at 40 °C. Excluding the first day of storage, during which expansions increase strongly due to the temperature rise, the GW prisms show a pronounced s-shaped progression. In case of the QG-prisms, the s-shape is less distinct, which corresponds to the results of the automated 60 °C-CPT. At 40 °C, the ASR proceeds more slowly so that the same storage interval between measurements of 28 days is sufficiently small to obtain more detailed information on the expansion behaviour. In this way, the slow fog chamber test is more suitable for assessing differences between different aggregates concerning the damage process than the conventional 60 °C-CPT. However, automated expansion measurement is preferable for studying ASR-induced expansion behaviour because it is less time consuming.

4. CONCLUSIONS

The presented results show, that the expansions of the automated and conventional 60 °C-CPT are consistent for both tested concrete mixtures. However, the expansions of the conventional test are systematically higher. This can be attributed to the effect of cooling and heating within the scope of the manual measurements as well as the increased leaching of alkalis into the water reservoir of containers of the automated test. The presumably design-related problem can be solved easily.

Compared to the conventional 60 °C-CPT, the fog chamber test at 40 °C reveals more detailed information on the ASR-damage process, as more expansion data is recorded per test duration. The fog chamber test, on the other hand, requires extra effort during the whole test period. The test lasts longer and requires more measurement events, a material-consuming sample production, and the handling of heavy prisms in an unpleasant foggy atmosphere. In addition, the necessary climate cabinet technique for the fog production is technically more complex than the 60°C-CPT reactor and prone to malfunctioning.

The presented automated 60 °C-CPT combines the easier and shorter test procedure of the conventional 60 °C-CPT with the more detailed recording of the expansion behaviour during the fog chamber test. Furthermore, it simplifies the test procedure by excluding manual measurements every 28 days.

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