INNOVATIVE MEASUREMENT TECHNIQUES FOR CHARACTERISING INTERNAL DAMAGE PROCESSES IN CONCRETE DUE TO ASR

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Abstract

This paper describes an innovative, non destructive measurement methodology that has already been successfully applied. For the first time a combination of continuous recording of length change, acoustic emission and ultrasonic velocity as well as discontinuous 3-dimensional micro X-ray computed tomography (μ-3DCT) measurements has been carried out. This unique combination of innovative measurement techniques enables a continuous monitoring of internal damage processes in concrete samples due to the ASR. Three phases of the ASR process have been observed in both types of concrete storage by application of the above mentioned continuous methods. In the beginning the hydration of concrete dominates, followed by the crack formation due to the ASR and finally the occurred cracks are presumably filled with reaction products. Moreover, the formation of cracks can be temporally and spatially visualized by μ-3D-CT. Microscopic analysis confirm the μ-3D-CT results.

Keywords: fog chamber, concrete prism test, length change, acoustic emission, ultrasonic velocity, μ-3D-CT

1 INTRODUCTION

Over the last years, Alkali-Silica-Reaction ("ASR") has increasingly occurred in 8-12-years-old concrete motorways. The damage process is initiated by darkening of the cross joints and transverse contraction joints. Later on it causes longitudinal cracks and meshed cracking. As a consequence, pop-outs and other damages appear. In spite of comprehensive studies the reasons for ASR-induced damage have not yet been sufficiently clarified.

So far, assessing the alkali-reactive-potential of an aggregate is particularly difficult because the existing testing methods do not cover a continuous measurement of the damage process. The 40 °C fog chamber storage according to the German Alkali-Guideline [1] and comparable international guidelines (ASTM [2], CSA [3] und RILEM AAR-3 [4]) as well as the 60 °C concrete prism test (pursuant to [1] and RILEM AAR-4.1 [5]) do not measure the damage indicators simultaneously but only discontinuously. In both tests, assessment criteria for the internal damage of concrete prisms, which are stored according to this guideline, are only discontinuously measured length and weight change measurements. As regards the cubes additionally stored in the fog chamber only the width of cracks is monitored discontinuously. Moreover, the ultrasonic velocity and the natural frequency of the prisms are determined. However, all these indicators display the internal condition of the concrete prism only at specific instants of time. Furthermore, the 60 °C concrete prism test requires a cooling-down of the prism prior to every measurement, which results in internal stress of the prism and consequently in additional cracks which are not related to the ASR.

At BAM an innovative, non destructive measurement methodology to follow in detail the internal structural changes during an ASR-provoking storage was developed and tested. This work forms part of a wider research project [6], which concerns the impact of the concrete's density of motorways on the damaging ASR and has been conducted in cooperation with the research institute of the German Cement Works Association and sponsored by AiF.

2 INNOVATIVE MEASUREMENT TECHNIQUES AND TEST PROGRAMM

2.1 General

The research at BAM was focused on the development and adaption of innovative measurement techniques to follow the internal structural changes in a specimen carrying out the 60 °C concrete prism test. Additionally some specimens were tested in the 40 °C fog chamber storage by application of the same innovative measurement technique. The results of two tested types of concretes are shown and discussed in this study.

2.2 Test methodology and methods

The continuous length change of the specimens and measurement of acoustic emission (AE) and ultrasonic velocity (US) are essential parts of the applied measurement methodology [7]. The application of these methods allows an integral description of internal microstructure changes during different ASR storages in the concrete specimen. Based on the results of these continuous measurement techniques, the 3-dimensional micro X-ray computed tomography (µ-3D-CT) is applied at defined instant of time. This enables a temporal and spatial visualisation of occurred crack formation. Microscopic analyses are envisaged to validate the CT-findings

Continuous measurement of the length change

To conduct the automatic continuous measurement of the length change in the 60 °C concrete prism test specially developed frames were designed and tested as shown in figure 1a and 1b. The specimens are placed vertically in these frames and are only in one direction free-mounted. The length change measurement itself is carried out by inductive displacement transducers (IDT's). These sensors had to be developed in cooperation with a producer exclusively for the ASR-storage since they had to resist the climate of 60 °C and 100 % RH.

Continuous measurement of acoustic emission and ultrasonic velocity

Whereas the measurement of the ultrasonic velocity is a common technique to follow the ASR-induced damage process discontinuously, the acoustic emission analysis were applied for the first time.

The acoustic emission analysis is a method to continuously determine the development of cracks. For this analysis piezoelectric sensors are fixed on both ends of the specimen. They help to observe the moment of crack formation and to locate the occurred cracks.

Crack formation in the specimen generates sudden material displacements, which propagate as elastic waves. The velocity, frequency and attenuation of the wave propagation depend on the elastic properties of the material. The piezoelectric sensors register the elastic waves and transform them into electric signals. Moreover, they are able to conduct a self test and can therefore measure the ultrasonic velocity of the specimen automatically. Due to the aggressive environmental conditions special AE-sensors had to be developed.

Figure 1 a and 1 c show the application of the AE-sensors on concrete cylinders for the continuous measurement of acoustic emission and ultrasonic velocity carrying out the 60 °C concrete prism test. These sensors are used to observe the crack formation on concrete cubes stored in the 40 °C fog chamber as well.

Discontinuous analysis of 3-dimensional micro X-ray computed tomography (µ-3D-CT)

By the application of the µ-3D-CT for the first time the development of ASR-induced cracks can be visualised temporally and spatially without destructive interference [8, 9]. The basis for this measurement technique is the radiography. The used measuring principle of µ-3D-CT is shown in figure 2a. It consists of a radiation source (in this case an X-ray tube), the specimen placed on a manipulator and a detector.

For this test, the specimen rotates in front of the static X-ray tube. X-rays penetrate the specimen from different angles. Variations in density and thickness of the specimen result in different attenuations of the primary radiation. Using a special reconstruction algorithm the variety of obtained single images allows determining the spatial distribution of the absorption coefficient in the specimen (figure 2a). Therefore aggregates, the cement matrix, pores and structural damages, like cracks, etc., can be visualised in the specimen three-dimensional.

The µ-3D-CT measurement setup, shown in figure 2b, was applied for this study. The used 225 kV X-ray tube and α-Si flat detector with a size of 2048 x 2048 pixels result in a high local resolution and good visualisation of internal structural damages. Furthermore cylinders with a diameter of 70 mm serve as specimens instead of prisms, which are usually used for the 40 °C fog chamber storage and the 60 °C concrete prism test. Thus the resolution of the obtained images can be improved up to 40 µm. A single measurement takes up to 16 hours to obtain this high resolution. Since the appropriate climate for this test includes a temperature of 40 °C / 60 °C and 100 % RH, specific measurement equipment (called "mini reactor") had to be designed as shown in figure 2b. Thus internal stress in the specimen due to changes in temperature and humidity could be avoided.

Every specimen was measurement at least four times by µ-3D-CT. The first measurement was directly after the demoulding of the specimen to record the initial state. Further on the condition of the specimen was detected by µ-3D-CT during and at the end of the ASR-storage. Carrying out the final measurement the specimen was tested in a wet and dry state.

Validation of the CT-findings by microscopy

Microscopic and micro chemical assessments shall serve to validate the CT-findings. For this purpose thin sections were made and tested by a transmitted and a reflected-light microscope. Additional tests with MRFA and REM/EDX help to analyze the type of ASR-gel.

2.3 Concrete and test programm

For the tests two types of concrete with a high potential of internal damage were produced by using cement with a high Na_2O-equivalent and a greywacke with a high alkali-reactivity in the sizes 2/8 mm and 8/16 mm. To verify the impact of the concrete's density on the ASR-damage process the water/cement-ratio ("w/c-ratio") was varied. Further information is provided in table 1. Table 2 gives an overview of the condition and damage indicators of the various ASR-provoking storages for both types of concrete.

3 RESULTS

3.1 Monitoring of the damage process in the 60 °C concrete prism test

Continuous measurement of length change, acoustic emission and ultrasonic velocity

Figures 3a and 3b show the length change, acoustic emission and ultrasonic velocity during the 60 °C concrete prism test of both types of concrete. For this test concrete cylinders (diameter 70 mm, length 280 mm) were used. An indicator for the acoustic emission is the number of acoustic emission hits per day.

Figure 3a shows the results of the length change, acoustic emission and ultrasonic velocity of the concrete with a w/c-ratio of 0.35. All curves correlate very well and therefore give useful information on the timing of the internal structural changes due to the ASR. The structural changes occur in three phases (marked in different colours). The first phase starts directly with begin of the ASR-storage. The hydration process dominates indicated by an increase of the ultra sonic velocity, only few acoustic emission hits and negligible length changes. In the second phase (approximately 7 to 30 days) most of the ASR-induced cracks occur. A strong increase of the length change is combined with numerous acoustic emissions and a reduction of the ultrasonic velocity. Phase three is affected by only few acoustic emissions and a re-increase of the ultrasonic velocity. The expansion of the concrete due to ASR is almost terminated. Assumable a filling of the occurred cracks with ASR-gel and/or ettringite formation takes place.

As regards the concrete with a w/c-ratio of 0.55 the internal structure also changes in three phases (see Figure 3b). However, the significantly lower modification of the values indicates a reduced internal structural change. Apparently the increase of the w/c-ratio from 0.35 to 0.55 strongly reduces the ASR-damage process.

Discontinuous measurements by μ-3D-CT

Figure 4 shows the same virtual cross section through a concrete cylinder with a w/c-ratio of 0.35 before and after the 60 °concrete test. Light grey areas represent a high radiographic density. The aggregate appears light, whereas pores and cracks are dark – and the colour of the cement is usually in-between. A comparison of both images shows that the quality of the image in the original state is lower. The worse signal-to-noise ratio is due to the increased moisture in the concrete cylinder and the water in the mini-reactor. In spite of the different image quality it can be seen that the storage in the 60 °C concrete test causes more cracks. The detailed illustration in Figure 5 also shows a significant crack formation after two months of reactor storage. This confirms the results of the continuous measurements of the length changes, acoustic emission and ultrasonic velocity.

3.2 Monitoring of the damage process during the 40 °C concrete test in the fog chamber

Figures 4a and 4b show the results of the conventional discontinuous measurement of the crack width and of the continuous measurements of the acoustic emission and the ultrasonic velocity during the 40 °C fog chamber storage. For these tests cubes (edge length 30 cm) made of either type of concrete are used. As in the 60 °C concrete prism test the number of acoustic emission hits per day serves as indicator for the crack formation.

During the 12-month-period of fog chamber storage the cubes of either type of concrete run through the same phases of internal structural changes as the cylinders in the 60 °C concrete prism test. In the first phase the cement hydrates. Indicators for the hydration are an increasing ultrasonic velocity combined with negligible acoustic emissions and a lack of visible cracks on the surface. During the second phase dominates the ASR-induced crack formation in the cube. Indicators are increased acoustic emissions and a decrease of the ultrasonic velocity. Moreover, cracks form and widen on the surface of the cube. In the third phase the ultrasonic velocity remains stable or increases, whereas the ultrasonic emissions are negligible and the width of the cracks remains stable. Presumably these effects in the third phase occur because the ASR-induced cracks are filled with ASR-gel and/or the concrete is subjected to a self-healing process.

A comparison of both types of concrete shows, that the second and third phases are much more pronounced with regard to the concrete with the w/c-ratio of 0.55. This is contradictory to the assessment of the concrete cylinders through the 60 °C concrete prism test.

4 DISCUSSION

The tests show that the w/c-ratio has a different impact in the 60 °C concrete test on cylinders on the one hand and in the 40 °C concrete test in the fog chamber on the other hand. This may be caused by a higher leaching of alkalis in concrete cylinders and by an increased internal stress in cubes. However, further research is necessary to verify these assumptions.

For the first time, internal structural changes in cylinders and cubes during an ASR-provoking storage are made visible through simultaneous continuous measurements of length changes, acoustic emissions and ultrasonic velocity. As a result of these measurements three phases of material changes can be differentiated:

- Phase 1: Dominance of hydration processes
- Phase 2: Dominance of ASR-induced crack formation
- Phase 3: Dominance of crack filling by ASR-gel (assumption)

Moreover, the ASR-induced crack formation is visualized by μ-3D-CT. These findings still have to be verified through microscopy.

5 CONCLUSIONS

Innovative measurement techniques provide for new ways to study ASR-induced damage processes. Internal structural changes can be analysed integrally by simultaneous measurements of length changes, acoustic emissions and ultrasonic velocity. Discontinuous μ-3D-CT measurements visualise the crack formation in time and space.

A further improvement of the testing methods and the evaluation procedures may result in a better understanding of the ASR-damage process. The application of the Region of Interest ("ROI")-technique may enhance the local resolution of the μ-3D-images up to 10 μm and therefore lead to a better visualisation of cracks [10]. Further on automatic crack identification would facilitate and accelerate data interpretation [11].

6 ACKNOWLEDGEMENTS

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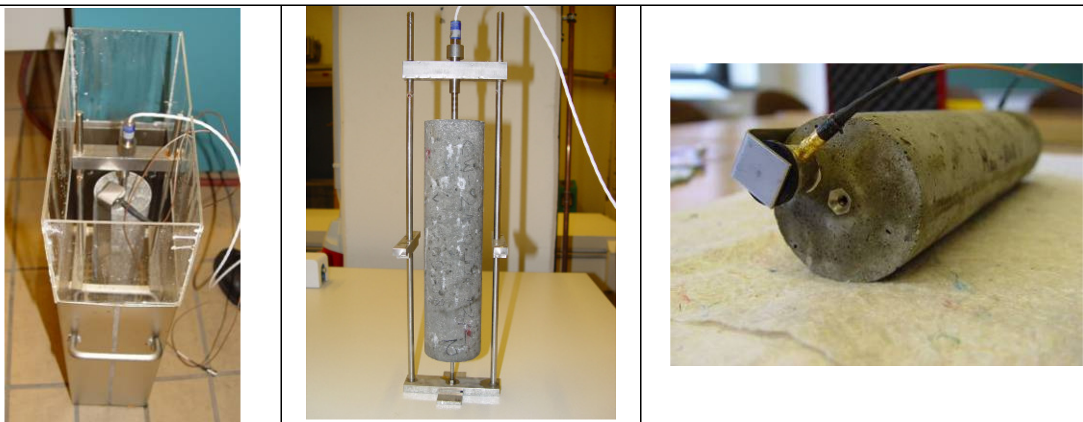
TABLE 1: composition of concrete

component	marking of Concrete	
	GW-Z1-0,35	GW-Z1-0,55
type of cement	CEM I 42,5R	
Na_2O-equivalent	1.18 wt%	
amount of cement	400 kg/m³	
water/cement-ratio	0.35	0.55
type of aggregate	30 vol.% Sand 0/2 mm 40 vol.% crushed greywacke 2/8 mm 30 vol.% crushed greywacke 8/16 mm	

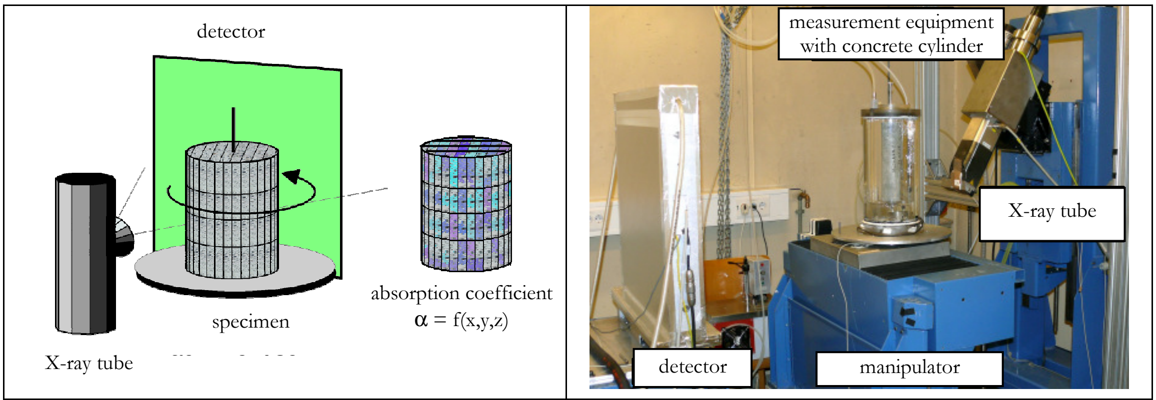
TABLE 2: test program

Condition and damage indicators		type of ASR induced storage for concrete sample	
		60 °C concrete prism test	40 °C fog chamber storage
		cylinder (Ø 70 mm, h = 28 cm)	cube (a = 30 cm)
crack width	discontinuous	-	X
length change	continuous	X	-
SE-activity		X	X
ultra sonic velocity		X	X
μ-X-Ray 3D-CT	discontinuous	X	-



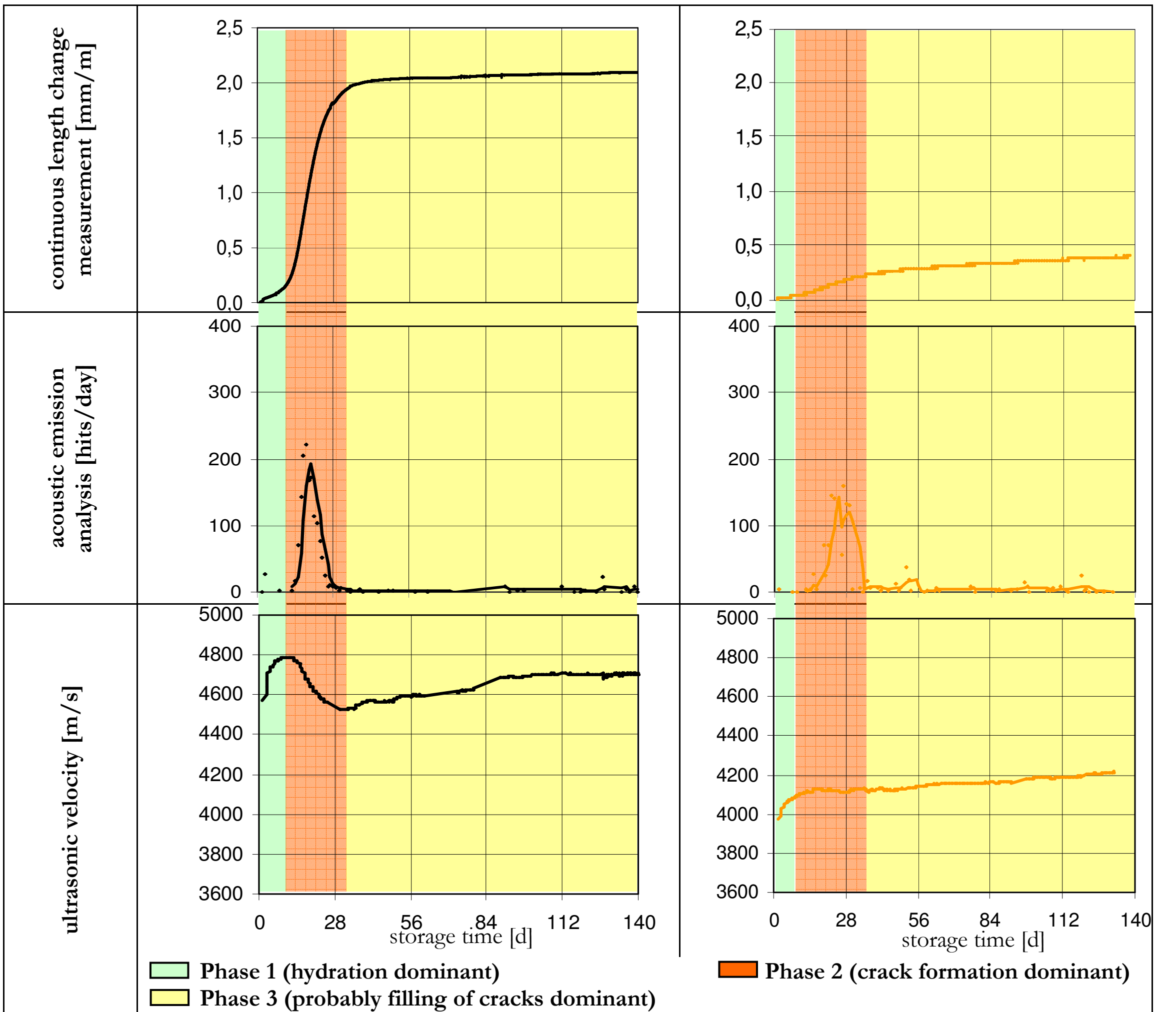
a. sample with sensor system in storage container | b. sample with sensor for continuous length change measurement | c. continuous AE- und US-measurement

FIGURE 1: Application of sensor system on concrete samples during 60 °C concrete prism test



a. Measuring Principle of µ-3D-CT	b. Applied measurement setup of µ-3D-CT for ASR

FIGURE 2: Measuring principle and setup of µ-3D-CT



a. GW-Z1-0.35	b. GW-Z1-0.55

Figure 3: temporal development of length change, acoustic emission and ultrasonic velocity on concrete cylinders at 60 ° by variation of water/cement-ratio

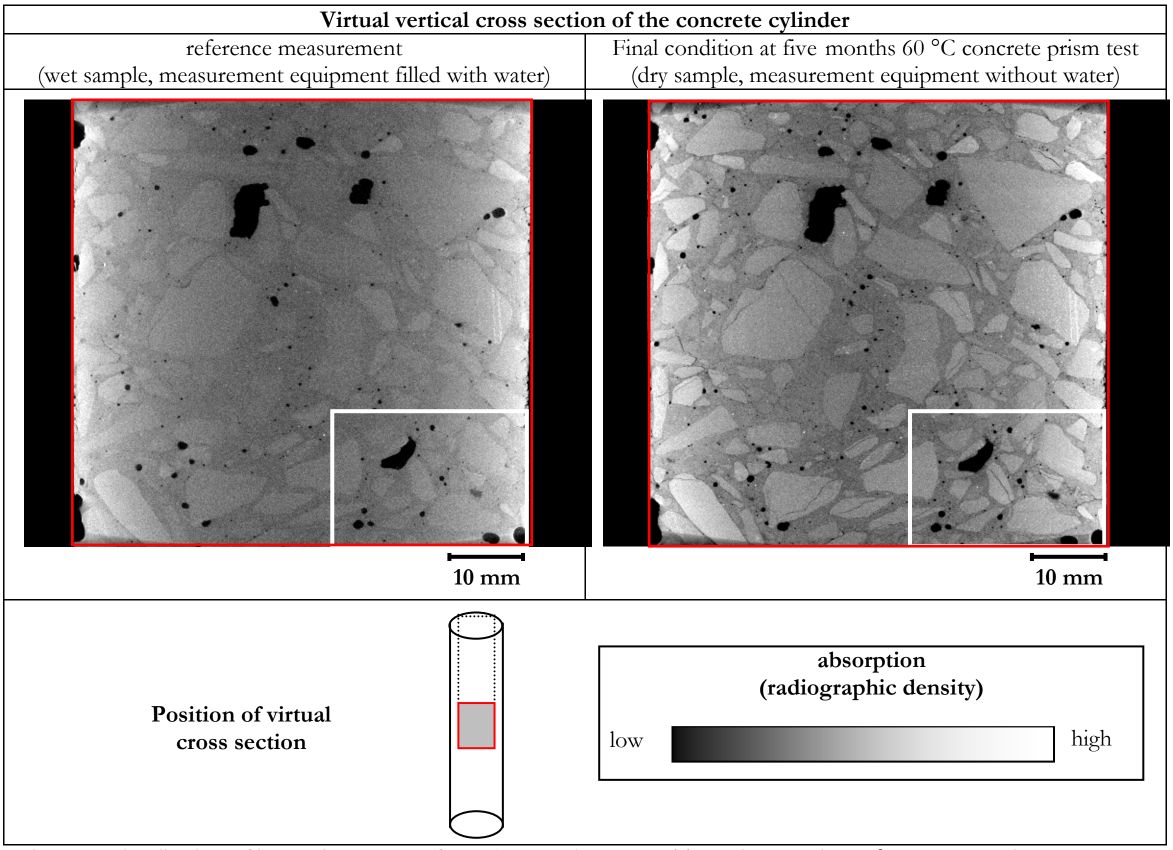


Figure 4: Visualisation of internal structure of GW-Z1-0.35 by µ-3D-CT carrying out the 60 °C concrete prism test

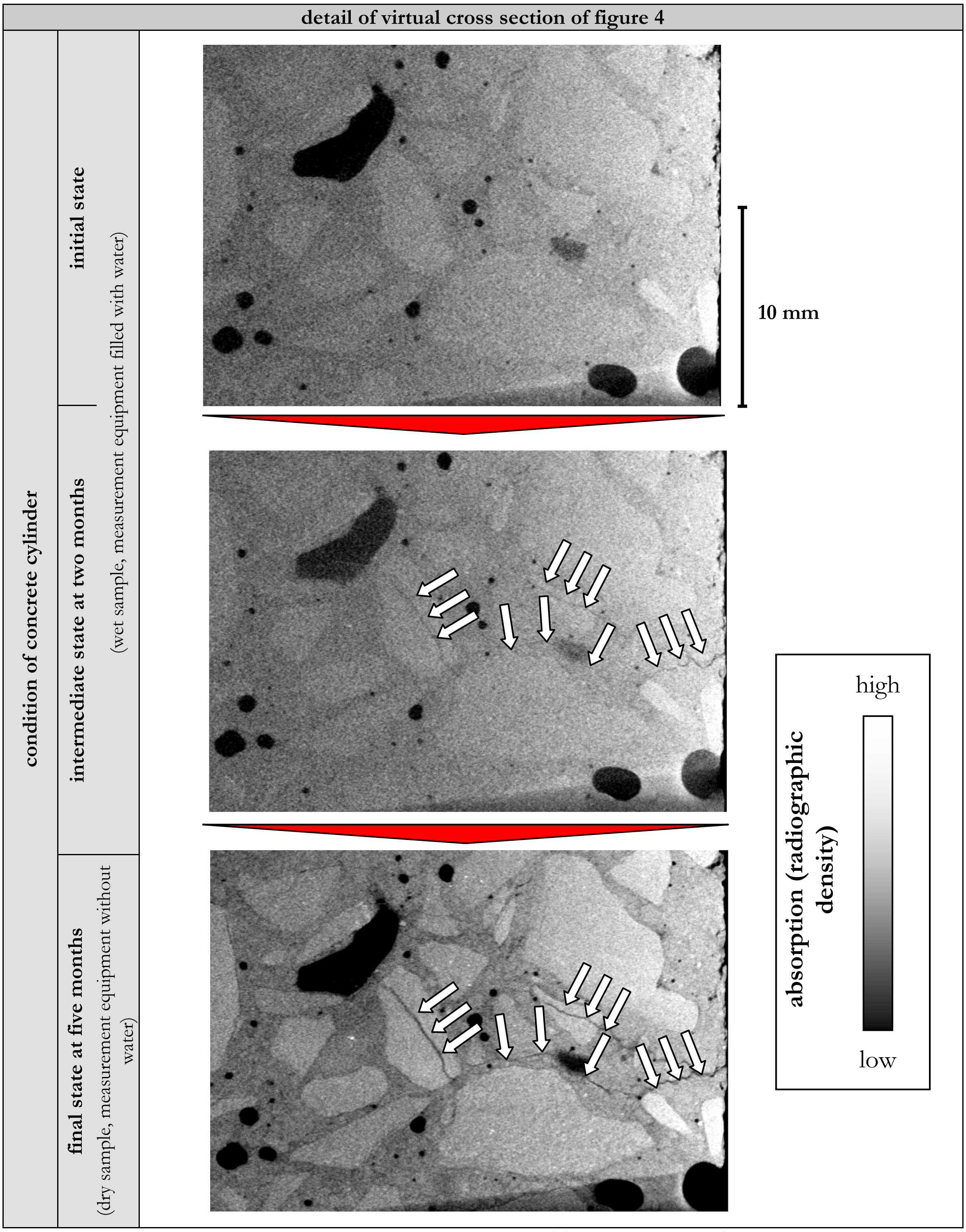


Figure 5: Visualisation of internal structure of GW-Z1-0.35 by μ-3D-CT carrying out the 60 °C concrete prism test

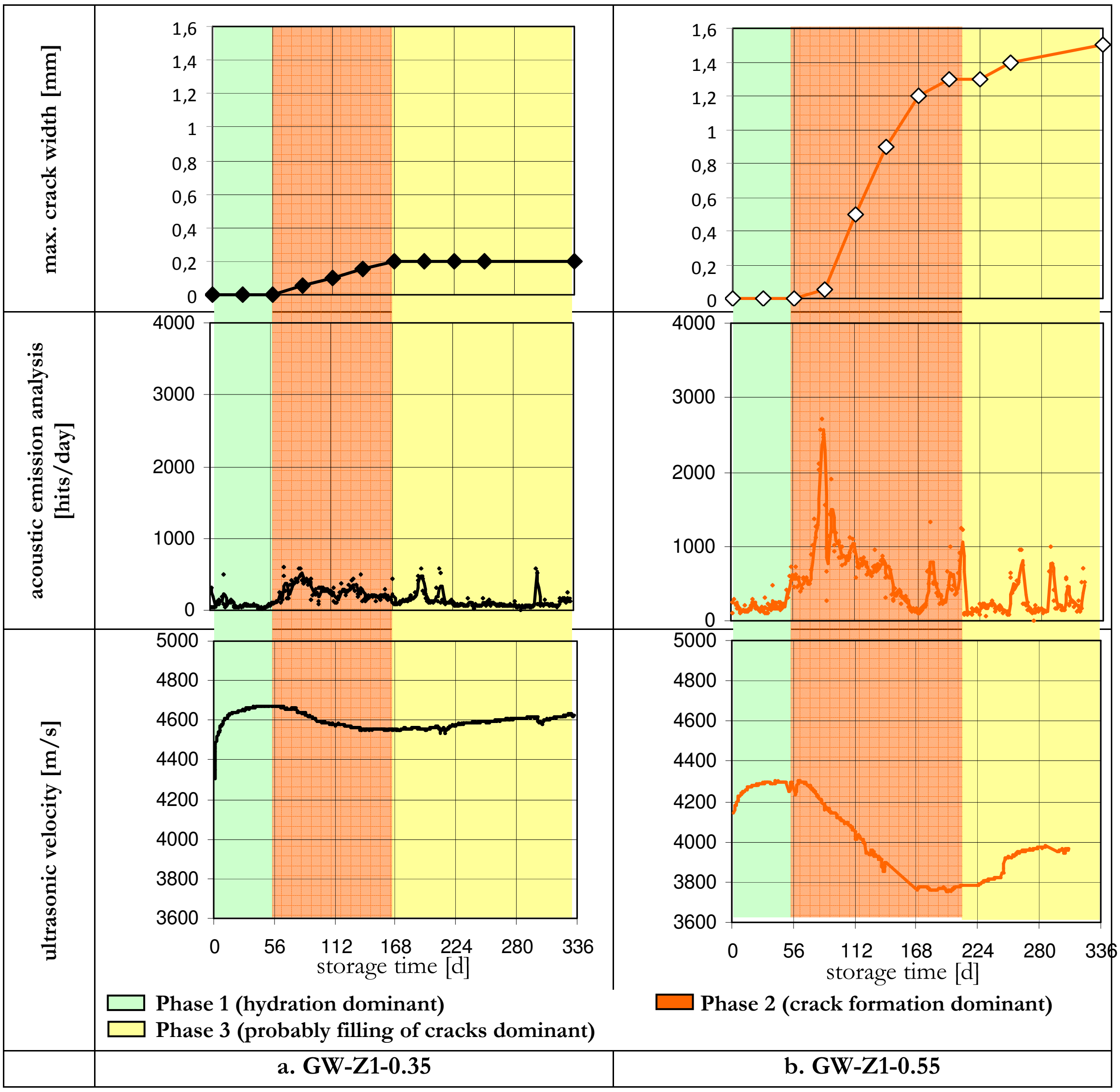


Figure 6: temporal development of length change, acoustic emission and ultrasonic velocity on concrete cubes during 40 concrete prism test by variation of water/cement-ratio