Non-destructive evaluation of interface fracture between matrix and aggregate

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ABSTRACT: The interfacial transitions zone (ITZ) between the matrix and the aggregates is of high importance with respect to the bearing and deformation behavior of concrete. Results of experimental investigations on "two-dimensional" model concrete by visual observation applying a digital image correlation technique allow a quantitative characterization of the ITZ due to mechanical loading. Corresponding ultrasonic investigations are in good agreement with these findings. Based on a correlation between these direct and indirect measurements a simplified approach could be derived, which describes the influence of interface fracture between matrix and aggregate on ultrasonic wave propagation. It was found in continuous loading and unloading experiments that the transmitted ultrasound energy precisely reflects the distortion process taking place in the ITZ and that these effects can be used to estimate the complete loading history of a concrete structure.

Keywords: digital image correlation, interface fracture, interfacial transition zone, non-destructive evaluation, ultrasound, uniaxial compression

1 INTRODUCTION

It is well known that the interfacial transition zone (ITZ), which provides mechanical bond between the concrete matrix and the aggregate, is of high importance with respect to the bearing and deformation performance of concrete (Verfuurt 1997). According to the strength of the interface, cracks initiate and propagate preferentially in this zone and cause a non-linear stress-strain behavior of concrete. Thus, for better control of desirable concrete properties and also precise assessment of the deterioration of the material, a quantitative characterization of this very small but important region is essential.

2 EXPERIMENTAL TECHNIQUES FOR DETECTING ALTERATIONS IN THE ITZ

2.1 *Indirect ultrasonic transmission technique*

A very suitable indirect method for evaluating internal changes in the structure of concrete is the ultrasonic transmission technique. It enables continuous measurements throughout the mechanical loading without any disturbing influence on the testing procedure. The propagation of ultrasound in concrete is strongly affected by scattering effects which result from the aggregates and the ITZ because of a high acoustical mismatch. Two parameters can be evaluated from the ultrasonic transmission measurements: the time of flight and the attenuation as a relative change in the pulse amplitude. Different researchers (Klemt 2001, Nogueira & Willam 2001) have shown that the latter is more suitable because of a higher sensibility. Previous investigations at the Institute for Concrete Structures and Building Materials have clearly indicated that changes in the ITZ strongly affect the scattering behavior and thus attenuation of ultrasonic waves (Klemt et al. 2001). But because there are no direct coherences between alterations in the ITZ and ultrasonic wave attenuation additional information from a direct measuring technique are necessary.

2.2 *Direct digital image correlation*

Digital image correlation (DIC) is a computer-based visualization technique for non-destructive, non-contact surface-displacement measurements with high accuracy on the micron range. Choi & Shah (1998) have developed and applied this technique in order to demonstrate crack initiation and growth in cementitious materials. This method uses a digital image correlation scheme, an algorithm which is based on the similarity between two images. Thus, by a successive point-to-point mapping between two images, a full-field deformation profile of the surface can be obtained.

3 EXPERIMENTAL INVESTIGATIONS

3.1 *Model concrete*

“Two-dimensional” model concrete representing real concrete in one plane was used for the investigations with ultrasonic transmission and digital image correlation. This was carried out by replacing the coarse spherical type aggregates by cylindrical type aggregates. These cylinders with a diameter of 13 mm were placed in a regular grid in a mortar matrix with parallel orientation of their length-axis. Specimen varying aggregate and matrix properties were used in the experiments; furthermore pure matrix material was investigated. Granite and limestone were used to represent normal respectively lightweight aggregates. The mortar matrix consisted always of fine sand and cement slurry with a water-cement-ratio between 0.35 and 0.55.

The specimens were subjected to alternately increased and decreased uniaxial compressive loading in steps of 5 % of estimated ultimate load. Ultrasonic measurement with longitudinal pulses in the range between 100 and 700 kHz were conducted at every loading and unloading level vertically to the loading direction and also vertically to the aggregate orientation. From the ultrasonic measurements attenuation was determined as a relative change in the pulse amplitude.

In collaboration with the Center for Advanced Cement-Based Materials at Northwestern University in Evanston, Illinois direct surface displacement measurements have been carried out applying the digital image correlation (DIC) technique. These investigations were conducted with the same type of specimen and under comparable loading conditions (Klemt 2001).

With the help of DIC displacement fields of the specimen surface (size: 75*75 mm) vertically to the aggregate orientation could be determined with accuracy at the micron range and presented in displacement contour maps, where areas of tightly packed contours reveal the location, shape and size of developing cracks.

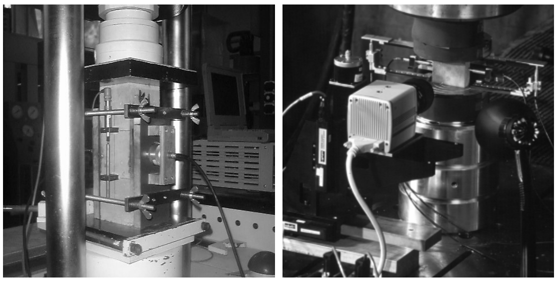

Figure 1. Test setup for ultrasonic measurements (left) and digital image correlation (right).

The test setup for the ultrasonic measurements and experiments with DIC is shown in Figure 1. For investigations with DIC uniaxial compression was ensured by inserting friction reducing material between the specimen and the loading platens. For the ultrasonic measurements this was assured by choosing a specimen slenderness height/width=3.

3.2 *Real concrete*

Ultrasonic transmission measurements were also conducted with real concrete specimens measuring 10*10*30 cm under equal loading conditions and comparable mixing design in order to transfer the findings from two-dimensional to three-dimensional conditions. In contrast to the measurements with model concrete for real concrete the transmission measurements were conducted continuously at intervals of 10 seconds.

4 EXPERIMENTAL RESULTS AND DISCUSSION

4.1 *Model concrete*

In Figure 2 the course of attenuation for normal model concrete (water-cement-ratio 0.55) is depicted for three different frequency pulses in the range between 100 and 700 kHz for increased loading and analogously for unloading after each loading step in Figure 3. The normalized load due to the different loading steps is plotted on the x-axis and attenuation as a relative change in the peak amplitude refers to the y-axis. The pulse attenuation after unloading the specimen refers to the previous load level.

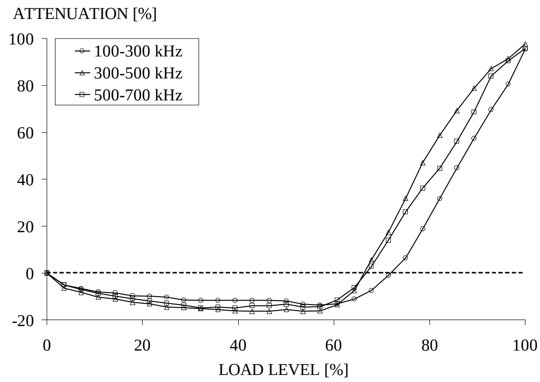

Figure 2. Attenuation for normal model concrete, loaded.

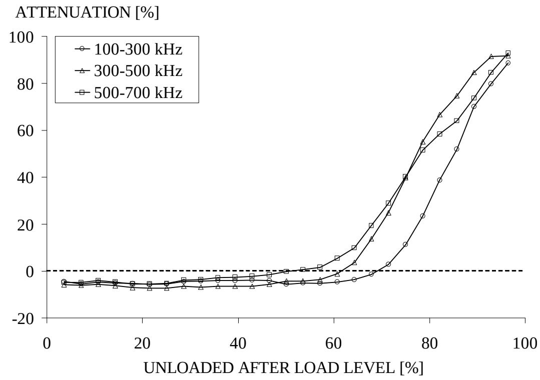

Figure 3. Attenuation for normal model concrete, unloaded.

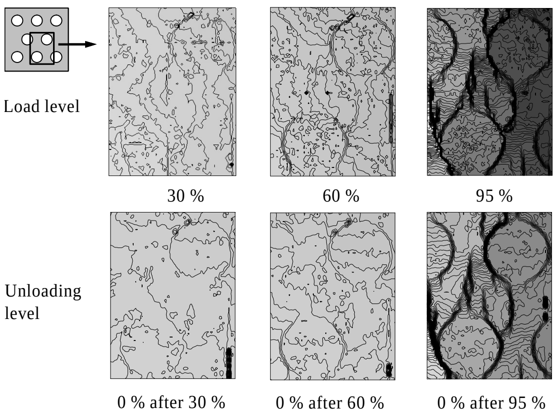

Figure 4. Development of cracks in normal model concrete.

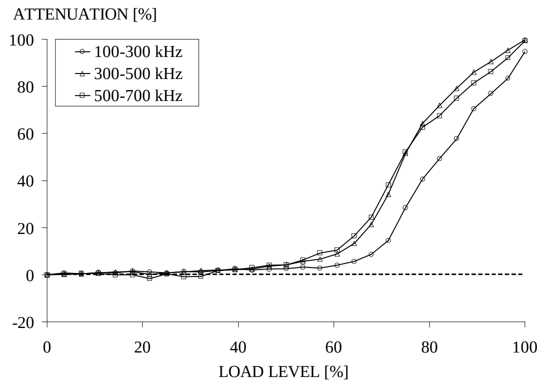

Figure 5. Attenuation for lightweight model concrete, loaded.

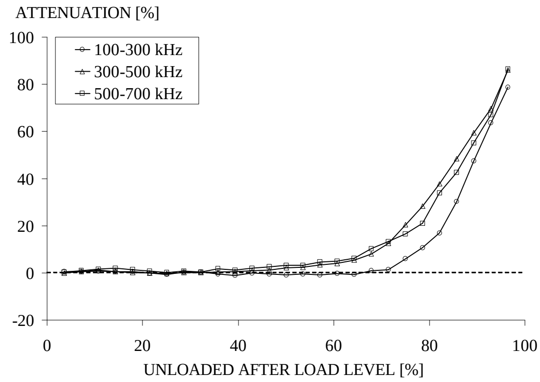

Figure 6. Attenuation for lightweight model concrete, unloaded.

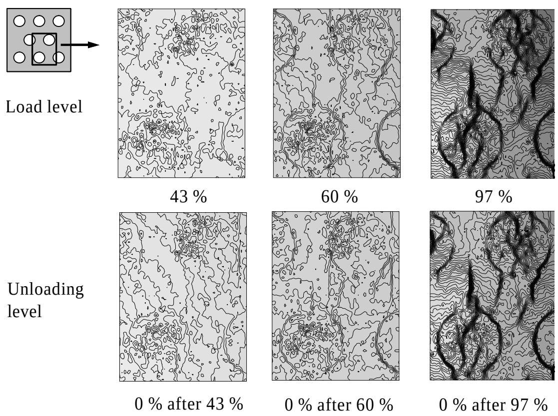

Figure 7. Development of cracks in lightweight model concrete.

The course of ultrasonic attenuation during increasing load can be divided into two characteristic intervals: Until 60 % of ultimate load a decrease of attenuation can be found, with other words, the intensity of the received signal increases. This was more pronounced for investigations with high frequency pulses. After approximately 60 % of the ultimate load until peak load a rapid increase in attenuation can be detected. This increase is also less pronounced for the lower frequency range.

Analogously to Figure 3 the course of attenuation for unloading conditions is shown in Figure 4. In this case, in opposite to the loading case nearly no change in attenuation can be found until 60 % of ultimate load. Later on a rapid increase in attenuation can be detected, also.

In Figure 4 the displacement contour maps are shown for three characteristic load steps. The pictures at the top show the horizontal displacement during loading and the pictures on the bottom displacement after unloading the specimen. Every line represents a displacement of 1 micron and areas of tightly packed contours reveal the location, shape and size of developing cracks.

From the contour maps it can be seen that at 30 % of ultimate load only slight alterations occur, which disappear after unloading. At 60 %, significant displacement concentrations in the ITZ occur, which are partly reversible. Until this range, ultrasonic attenuation shows a characteristic difference between loading and unloading. At higher load levels displacement concentrations at the ITZ increase, furthermore they can be found in the matrix, also. These deformations remain after unloading. The course of sound attenuation reveals these findings. Here a rapid increase of attenuation takes place and nearly no difference can be found between loading and subsequent unloading the specimen.

It seems that the development of interfacial micro cracks around the aggregates, which have higher acoustical impedance than the cement matrix, leads to a reduction in the acoustical mismatch between the two materials and thus the intensity of the transmitted wave increases. When the cracks exceed a certain value, from the view-point of wave propagation the aggregate turns into a void, the acoustical mismatch increases again which leads to an increase of attenuation. Furthermore matrix cracking leads to a pronounced increase of attenuation. This phenomenon was predicted by Coussy (1984). He calculated the scattering cross-section for a spherical inclusion with varying length of interfacial cracks.

In Figures 5-7 the corresponding results for lightweight concrete are depicted. In contrast to normal concrete, only marginal changes in attenuation can be detected for this material until 60-70 % of the maximum load (Fig. 5). At higher load levels, attenuation increases nearly linearly to its maximum.

Furthermore the course of attenuation after unloading the specimen after each loading step is shown in Figure 6. The course is very similar to the loading case, besides the fact, that unloading the specimen causes a distinct decrease in attenuation at higher load levels. This could not be found for normal concrete.

From the displacement contour maps in Figure 7 it was found that for lightweight concrete the displacements are concentrating inside the aggregates. Only slightly deformations can be found around the aggregates. At higher loading displacement concentrations occur within the matrix, also. A comparison of the unloaded with loaded stage, shows again, that some of the displacements are relaxing. The ultrasonic measurements reveal this behavior. They also show, that internal changes within the aggregate and in the ITZ have nearly no influence of ultrasonic attenuation. It seems that sound waves are totally absorbed in the porous aggregates before applying any load. For this material, only deformations within the matrix have an influence on ultrasonic attenuation.

4.2 *Real concrete*

Figure 8 shows the complete course of attenuation (frequency range: 300-500 kHz) during continuously measurements on real normal concrete (w/z-ratio=0.55, maximum grain diameter: 8 mm) in intervals of 10 seconds. The time in seconds is plotted on the x-axis, attenuation refers to the left y-axis and the normalized load due to the different loading steps refers to the right y-axis.

The relationship between applied load and sound attenuation is obvious with a characteristic curvature during every loading and unloading cycle. In contrast to the model concrete no absolute decrease of attenuation occurs. But analogously to the model concrete a marked increase in sound attenuation during unloading the specimen occurred, which decreases when reloading the specimen to the previous loading level. Furthermore, corresponding to the Kaiser effect

(Kaiser 1950) the microstructure of the concrete seems to memorize the maximum load and a further irreversible increase in sound attenuation takes place only after the load exceeds the preload.

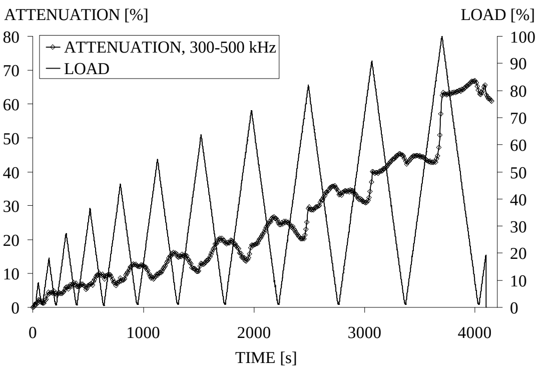

Figure 8. Pulse attenuation for real concrete (w/z-ratio=0.55, maximum grain diameter: 8 mm).

The Kaiser effect which was first investigated by Kaiser describes the phenomenon that a material under load emits acoustic waves only after a primary load level is exceeded. During reloading these materials behave elastically before the previous maximum load is reached. If the Kaiser effect is permanent for these materials, little or no acoustic emission will be recorded before the previous maximum stress level is achieved.

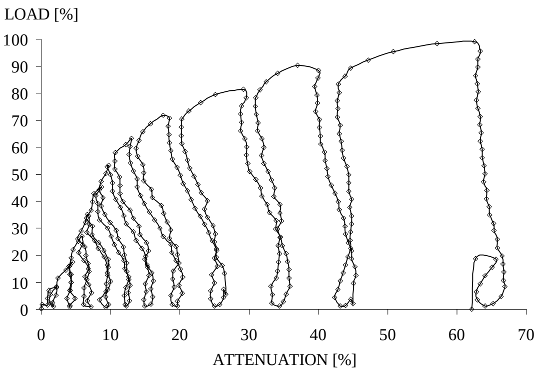

Figure 9. Load-attenuation curve for real normal concrete (w/z-ratio=0.55, maximum grain diameter: 8 mm).

In Figure 9 the load-attenuation curve is shown for the results of the experimental investigation discussed above. Attenuation is plotted on the x-axis and load refers to the y-axis. This diagram clarifies that the course of attenuation can be divided into an initial loading curve with increasing attenuation and a reloading curve, where no additional attenuation takes place as described before. According to the findings from the experiments with model concrete, the initial loading curve shows a characteristic course of attenuation with a rapid increase after 60 % of ultimate load when the cracks start to propagate within the matrix.

In terms of a practical application this load-attenuation diagram can be used to get an estimate of the loading history especially the maximum load of a structure during its life time. As long as there is no increase in attenuation, the historic maximum load was always higher.

5 MODELING OF SOUND PROPAGATION

For verification and also refinement of the findings, the propagation of elastic waves and particularly the scattering of sound waves by inclusions with interfacial cracks will be simulated by applying a numerical viscoelastic finite difference modeling. These investigations are currently carried out.

Figure 10 gives an insight in the first modeling results. On the left, a time snapshot of a propagating longitudinal line wave from the left to the right in normal model concrete with an intact ITZ is plotted. On the right the same situation is shown for a model concrete with a totally cracked interface between the matrix and the aggregates.

In a further step a wide spectrum of parameter studies will be carried out in order to simulate the specific influence of alterations in the ITZ on the ultrasonic wave propagation by simulating the findings of the digital image correlation.

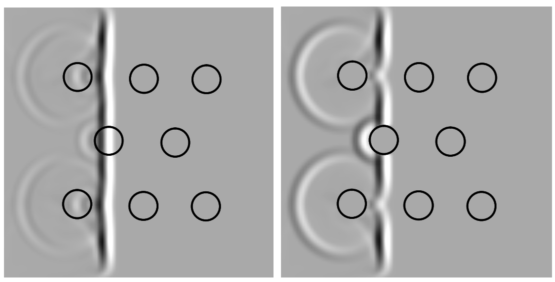

Figure 9. Time snapshot of a longitudinal sound wave propagating from the left to the right in normal model concrete (left: intact ITZ, right: totally cracked ITZ).

6 CONCLUSIONS

The investigations have clarified the correlation between attenuation of transmitted sound waves and internal processes in the structure of concrete caused by mechanical loading. It was found in loading and unloading experiments that the transmitted ultrasound energy reflects the distortion process taking place in the interfacial transition zone (ITZ). They have proven that pulse attenuation is able to indicate even small alterations at low load levels with inducing signals of high frequency ranges.

With the help of a combined application of indirect ultrasonic transmission and the direct visualization technique digital image correlation a simplified approach could be derived, which describes the influence of either the interface fracture between matrix and aggregate or the crushing within the aggregates on ultrasonic wave attenuation. The investigations have clarified that for interpretation of the results of the ultrasonic measurements a proper understanding of the theory of elastic wave propagation is essential.

It has been shown that for practical application of this concept, the effect of a clearly distinguishable initial loading curve with increasing attenuation and a reloading curve, where no additional attenuation takes place, can be used to get an estimate of the loading history especially the maximum load experienced by a structure during its life time.

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