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Internal alterations of the structure of concrete due to compressive loading

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ABSTRACT: The understanding of internal alterations in the structure of concrete constitutes an essential link in gaining better explanations for the bearing and deformation performance of concrete. For the detection of internal alterations a combination of indirect and direct methods is applied. The indirect ultrasonic transmission technique provides the opportunity to measure throughout the testing procedure. With the integral parameter ultrasonic attenuation it is possible to detect alterations of different dimensions in the structure of concrete due to mechanical loading. Significant differences between the tested frequency ranges were detected for alternately increased and decreased loading. It is possible to explain this phenomenon with alterations in the interfacial zone between coarse aggregate and matrix. For the visualization of the alterations different direct techniques are applied in order to verify the indirect observations.

1 INTRODUCTION

The understanding of internal alterations of the structure of concrete due to mechanical loading constitutes an essential link in gaining better explanations for the bearing and deformation performance of concrete. In this context concrete can be regarded at its mesolevel as a two phase material where coarse aggregate as the dispersed phase is embedded in the continuous matrix. The properties of the two phases and their interface as well as their interaction have to be taken into account in order to choose the compositon of a concrete with regard to the intended use.

2 TECHNIQUES FOR DETECTING INTERNAL ALTERATIONS

Various techniques have been applied in order to detect internal alterations in the structure of concrete. At the one hand indirect methods provide an integral parameter for the tested length (e.g. strain measurements) or a tested volume (acoustic methods). On the other hand optical or direct methods can visualize alterations at the surface during a testing procedure or the internal structure of concrete is pictured at certain stress levels.

With regard to the concrete behaviour due to compressive loading both the type, size and amount of the alterations and the stress level of their occurance are of particular interest. Therefore a combination of direct and indirect methods is the most suitable way for the investigations.

It is essential to get information about internal alterations throughout the testing procedure regardless of the loading type without influencing the test course or the test result. Methods which use mechanical waves provide this opportunity. Beyond that certain phenomenons can be visualized with the help of suitable optical techniques.

3 INVESTIGATIONS WITH MECHANICAL WAVES

3.1 *Ultrasonic transmission technique*

The physical principle, that the motion of any wave will be affected by the medium it travels through, forms the basis for the ultrasonic techniques. Thus, changes in parameters associated with the passage of a sound wave of high frequency through concrete can often be correlated with changes in physical and geometrical properties. For investigations with ultrasonic transmission at specimen an ultrasonic pulser is attached to one side of the specimen, while an ultrasonic receiver is fixed on the other side.

Two different parameters can be gained from ultrasonic transmission: The ultrasonic pulse velocity and the amplitude.

The general suitability of the ultrasonic transmission technique for investigations at concrete specimen has been proved by Suaris & Fernando (1987)

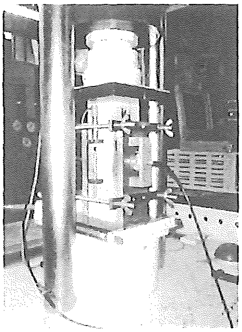

Figure 1. Concrete specimen prepared for testing

and Shah & Chandra (1970) to mention but a few.

3.2 *Experimental details*

A testing method for investigations with ultrasonic transmission at concrete specimen subjected to compressive loading was developed. Most of the investigations were carried out at concrete and mortar prisms measuring 10*10*30 cm. At middle height of the specimens the ultrasonic pulser and receiver were coupled to the concrete specimens opposite of each other in order to measure transmission lateral to the loading direction. A special spring-supported fixing system ensured constant coupling conditions throughout the testing procedure. Figure 1 shows a concrete specimen prepared for testing.

Compressive load was always supplied centrically. Different loading procedures have been applied including monotonically increasing and alternately increasing and decreasing loading as well as special loading procedures for investigations on the creeping behaviour and the elastic and delayed elastic behaviour. At certain loading and unloading levels ultrasonic measurements were carried out.

The two phases matrix and coarse aggregate have been varied in order to obtain a wide spectrum of different types of concrete. Natural gravel, expanded clay of different densities and aggregates with high density have been used and water cement ratios of

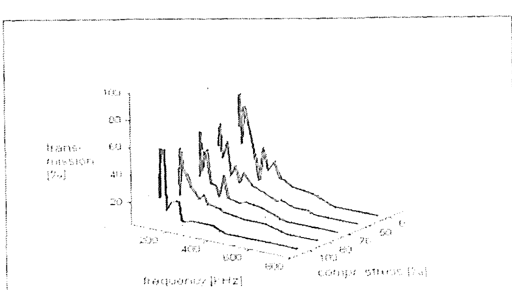

Figure 2. Transmission coefficient for signals with different frequencies measured at a normal concrete, w/c-ratio=0.55

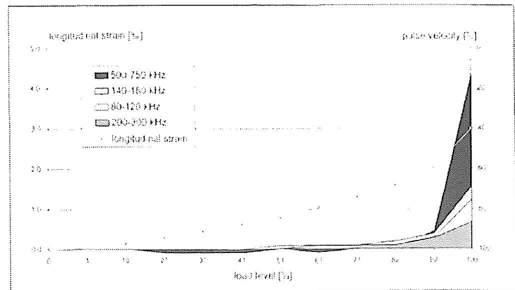

Figure 3. Pulse velocity for a normal concrete, w/c-ratio=0.55

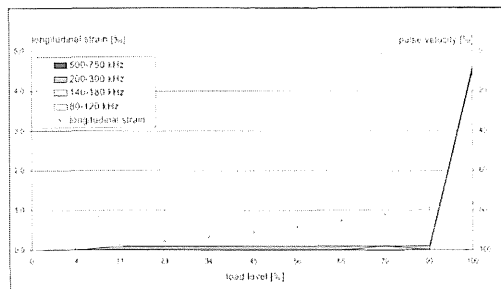

Figure 4. Pulse velocity for a lightweight aggregate concrete, w/c-ratio=0.55

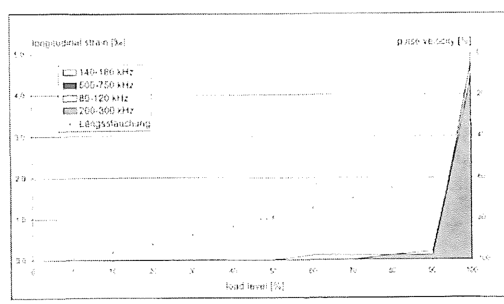

Figure 5. Pulse velocity for a high strength concrete, w/c-ratio=0.35

0.65, 0.55 and 0.35 and portlandcements of normal and high strength. With these components the tested materials showed compressive strengths from 20 to 95 N/mm² and densities from 1.7 to 3.0 kg/dm³. Additional investigations were carried out at mortar specimens with the same compositions that had been used for the matrix of the different types of concrete. For more detailed information about the tested materials it is referred to Klemt (2000).

3.3 *Experimental results*

Figure 2 shows the transmission coefficient for signals induced with frequencies from 100 to 750 kHz into a normal concrete with a water cement ratio of 0.55. The transmission coefficient was evaluated from the peak amplitude. The results of signals with frequencies lower than 80-100 kHz were rather inconsistent.

Therefore, in the further investigations signals were induced with four different frequency ranges varying from 80 to 750 kHz.
The pulse velocity was calculated as the depth of the specimen divided by the elapsed time. The pulse attenuation was defined as a relative decrease in the peak amplitude. Evaluation was based on a comparison of the pulse velocity and attenuation at different load steps with the values gained from the unloaded specimen. If a constant amplitude of the induced signal is assumed the variations of the amplitude of the received signal are proportional to variations in the attenuation (Klemt et al. 2000).

Regardless of the concrete composition the pulse velocity shows almost no change up to 80-90 % of the ultimate stress. Afterwards it decreases significantly (Figs 3-5).

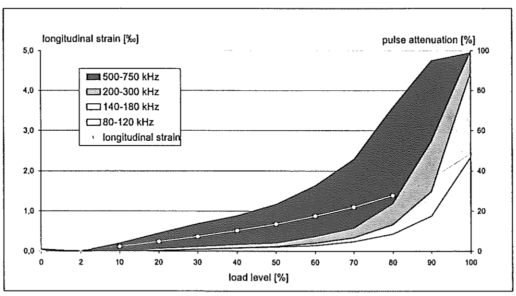

Figure 6. Pulse attenuation for a normal concrete, w/c-ratio=0.65

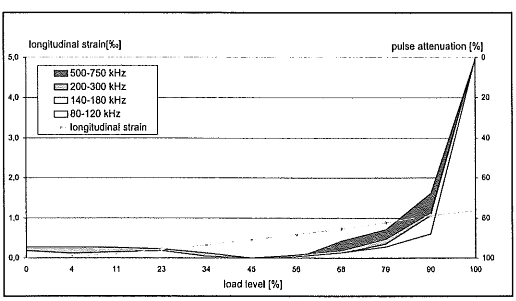

Figure 7. Pulse attenuation for a lightweight aggregate concrete, w/c-ratio=0.65

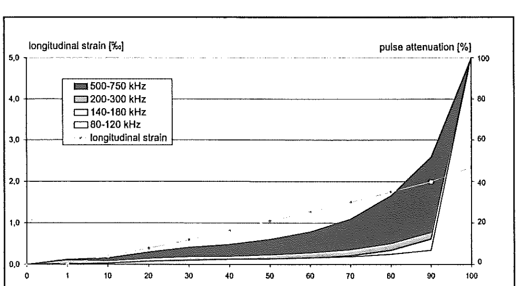

Figure 8. Pulse attenuation for a high strength concrete, w/c-ratio=0.35

The pulse attenution measured at a normal concrete with a water cement ratio of 0.65, which was subjected to monotonically increased loading is shown in Figure 6. The x-axis indicates the load levels as stress in percentage of the maximum stress. The longitudinal strain is plotted as a single line referring to the left y-axis. The pulse attenuation at the investigated frequency ranges is depicted by the area-curves in different grey scales. They refer to the right y-axis.

The diagram shows that an increase of stress leads to an increase of attenuation. With higher frequency-ranges of the induced signal the reaction of the attenuation becomes more sensitive.

The evaluation of different types of concrete leads to characteristic courses of the pulse attenuation (Figs 6-8).

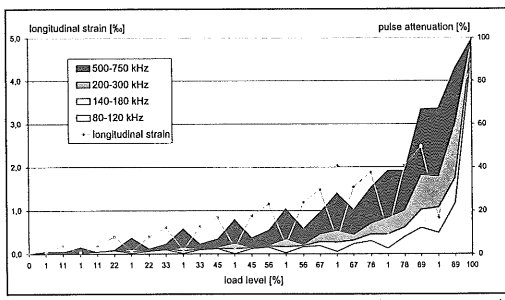

Figure 9 .. Pulse attenuation for a normal concrete, w/c-ratio=0.55, alternately increased and decreased loading

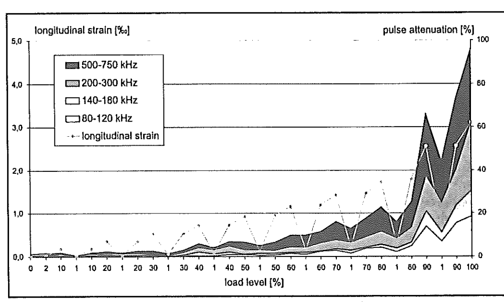

Figure 10. Pulse attenuation for a lightweight aggregate concrete, w/c-ratio=0.55, alternately loading

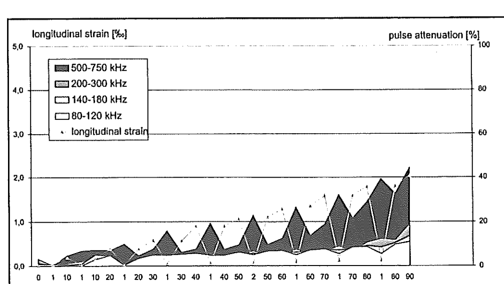

Figure 11. Pulse attenuation for a high strength concrete, w/c-ratio=0.35, alternately loading

To the same types of concrete a loading procedure with alternately increasing and decreasing loading was applied. Generally the course of pulse attenuation is comparable to the course measured at monotonically loaded specimen.

Normal concrete shows an increase in attenuation during loading for the low frequencies (Fig 9). With unloading this increase is set back –at low load levels completely and at higher load levels partly. The course of attenuation is analogous to the course of longitudinal strain, which increases with increasing stress and is reduced with decreasing stress.

The behaviour of pulse attenuation with the highest frequency range, which has a spectrum from 500 to 750 kHz, is remarkable: It shows a contrary course. Attenuation increases during unloading, which can be clearly seen by the peaks of the black area curve. This phenomenon can be observed up to a load level of approximately 70 % of maximum load.

A comparison of the course of pulse attenuation for concrete with different composition is of particular interest. Figure 10 shows the attenuation for a lightweight agggregate concrete with the same matrix composition as the normal concrete in Figure 9. For lightweight aggregate concrete the discussed phenomenon with increasing attenuation during unloading can not be observed. The high strength concrete depicted in Figure 11 consists of the same aggregate as the normal concrete. Instead of a normal strength matrix a high strength matrix was used. The peaks of attenuation during unloading are even more significant for high strength concrete than for normal concrete.

3.4 *Discussion*

The pulse velocity shows more than a marginal decrease only at load levels directly prior to failure. Therefore it is not a suitable parameter to indicate small alterations in the structure of concrete.

It can be clearly seen in the Figures 6-8 that an increase of stress leads to an increase of pulse attenuation. This can be ascribed to alterations in the structure of the transmitted concrete, since the induced signal and the coupling conditions remain constant throughout the testing procedure. With higher frequency-ranges of the induced signal the reaction of the attenuation becomes more sensitive. As higher frequency ranges have smaller wavelengths they are significantly influenced even by small alterations.

The attenuation measured at normal concrete shows an increase even for low load levels. That means that microcracking occurs already at these low load levels. For lightweight aggregate concrete and high strength concrete a significant increase of attenuation appears only at higher load levels, their courses are steeper as for normal concrete. That means that the deformation performance of normal concrete is more ductile compared to lightweight aggregate concrete and high strength concrete. The internal structures of these concretes are not undergoing a detectable change at lower load levels. As soon as structural alterations can be detected they propagate rapidly.

The pulse attenuation shows an increase for the specimen during unloading. This is true for the high frequency ranges measured at normal concrete and even more significant for high strength concrete (Figs 9, 11).

As already described the higher frequency ranges react to smaller alterations in the structure of concrete than lower frequency ranges do. For that reason the opposite course of attenuation of the high frequency ranges indicates, that unloading causes small alterations in the structure of concrete, which influence the ultrasonic pulses induced with small wavelengths. Pulses with lower frequency ranges and therefore longer wavelengths are not affected by alterations of these dimensions or the reaction is overlapped by the reaction to alterations with larger dimensions. They react to the larger alterations with a decrease of attenuation during unloading.

It is remarkable that the peaks in pulse attenuation during unloading do not occur for all types of concrete. Normal concrete and high strength concrete show these peaks during unloading as described. Apart from them high density concrete and steel fiber concrete behave similarly. This phenomenon does not appear for lightweight aggregate concrete (Fig 10). That leads to the assumption that the different behaviour of the different types of concrete is due to alterations in the interfacial zone beweeen matrix and aggregate. Investigations at mortar prisms, where peaks of the attenuation during unloading can not be observed confirm this.

4 INVESTIGATIONS WITH DIRECT METHODS

4.1 *Stabilization of microcracks with injected epoxy resin*

To visualize internal alterations in the structure of concrete the specimens are mostly cut into slices and observed with techniques like the stereomicroscopy or the scanning electron microscopy. However, the preparation of the specimen (slicing, drying, vacuumization, etc.) often causes more cracks and it is difficult to distinguish them from the internal alterations due to loading.

These disadvantages are evaded if an injected medium hardens in the cracks while the specimen is continuously under load, and the preparation and analysis are carried out afterwards.

Therefore an experimental setup was developed which provides the opportunity to stabilize the internal alterations while the specimen is sustained to compressive load. An injection pump was connected to a special introduction-system which was integrated in the loading platen. An epoxy resin with low viscosity was blended with a fluorescent pigment and used as medium for the injection.

At defined load levels the loading procedure was stopped and the resin injected. After the hardening of the resin the specimens were discharged.

The sliced specimens were examined under a microscope while the fluorescence was animated by the use of ultraviolet light. For the analysis the places filled with resin were charted to develop a three-dimensional model of the structure of concrete.

The results provide information as an overview on the structure of the specimen at the investigated load level. Of course different specimens can be observed at different load levels, but with this technique pictures cannot be gained continuously throughout the testing procedure.

4.2 *Digital Image Correlation*

The digital image correlation technique allows to investigate the surface of a specimen continuously throughout the testing procedure. Therefore it is a suitable method for the verification of the conclusions drawn from the study with mechanical waves. This technique was developed for fracture study of quasi-brittle materials by Choi & Shah (1998).

Since the surface image of a specimen changes as compressive load increases each image corresponds to a deformation level. The method of computing displacements uses a digital image correlation-scheme. After a small subimage is selected, computer algorithms find the same pattern on the deformed image using a normalized cross-correlation coefficient, which defines the level of resemblance between two subimages. The accuracy of the measurements are in the micron level (Choi & Shah 1998, Choi & Shah 1999).

The investigations with the digital image correlation technique are currently in preparation. They will be carried out in cooperation with the Center for Advanced Cement-Based Materials at the Northwestern University at Evanston, Illinois. As the analysis focuses on the specimen surface a special model concrete is tested, which consists of cylindrical aggregates embedded in a matrix, hence material properties can be anticipated as constant through the depth of the specimen. Different types of model concrete are prepared with varying aggregate properties and matrix properties. They are chosen analogously to the compositions of the concrete tested with ultrasonic transmission. For the use as aggregates cylinders of granite and limestone are cored out of blocks. Matrix is varied in the water cement ratio and addition of silica-fume.

The specimen will be tested with monotonically increased and alternately increased and decreased loading. The evaluation includes the presentation in displacement contour maps from the entire front surface area of the specimen.

5 CONCLUSIONS

For the detection of internal alterations in the structure of concrete due to mechanical loading it is most suitable to use both indirect and direct techniques.

As an indirect method the ultrasonic transmission technique was applied to specimen of mortar and concrete with different compositions. The investigations have proofed that the pulse attenuation is able to indicate even small alterations at low load levels with inducing signals of high frequency ranges with smaller wavelengths, while pulse velocity does not react sensitive enough.

An increase of pulse attenuation can be related with an increase of alterations in the structure of the transmitted volume. With inducing signals of different frequency ranges the technique is able to detect alterations with different dimension independent of each other.

The pulse attenuation shows characteristic courses for the different types of concrete. The principal course provides information about the ductility of the tested material.

Of particular interest is the behaviour of the pulse attenuation with different frequency ranges for alternately loaded and unloaded specimen, which depends on the composition of the tested concrete. It can be explained with alterations in the interfacial zone between matrix and aggregate.

Direct techniques are applied in order to verify the observations and conclusion drawn from the ultrasonic measurements. First, the alterations in the structure of concrete due to loading are stabilized at certain stress levels by injecting a fluorescent epoxy resin. The specimens are sliced and investigated with a microscope under ultraviolet light. The results provide information as an overivew on the structure of the specimen at the investigated load level.

And second, the surface of model concrete with well defined compositions is observed throughout different testing procedures with the help of the computer vision system. This technique is based on the method of computing displacements using a digital image correlation scheme (Choi & Shah 1998). The investigations are currently in preparation.

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