DEVELOPMENT OF AN ULTRASONIC TESTING METHOD FOR CONTINUOUS MEASUREMENTS ON CONCRETE WITH DIFFERENT MOISTURE LEVELS UNDER COMPRESSIVE FATIGUE LOADING

ENTWICKLUNG EINES ULTRASCHALLPRÜFVERFAHRENS FÜR DAUERMESSUNGEN AN BETON UNTERSCHIEDLICHER FEUCHTIGKEIT UNTER DRUCKSCHWELLBEANSPRUCHUNG

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SUMMARY

Recent research in the project “Temperature and humidity induced damage processes in the concrete due to cyclic compressive fatigue loading” of the priority program SPP2020 focuses on the influence of humidity on the fatigue behaviour of concrete. It is shown that there is a significant influence of humidity on the fatigue resistance. For a better understanding of these effects, ultrasonic examinations are to be carried out on cylindrical samples. The change of the sound velocity (P-waves) and the coda waves are to be investigated.

The present paper shows the first development steps for a possible setup for ultrasonic testing of concrete with different humidity levels under compressive fatigue loading. A special focus lies on the selection of a suitable coupling medium and the influence of concrete moisture.

ZUSAMMENFASSUNG

In aktuellen Forschungen im Projekt “Temperatur- und feuchteinduzierte Schädigungsprozesse infolge zyklischer Druckschwellbeanspruchung” des Schwerpunktprogramms SPP2020 wird der Einfluss der Feuchtigkeit auf die Betonermüdung untersucht. Dabei zeigt sich, dass es einen signifikanten Einfluss der Feuchtigkeit auf den Ermüdungswiderstand gibt. Um diese Effekte besser zu verstehen, sollen Ultraschalluntersuchungen an zylindrischen Proben durchgeführt werden. Dabei sollen die Änderung der Schallgeschwindigkeit (P-Wellen) sowie die Form der Coda Wellen untersucht werden.

Die vorliegende Arbeit zeigt die ersten Entwicklungsschritte für ein mögliches Setup zur Ultraschalluntersuchung von Beton unterschiedlicher Feuchtigkeit unter Druckschwellbeanspruchung. Ein besonderes Augenmerk liegt dabei bei der Auswahl eines geeigneten Koppelmittels sowie dem Einfluss der Betonfeuchte.

1. INTRODUCTION

The fatigue behaviour of concrete, especially of high-performance concrete (HPC), is very complex and even after many years of research, the design remains very conservative, although the fatigue behaviour of HPC is of growing importance with respect to service life design. Mainly the influence of frequency or amplitude is studied. The latest research in the priority program SPP2020 "Cyclic deterioration of High-Performance Concrete in an experimental-virtual lab", funded by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) has shown that humidity has a significant influence on fatigue behaviour [1-4]. Besides the usual indicators, such as the number of cycles to failure and the strain, ultrasound analysis of longitudinal waves (P-waves) offers a non-destructive way of describing the damage process [5]. The development of cracks leads to a decrease in the speed of sound and a change in the dynamic modulus of elasticity [6]. The main focus is to describe the effects of varying moisture contents on concrete. Besides the change of the concrete velocity, the change of the coda of the P-wave shall be investigated in detail. Before an ultrasonic testing method can be chosen, it is necessary to design a setup, select the right sensors with an appropriate frequency and a suitable coupling medium. This allows for a good transfer of the ultrasonic signals from the sensor via the coupling medium into the concrete. A separate focus concentrates on the humidity of the concrete and the change in humidity over time.

2. THEORETICAL BACKGROUND

In order to be able to design a suitable setup, the theoretical background of fatigue, ultrasound examination and coda wave interferometry must first be examined.

2.1 FATIGUE STRENGTH

To define the fatigue strength of concrete, Wöhler curves (S-N relations) are generated (see Fig. 1). For this purpose, the static compressive or tensile strength is first determined. Based on this, a related upper and lower stress level can then be calculated. The number of cycles to failure is plotted as a function of the level of upper and lower stress. This allows the estimation of the number of cycles to failure at a low upper stress which cannot be determined experimentally due to the excessive running time.

Various studies have shown that the fatigue strength of concrete depends on the type of stress (Fig. 2), whereby concrete under compressive loading reaches the highest number of cycles to failure. The fatigue strength of concrete under tensile loading is lower [7]. The lowest fatigue strength is resulted by concrete under alternating stress [8].

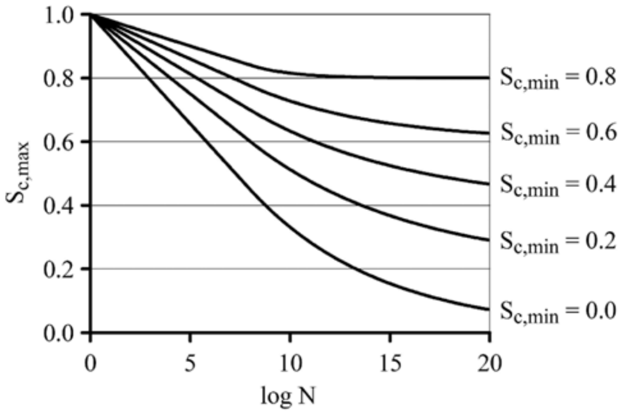

Fig. 1: S-N relations (Wöhler curves) [9]

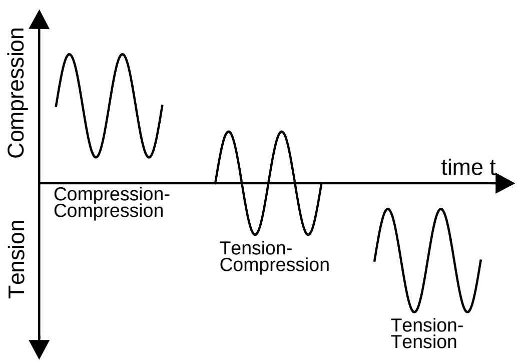

Fig. 2: Stress conditions in the fatigue test according to [10] (translated)

The chosen test frequency has an influence on the fatigue strength, as the fundamental influence of the load speed has been proven several times [4], [11], [12], [13]. Additionally, in contrast to metals, the stress amplitude and the level of the lower stress have a critical influence. The number of cycles to failure decreases significantly with increasing lower stress level and constant amplitude [14]. A good overview over the fatigue behaviour of concrete under various conditions is given in [15] and [16].

2.2 ULTRASONIC

Ultrasonic technology is widely used and much advanced in the fields of medicine, steel construction and rock physics [17]. Ultrasound measurements in concrete are more complex due to its multi-phase material composition and are thus not yet very common apart from ultrasound scanning of fresh concrete [18]. But recent studies focus on applying ultrasonic technology in regard of fatigue [6].

A general workflow for this application of ultrasound is shown in Fig. 3. The propagation of the mechanical signal, i.e. the time it takes for the soundwaves to travel from the transmitter to the receiver, in through-transmission-mode (see section 3.2) is called time-of-flight (TOF). To determine the TOF, the time of the first arrival of the ultrasound signal is recorded, e.g. read from the abscissas in Fig. 3, and corrected by a system offset time. Dividing the TOF by the distance between the transmitters equals the sound velocity. The sound intensity of the signal corresponds to the electrical amplitude, taken e.g. from the ordinates in Fig. 3 in millivolts.

The speed of sound is a material constant that depends on the density and elastic properties of the material (see equation 1 from [19]). Therefore, the analysis of the velocity of sound waves, as well as that of the sound intensity in a material, enables determining the existence and location of inhomogeneities and imperfections plus changes in the elastic properties. Relevant for through-transmissions are the compression waves, also called longitudinal or primary waves (P-waves). Another occurring wave form is the shear wave, also referred to as transverse or secondary wave (S-waves). Other modes of wave propagation also exist but are not considered here.

$$c_L = \sqrt{\frac{E}{\rho}} \cdot \sqrt{\frac{1-\nu}{(1+\nu)(1-2\nu)}} \tag{1}$$

c_L sound velocity (longitudinal waves)
E modulus of elasticity
ρ raw density
ν Poisson’s ratio

The more imperfections i.e. cracks there are in a material, the more interfaces there are in addition to the existing material interfaces due to the concrete composition. Because of differences in the impedance of the adjacent materials, sound waves are reflected and scattered [19]. The impedance of a material is equal to its density times its sound velocity. The reflection factor R, in turn, is calculated as follows:

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \qquad (2)$$

High impedance differences $Z_2 >> Z_1$ result in a reflection factor of nearly 100%. This is the case with interfaces between concrete and air, e.g. in cracks caused by fatigue. This results in attenuation of the sound waves, marked by a decline in sound velocity and intensity. Therefore, the damage development caused during fatigue tests can be determined by analysing these factors (see Fig. 3).

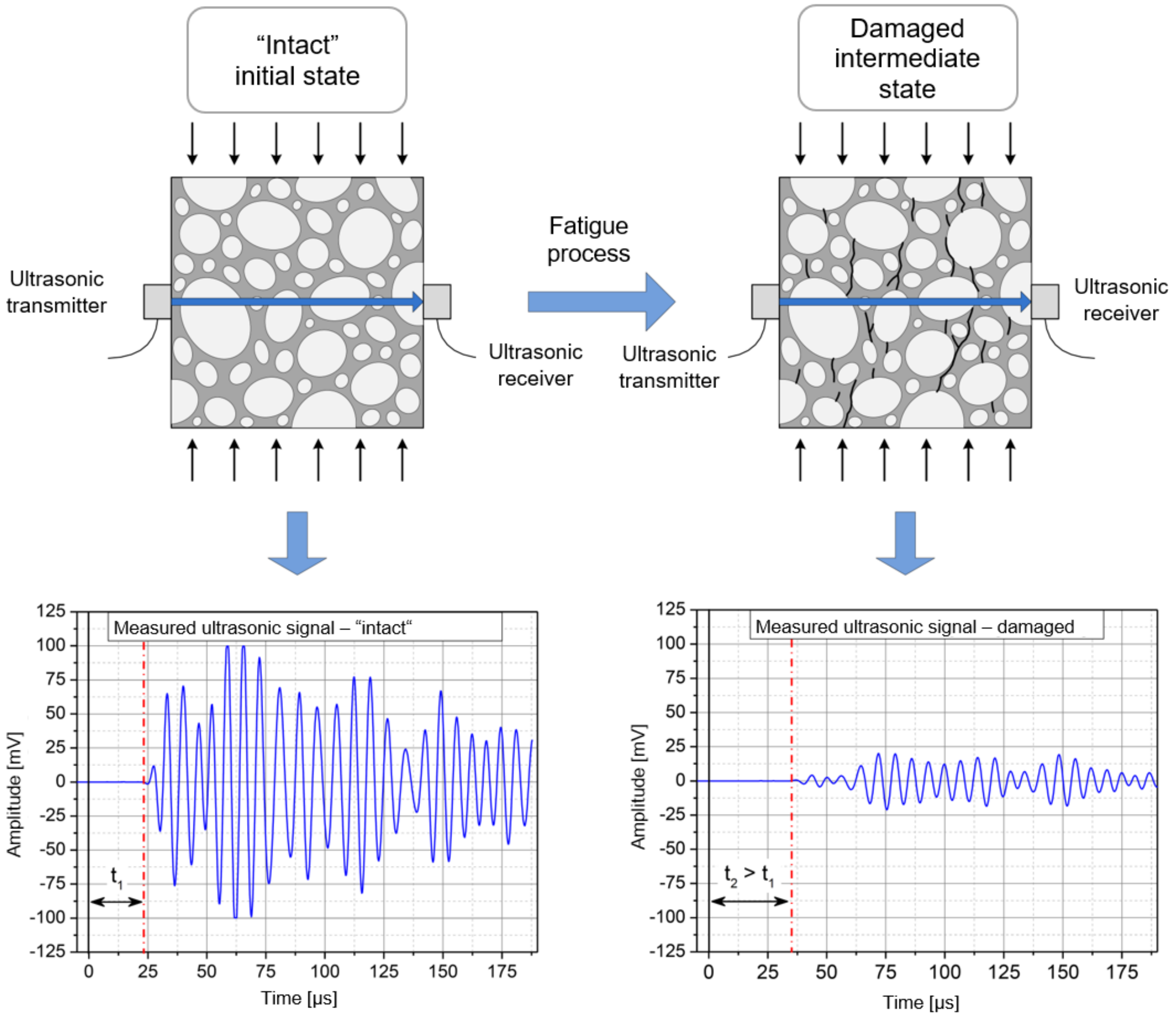

Fig. 3: Determination of the time-of-flight (here t_1, t_2) and assessment of damage development using ultrasonic technology [20] (translated)

In general, ultrasound waves cover a frequency range 20 kHz until 1 GHz, whereas the frequency of sound waves used in test methods on concrete structures is mostly between 20 kHz and 150 kHz [21]. For material characterisations, as described here, or for test methods on steel, higher frequencies up to about 10 MHz are typical [22]. The wavelength is inversely proportional to frequency and is an important factor regarding the decline of sound amplitude in a heterogeneous material. The bigger inhomogeneities are compared to the wavelength, the more sound wave disruptions occur, which ultimately leads to more loss of sound energy as a result of internal friction [23]. Therefore, the frequency is usually determined to account for a wavelength larger than the aggregates in the tested concrete. On the other hand, higher frequencies provide more information on changes in the microstructure in the late, incoherent part of the ultrasonic signal, also called coda waves.

2.3 CODA WAVE INTERFEROMETRY

An informative review of CWI in concrete has been published under [24]. This method has been applied e.g. in [25] to monitor load tests of concrete beams. A related method has been applied in [26] to determine the diffusion characteristics of sintered glass beads. In the following, only a short overview of CWI in material testing is given.

The term 'coda', originally taken from seismology, in this context refers to the diffusive or incoherent part of the ultrasonic signal, i.e., the part which arrives at a later time and which is mostly affected by multiple wave scattering and reflections. A clear separation from the coherent part in the time domain is difficult, but papers like [26] hint at a dominating influence of shear waves (S-waves) in the coda, due to persistent local wave mode conversions from P-waves to S-waves. Since the travel paths and transit times of coda waves are much longer, this technique can be used to reveal subtle perturbations in concrete, e.g. structural changes such as cracks due to fatigue, which are not yet identifiable in the coherent direct waves, making it a very sensitive detection tool [25], see Fig. 4.

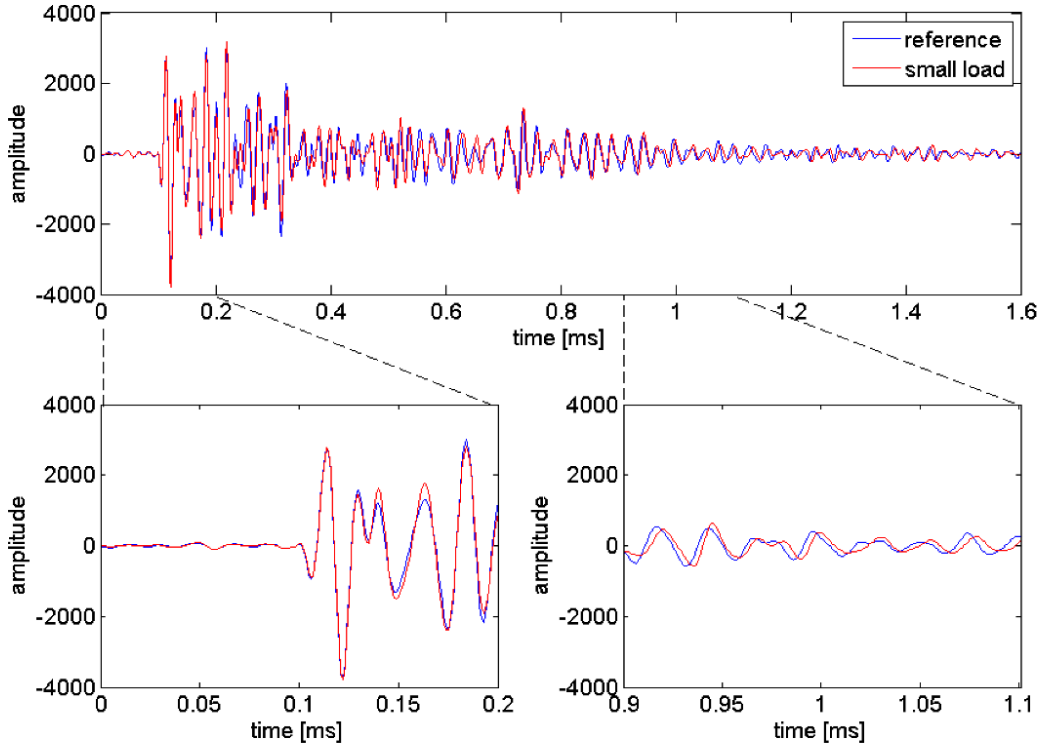

Fig. 4: Change of TOF and Coda [25]

CWI is based on determining the cross-correlation [24]

$$CC(\varepsilon) = \frac{\int_{t_1}^{t_2} \varphi'(t')\varphi(t)dt}{\sqrt{\int_{t_1}^{t_2} \varphi'^2(t')dt \int_{t_1}^{t_2} \varphi^2(t)dt}}; \quad t' = t(1-\varepsilon), \tag{3}$$

here by means of time stretching by a factor ε, between reference and manipulated disturbed time signal $\varphi(t)$ and $\varphi'(t')$, respectively. The maximum stretching factor reflects the overall velocity change $\frac{dv}{v_0} = \varepsilon_{max}$ between reference and disturbed signal.

3. TEST SET-UPS

3.1 TEST SET-UP FATIGUE TEST

The most fatigue tests in literature were conducted on a servo-hydraulic testing machine and were mostly operated load controlled. A typically testing machine and test set-up are shown in Fig. 5 and Fig. 6.

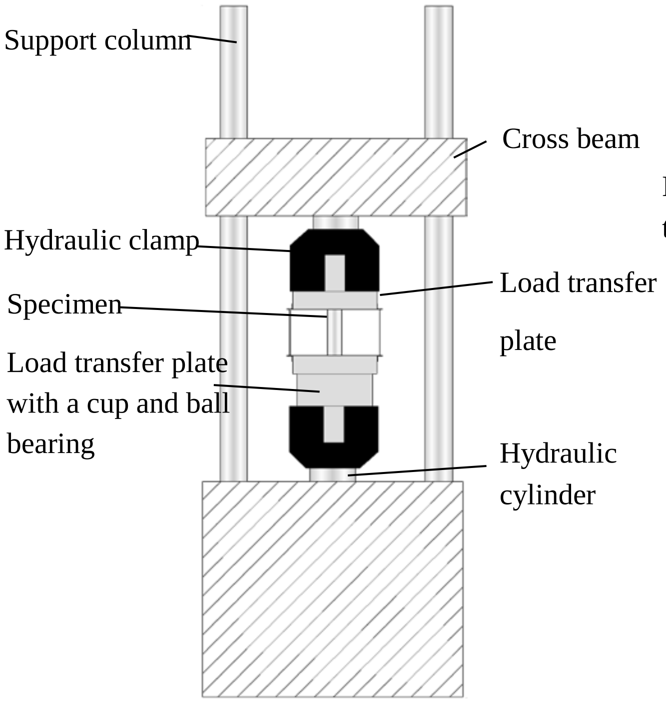

Fig. 5: Typical experimental set-up [1]

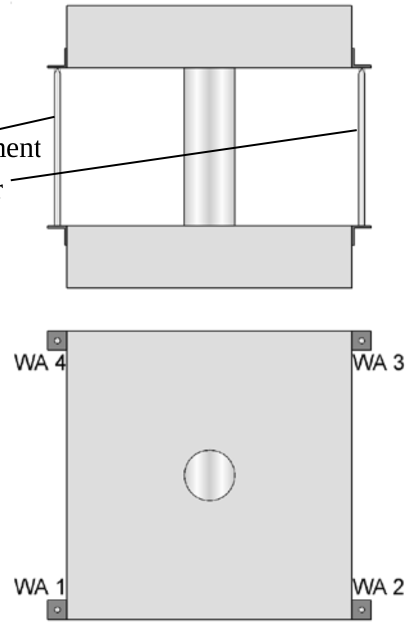

Fig. 6: Positions of the displacement transducers [1]

To minimise unintended bending of the test specimen due to imperfection of the plane-parallel top and bottom sides of the cylinders, a load transfer plate with a cup and ball bearing is used. During the fatigue tests the number of load cycles, the applied loads, the deformation of the specimen and the temperature development are measured.

3.2 SET-UP ULTRASOUND TEST

A typical set up for an ultrasound test consists of the test object (cylindrical sample with two grinded sides), pulser, transducers and an oscilloscope. The method applied here is the through-transmission, meaning one transducer transmits sound waves continuously in a given frequency on one side of the object while the other one receives and transforms them back into electric impulses for the oscilloscope to display (see Fig. 7). Employed here are 2-MHz transducers by

Doppler, model name N2P10L, to minimise the amount of grinding at the two sides.

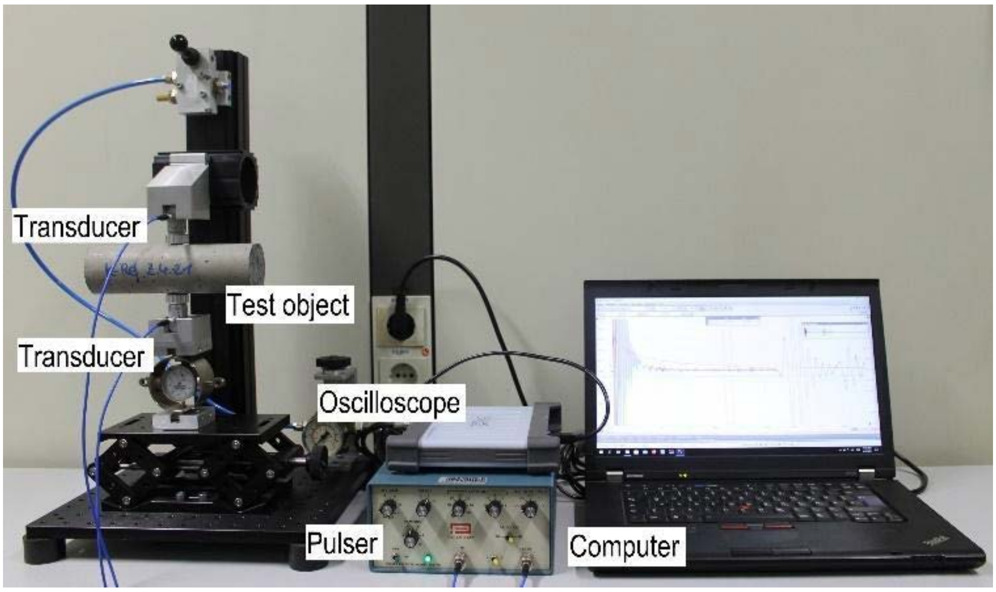

Fig. 7: Set-up ultrasound test

The PC-Oscilloscope used is a 16bit model Picoscope 5444B from manufacturer Pico Technology. This needs to be connected to a computer for the display and operation, made possible with the software Picoscope6. As for the pulser, which is required for the generation of the sound waves, the square pulser generator 5052 PR from Olympus-NDT was used. This set up is adjustable to be applied during fatigue tests, using pneumatic cylinders to position the transducers with constant contact onto the test object.

4. COUPLANT

The application of a couplant is essential for an optimal transmission of sound waves from the transducer into the test object (Fig. 8). The couplant compensates for unevenness of the contact surfaces and eliminates the presence of air, which would almost completely reflect the sound waves due to its high impedance difference to concrete. Mostly, couplants used are viscose, easy-to-remove liquids, though also visco-elastic solid materials can be used.

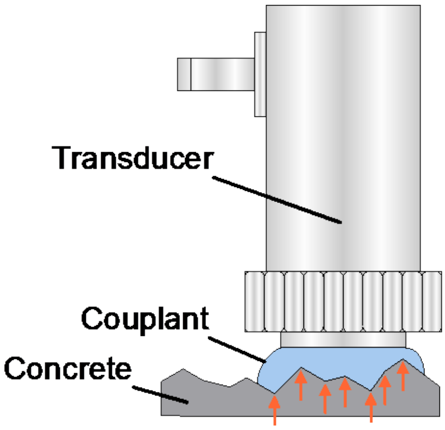

Fig. 8: Compensation of surface roughness by couplant

To select the optimal couplant for the experiments, tests with various materials have been conducted to assess their suitability regarding acoustic intensity and time of flight as well as their durability. To do so, each couplant is respectively applied to the same concrete specimen and the ultrasound signal is monitored over a period of 6 hours.

Table 1: Couplants and their absolute values of amplitude and ultrasonic velocity before and after a test period of 6 hours

Couplant	**Description**	**Initial / final amplitude [mV]**	**Initial / final ultrasonic velocity (P-Wave) [m/s]**
Water	Tap water (exemplarily)	15.23 / -	5089.82 / -
Echotrace	Couplant from “Karl Deutsch” made of water-based gel	82.37 / 28.79	4724.98 / 4722.41
Glycerine	Couplant B from “Olympus”	293.11 / 151.27	5202.91 / 5251.16
Honey	Liquid bee honey of the brand „Dr. Kriegers“	216.41 / 222.08	5214.78 / 5214.68
Fermit	Permanently plastic sealing compound made of plastic	67.68 / 83.90	4692.32 / 4729.43
Adhesive pads	„UHU-Patafix”	25.97 / 52.21	4163.26 / 4384.23
Rubber discs	Sealing dishers from „Kirchhoff“ made of rubber, d=2mm	14.52 / 15.99	4136.75 / 4162.32

Table 1 shows that honey exhibits the highest amplitude (intensity of sound) and ultrasonic velocity alongside glycerine. Fig. 9 visualises that the amplitude increases or decreases with time depending on the couplant. The signals given by water and the water-based “echotrace” disappear after a while; this is due to the evaporation of the water, which cancels out the coupling. The adhesive pads, on the other hand, show a strong increase in amplitude. This can be attributed to the fact that the adhesive pads were compressed due to the constant load, thus reducing the thickness of the couplant over time. A related effect could be observed in Fig. 10 for the ultrasonic velocity, which increases for water and adhesive pads. Comparing the development of honey and that of glycerine – the couplants with the highest amplitudes – honey remained the most constant over time. Therefore, honey represents an ideal couplant for the ultrasonic monitoring.

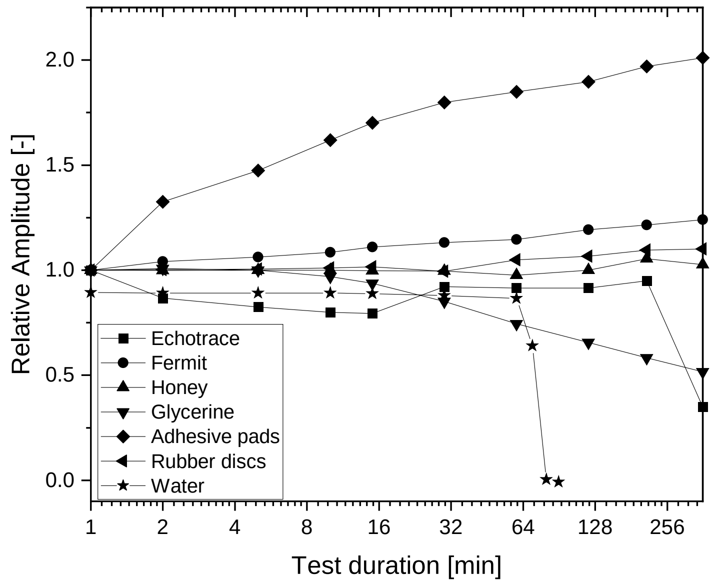

Fig. 9: Relative amplitude of all couplants over 6 hours

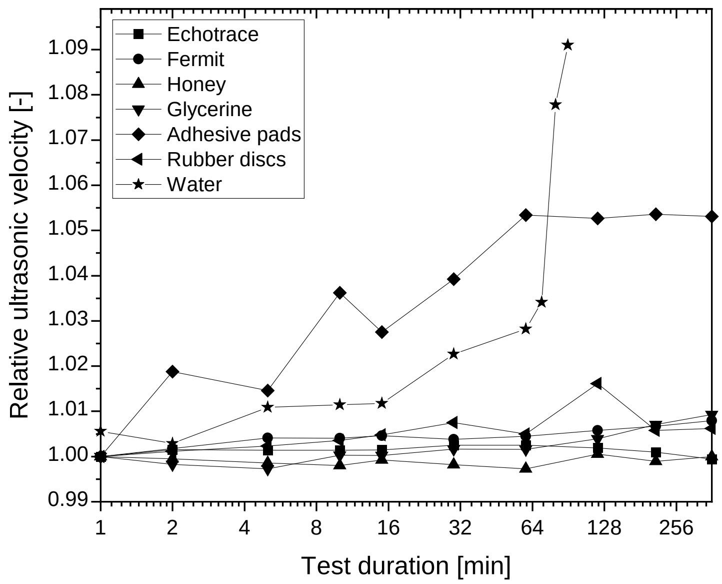

Fig. 10: Relative ultrasonic velocity of all couplants over 6 hours

5. INFLUENCE OF MOISTURE

5.1 INFLUENCE OF MOISTURE ON FATIGUE RESISTANCE

Concrete structures with higher moisture contents have been proven to exhibit a lower fatigue resistance [1-4]. It is assumed that the higher content of chemically unbound water leads to an increase of pore water pressure, which in return causes additional damaging tensile stresses in the concrete structure [3]. Higher moisture content is also proven to lead to a greater decline of stiffness during fatigue tests [2] as well as a larger gain of deformation and temperature [1].

5.2 INFLUENCE OF MOISTURE ON THE ULTRASONIC SIGNAL

Concrete moisture affects the ultrasonic signal significantly, due to the porous nature of this material. Consequently, wave propagation inside it behaves like in any porous material, i.e., its effective ultrasound wave velocities result from the properties of its skeleton and fluid phase [27]. The higher the moisture content, the greater the signal propagation velocity and the more sound energy is transmitted. This is the case because air voids increasingly fill up with water, which has a higher ultrasonic velocity than air. The resulting smaller difference in impedance compared to concrete then leads to a higher transmission of sound pressure, resulting in higher ultrasonic velocities and amplitudes [28]. Therefore, it is essential to seal the concrete cylinders to keep the moisture content constant and prevent the distortion of the ultrasonic signal results from the fatigue experiments.

Fig. 11 shows how the ultrasonic signal is affected when the concrete moisture declines with time. To do so, a test object is taken out of its under-water storage and left to dry while monitoring the ultrasonic signal. During the test, the concrete moisture declined by 0.5 g, which represents about 10% of the total moisture content. As expected, the amplitude and ultrasonic velocity clearly decrease due to the dehydration. The amplitude declines faster and steeper and therefore poses a more sensitive parameter to determine the drying of the concrete.

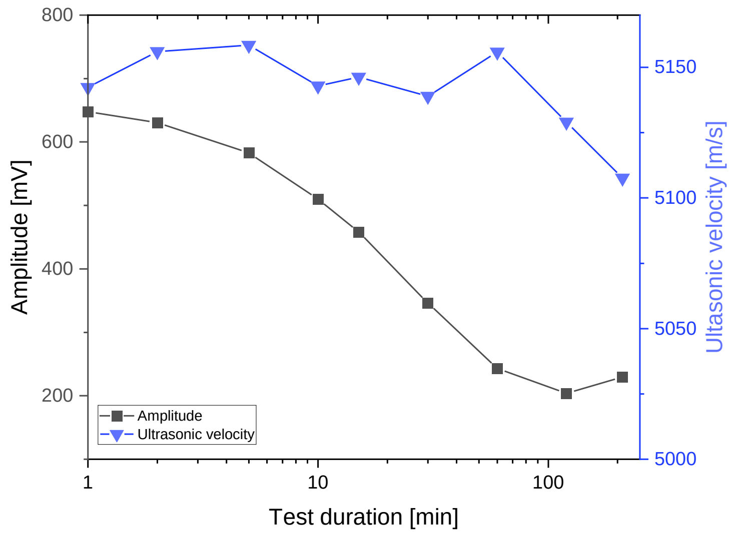

Fig. 11: Amplitude and Ultrasonic velocity during moisture reduction

6. CONCLUSION AND OUTLOOK

In summary, the preliminary experiments conducted lead to a functioning setup. The 2-MHz transducers were chosen amongst others due to its small diameter. Honey was finally selected as the couplant for an optimal coupling of the transducers and the cylindrical concrete test specimens. It is proven to have the best long-term behaviour. The other tested liquid (water-based) couplants lost their coupling functions over time due to evaporation. The solid couplants exhibited an excessive attenuation or rather the ultrasonic velocity and amplitude declined continuingly due to their creeping properties.

Test objects out of concrete with higher moisture contents must be optimally sealed to prevent loss of moisture since ultrasonic velocity and amplitude rise with less moisture content. If the concrete dries out during a fatigue test, it would affect the actual changes in the ultrasonic parameters.

To guarantee that the transducers are always coupled consistently, they should be positioned using pneumatics. Furthermore, the cylindrical test specimens should not have to be grinded on two sides anymore. Rather, arched delay lines should be applied to couple the transducers onto the round surface.

Finally, the fatigue experiments should be conducted with simultaneous ultrasound monitoring. Moreover, it should be considered if the test frequency of the transducers of 2-MHz is small enough or if a smaller frequency is necessary, which at the same time also means a bigger sensor surface.

Using the data out of the ultrasonic analysis during the fatigue tests, differences in the ultrasonic velocity as well as in the coda waves between dry concrete and concrete with higher moisture contents should be compared to achieve a better understanding of the effect of moisture on concrete under fatigue loading.

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