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1 Introduction

The fatigue behaviour of concrete, especially of HPC, is very complex and even after many years of research, the design is still very conservative. Previous studies on normal strength concrete prove that the number of cycles to failure under pure compressive cyclic loading mainly depends on frequency and amplitude. An increase of the loading frequency leads to a higher number of load cycles to failure [1]. In addition to the frequency, the related upper and lower stress level influences the number of cycles to failure [2]. Recent research work shows that the humidity of the specimen is also influencing the fatigue behaviour of concrete. [3] shows that the fatigue behaviour of concrete under water is worse compared to dried samples. In addition to humidity, temperature also plays an important role and the test frequency is influencing the temperature development of the concrete [4]. However, the interaction of humidity and temperature at the same time has not been explicitly investigated yet. Therefore, this paper presents the results of experimental investigations concerning this matter. In those investigations, humidity, frequency and amplitude have been varied. Special attention was paid to the examination of the microstructure. Various investigations have already shown that the development of damage can be determined by e.g. ultrasonic transmission measurements [5]. For these tests the resonance analysis was used as a non-destructive test method to determine the humidity as well as the degree of damage.
2. Experiments

2.1. Material used and storage conditions

For the experimental work, an HPC with a water/cement ratio of 0.35 was used. For comparability between the different batches, the same amount of concrete was produced with a conventional single-shaft mixer at each concreting.

Three test series with different storage conditions were planned to investigate the influence of the concrete humidity. The test series N with storage conditions according to [6], the test series UW with under water storage and the test series D with dried test specimen were conducted.

After concreting all samples were stripped after 24 h and stored under water for 7 days. Subsequent the test specimen were cut to length and the top surfaces were grinded plane-parallel and polished. The test specimen of series UW remained under water until the test. The storage conditions of test series N were defined to a temperature of 20 °C and 65 % relative humidity. To minimise the influence from drying on the concrete hardening process the test specimen of series D were stored under the same conditions like series N for the first 56 days. Afterwards they were stored at 105 °C for 28 days until the age of at least 70 days. Before testing, all specimens were wrapped in a diffusion-tight foil to prevent changes of the concrete humidity during the test. At the same time the humidity of the concrete was determined for each test series on two samples by oven drying at 105 °C. The storage conditions and the concrete humidity are summarised in Table 1.

Table 1. Humidity and storage conditions of the three series.

| Series      | Day 1 | Day 1-7 | Day 8-56 | Day 56 - Test | Before testing | Test | Humidity |
|-------------|-------|---------|----------|---------------|----------------|------|----------|
| D (Dry Specimen) |       |         |          |               | 20 °C / 65 % | 105 °C | ca. 25 °C | 0.1 % |
| N (Normative Storage) | strip the formwork | under water | 20 °C / 65 % | 20 °C / 65 % | 105 °C | wrap at the start | 4.0 % |
| UW (Under Water Storage) | 20 °C / 65 % | underwater | 20 °C / 65 % | 20 °C / 65 % | 105 °C | 5.1 % |

2.2. Experimental programme and test setup fatigue test

The fatigue tests were conducted on a servohydraulic Schenk testing machine with a maximum load capacity of 400 kN. Each test was operated load controlled and carried out with a sinusoidal loading at a constant frequency of 10 Hz. The normalised minimum stress was $S_u = \sigma_u / f_c,cyl = 0.05$ and the normalised maximum stress $S_o = \sigma_o / f_c,cyl$ was varied from $S_o = 0.5$ to $S_o = 0.8$. Tests with more than 2.5 million load cycles were treated as run-outs. The test program of the three series is shown in Table 2.

Table 2. Experimental outline of the three series.

| $S_o$ | $S_u$ | Frequency [Hz] | Sealed/Unsealed |
|-------|-------|----------------|-----------------|
| D     | 0.8/0.7 | 0.05 | 10 | Sealed |
| N     | 0.8/0.6/0.55 | 0.05 | 10 | Sealed |
| UW    | 0.7/0.55/0.5 | 0.05 | 10 | Sealed |

To minimize 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 was used. During the tests the number of load cycles, the applied loads, the deformation of the specimen and the temperature development were measured. The deformation was measured by four displacement transducers WA 1 - 4 adapted between the load transfer plates. The strain will be calculated from the measured deformations under the assumption of constant strain over the height of the specimen. The testing machine and the test setup are shown in figure 1, the positions of transducers and the temperature sensors in figure 2.
2.3. Resonance analysis
In resonance analysis, the specimen is excited impulsively with the aid of a small metal ball and made to vibrate. The vibrations are perceived with a microphone and evaluated. In particular, the resonance frequency and the speed of sound are measured. Together with the weight, height and diameter, the dynamic and static modulus of elasticity can then be calculated from these measured values [7]. Since only a small metal ball falls from a low height onto the specimen, this method is non-destructive. The analysis was performed, prior to the experiment, on all samples with the measuring instrument RA100 Concrete by Lang Sensorik and in case of run-outs also after the test.

3. Experimental results

3.1. Fatigue tests
The results of the fatigue tests are given in figure 3, the number of cycles to failure is plotted in log scale versus the normalized maximum stress $S_o$. Besides that, a linear regression function was determined by using the function $f = m \times \log(N) + b$ for each of the three test series. Because of the few test results up to now the run-out tests were also used for the regression which is normally not the case in evaluation of fatigue test results. In figure 3 the run-out tests are marked with an arrow.

Comparing the tests at the highest stress level $S_o = 0.8$ it becomes clear that the test specimen of N Series with a concrete humidity of 4 % fail significantly earlier than the test specimen with dried concrete (concrete humidity of 0.1 %). On the stress level $S_o = 0.7$ the same effect becomes visible. The humid concrete test specimen (4 % and 5.1 %) of series N and UW fail about two decades earlier than the dried concrete specimen. At stress levels of $S_o \leq 0.6$ it was not possible to generate failures with dried concrete specimens up to $n = 5 \times 10^6$ cycles. With humid concrete specimen at a stress levels $S_o = 0.6$ and $S_o = 0.55$ respectively it was possible to generate failure. The comparison of the humid concrete test series N and UW over all load levels also indicate a correlation between the number of cycles to failure and the concrete humidity.
The three trend lines in figure 3 are relatively parallel to each other, especially for the test series UW and N. All three trend lines support the assumption that higher concrete humidity values lead to early failure compared to dried concrete. Because of the small amount of test data this assumption must be validated with upcoming additional tests. To better understand the influence of the humidity on the fatigue behaviour the available test data is evaluated with respect to the development of strain and temperature in the next section.

![Figure 3. Normalised stress versus number of cycles to failure.](image)

### 3.2. Temperature

A warming effect of grout material due to fatigue loading was already described in [4] with respect to different loading speeds between 1 Hz and 10 Hz. Because the own tests were tested with 10 Hz a warming during the fatigue tests was expected for the HPC as well. To investigate the warming effects, the temperature was measured as described in 2.2 and is shown in figure 2. The temperature heats up mostly in the middle of the sample (T2). For further contemplations, only the temperature increase in the middle to the specimen compared to the room temperature is considered.

Figure 4 shows the maximum temperature increase values of all tests plotted versus the number of cycles to failure. The run-out tests were not considered. It can be seen that for the dried samples the maximum temperature increase is lower compared to the tests with a concrete humidity of 4.0 % and 5.1 % respectively (series N and UW) even if the number of cycles to failure is in the same order. If the temperature is again interpreted as a damage indicator, the damage increase due to the concrete humidity as already described in section 3.1, figure 3 can be supported.

It is obvious that the temperature increase rises with increasing number of load cycles for both humid and dried samples because the specimen has more time to heat up. The temperature increase depending on the concrete humidity is exemplary shown for three tests at the stress level of S_0 = 0.7 in figure 5. For both humid concrete specimen (series N and UW) the temperature increase is much faster compared to the red curve of the dried concrete.

As documented in literature the strain development plotted versus the applied load cycles is a very good damage indicator [8]. To illustrate the influence of the humidity on the damage process in Figure 6 the increase of strain is plotted on the same load level S_0 = 0.7 for the three different concrete humidity values. Series UW with the highest humidity shows a more rapid strain development compared to the test series N. It can be assumed that the damage process in the UW test series was accelerated by additional water in concrete pore volume. The further reduced amount of water in the concrete of test series D leads to an increased number of load cycles to failure.
The increase of strain and temperature showed a similarity. It can be concluded that the gradient of temperature increase corresponds to the damage speed and therefore that an increase in concrete humidity results in an increase in damage velocity.

**Figure 4.** Maximum temperature increase of the three series.

**Figure 5.** Temperature increase of the three series at the load level $S_o = 0.7$.

**Figure 6.** Strain increase for stress level $S_o = 0.7$ for different concrete humidity.

### 3.3. Resonance analysis

The concrete humidity and the static and dynamic modulus of elasticity as results of the resonance analysis are summarised in figures 7 and 8. Comparing these results of the resonance analysis with the respect of the concrete humidity it becomes clear that the values are noticeable influenced. The modulus of elasticity combines the effect of resonance frequency and sound velocity as well as density. It is therefore a very sensitive indicator for the concrete humidity, which can be determined in a non-destructive manner. This can be used to determine the individual humidity of specimen to be used in fatigue tests and therefore to improve the knowledge about the correlation between the concrete humidity and its fatigue behaviour.
4. Conclusions and outlook

The results of 3 fatigue test series presented here have shown, that the humidity of the specimen is influencing the development of temperature and strain during the load cycles. The results indicate that beside the strain the temperature increase can be used as a damage indicator in fatigue tests. Increasing humidity of the specimen in tests at identical load levels leads to a faster increase of temperature and strain and to shorter fatigue life.

In further test series the study shall be extended to different mix design and mixing procedure. In addition test series with loading frequencies of 10 Hz and 1 Hz are scheduled with elevated environmental temperatures and accordingly preheated specimen. Additionally for all test specimen in further tests resonance analysis shall be used in order to determine the humidity and correlate it with the fatigue behavior. Beside damage indicators monitored so far it is planned to observe cracking of the specimen by means of mercury intrusion porosimetry and acoustic emission analysis.

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