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INFLUENCE OF WATER-INDUCED DAMAGE MECHANISMS ON THE FATIGUE DETERIORATION OF HIGH-STRENGTH CONCRETE

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Influence of water-induced damage mechanisms on the fatigue deterioration of high-strength concrete

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Abstract

Concrete specimens which are submerged in water have a significantly lower fatigue resistance than specimens which are stored and tested in air. This phenomenon was recognised in the past, but how the moisture content in the microstructure of the concrete influences its resistance against fatigue deterioration is still unknown. Well-instrumented fatigue tests on high-strength concrete specimens are conducted to investigate how the moisture content in the microstructure of concrete influences its fatigue resistance and which additional water-induced damage mechanisms are involved in the degradation process. Furthermore, a dependency of different load frequencies is examined. Since water-induced damage mechanisms act on a very small scale, which cannot be directly observed during the tests, a multiscale numerical approach is necessary to describe water-induced damage mechanisms in fatigue-loaded concrete.

This paper presents results of fatigue tests on high-strength concrete specimens with different moisture contents and load frequencies tested in air and under water. The number of cycles to failure, the development of stiffness and the acoustic emission are analysed over the degradation process of the concrete. Finally, a numeric modelling approach is presented.

Keywords: High-strength concrete, fatigue deterioration, water-induced degradation mechanisms, moisture content, stiffness, phase-field, porous media, microscale model.

1. Introduction

The use of offshore wind energy is expanding and fatigue-loaded concrete structures that are submerged in water are being built. This already currently applies to the so-called grouted joints, where high-strength fine-grained concrete (grout) is used in the steel support structures of offshore wind turbines. Such constructions are subjected to several hundred million load cycles within their service life. An increased moisture content in the microstructure of the concrete results from the offshore exposure of the construction, which is principally different to those onshore. Comparatively few investigations of fatigue-tested concrete specimens immersed in water are documented in the literature (see e.g. Huemme 2018, Petković 1991, Nygard et al. 1992 and Sørensen et al. 2011). A clear tendency can be observed despite the fact that considerable scattering exists in these results. Specimens that are immersed in water have a significantly lower fatigue resistance compared to those tested in air. Some investigations also show that fatigue-loaded concrete specimens immersed in water show a significantly different fracture behaviour than specimens tested in air. This is seen, for example by ascending air bubbles, wash-out of fine particles and premature crack initiation, as described in Huemme (2018). Water-induced damage mechanisms in fatigue-loaded concrete have indeed been recognised in the past, but they were not identified and described with sufficient precision. Consequently, they could not be quantified reliably. Based on the existing knowledge gap, most of water-induced damage mechanisms have escaped numerical modelling and simulation.
2. Experimental investigation

2.1. Material

The experimental investigations of the fatigue behaviour under uniaxial compressive fatigue loading were conducted on two different high-strength concretes. A high-strength concrete with a water/cement (w/c) ratio of 0.33 and a maximum grain size of 8 mm was used to investigate different moisture contents in the microstructure. The aggregate consists of basalt and the concrete composition contains no other reactive additives, such as fly ash or microsilica. This concrete is called HPC-A in the following. Table 1 shows the complete composition of the HPC-A used in detail.

Table 1: Concrete composition of the high-strength concrete HPC-A

<table>
<thead>
<tr>
<th>components</th>
<th>content [kg/m³]</th>
<th>components</th>
<th>content [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>cement (CEM I 52,5 R-SR3)</td>
<td>500</td>
<td>basalt (5/8 mm)</td>
<td>570</td>
</tr>
<tr>
<td>quartz sand (0/0.5 mm)</td>
<td>75</td>
<td>pce plasticizer</td>
<td>5.00</td>
</tr>
<tr>
<td>sand (0/2 mm)</td>
<td>850</td>
<td>stabilizer</td>
<td>2.85</td>
</tr>
<tr>
<td>basalt (2/5 mm)</td>
<td>350</td>
<td>water</td>
<td>176</td>
</tr>
</tbody>
</table>

However, the investigation of the frequency dependency was carried out on a high-strength concrete whose detailed composition is not known. The concrete used is assigned to the concrete strength class C80 according to the manufacturer’s specifications. This concrete is called HPC-B in the following.

2.2. Preparation process of the test specimens and storage conditions

Cylindrical test specimens of HPC-A with the dimensions of h/d = 300/100 mm were manufactured for the experimental investigations. The concrete was filled into plastic formworks and compacted on a vibratory table. After a curing time of 48 h, the formworks were removed. Fourteen days later, the test specimens were cut in length and the top and bottom sides of each test specimen were polished. The test specimens prepared were divided directly after the manufacturing process into five series to adjust the different moisture contents in the microstructure of the concrete (cf. Table 2).

Table 2: Definition of the storage and test conditions investigated

<table>
<thead>
<tr>
<th>acronym</th>
<th>storage condition</th>
<th>sealing</th>
<th>test condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>dried (105 ± 5 °C)</td>
<td>Al-coated butyl tape</td>
<td>dry</td>
</tr>
<tr>
<td>C</td>
<td>climate chamber (20 °C, 65 % RH)</td>
<td>Al-coated butyl tape</td>
<td>dry</td>
</tr>
<tr>
<td>M</td>
<td>intrinsic moisture (sealed until testing)</td>
<td>Al-coated butyl tape</td>
<td>dry</td>
</tr>
<tr>
<td>WS</td>
<td>water storage (stored underwater)</td>
<td>Al-coated butyl tape</td>
<td>dry</td>
</tr>
<tr>
<td>WST</td>
<td>underwater (stored and tested underwater)</td>
<td>-</td>
<td>underwater</td>
</tr>
</tbody>
</table>

The first series contains dry test specimens (D) which only contain non-vaporable, essentially chemically bound water in its microstructure. These specimens were dried at 105 ± 5 °C in a drying chamber to a constant mass. The second series contains test specimens with a quasi-natural moisture content (C). These test specimens were stored for at least 90 days in a climate chamber at constant ambient conditions (20 °C, 65 % RH). The third series contains specimens which represent an almost unaffected core zone area of a massive structural concrete element in which a direct moisture exchange with the environment is prevented. These specimens show a nearly intrinsic moisture content (M) and are sealed (with aluminium (Al)-coated butyl tape) immediately after the stripping process from the formwork to prevent a desiccation of the concrete. The fourth series represents a water-saturated concrete structure. The test specimens of this series are permanently (directly after the concreting process until testing) submerged in water (WS) and stored at a constant temperature (20 °C). In addition the shell surfaces of the test specimens (of the storage conditions D, C and WS) were
wrapped with a waterproof Al-coated butyl tape before testing to prevent desiccation of the concrete during the fatigue tests. Consequently the specimens of the storage conditions D, C, M and WS were tested in a sealed way in a dry environmental condition to investigate the influence of the moisture content in the microstructure. Additional fatigue tests with unsealed test specimens were conducted to verify the influence of a possible ingress of external surrounding water. These specimens form the fifth series and were stored and tested underwater (WST).

The test specimens of HPC-B have the same dimensions as those of HPC-A but were prefabricated (manufacturing and preparation process) by a concrete plant. The test specimens of HPC-B were stored and tested underwater analogously to the conditioning type WST.

2.3. Experimental set-up and measurement equipment

The whole experimental investigation was performed in a 2.5 MN servo-hydraulic testing machine with a specially developed test set-up, which is shown on the left-hand side in Figure 1, due to the special requirements of fatigue tests submerged in water. The peculiarity of the test set-up is the cylindrical water basin, which allows fatigue tests in a dry environmental condition and fully submerged in water to be carried out. A force-controlled loading is applied in the fatigue tests. At the beginning of the test, the axial force is monotonically increased up to the mean stress level and afterwards, is switched into a sinusoidal fatigue loading. The related minimum and maximum stress level were kept constant throughout the whole investigation period with $S_{\text{min}} = 0.05$ and $S_{\text{max}} = 0.65$. Three specimens of each storage condition (except storage condition D) were investigated for the fatigue investigations. Storage condition D was tested with one test specimen. A constant load frequency of $f_p = 1.0 \, \text{Hz}$ was applied in the fatigue tests. Due to no rupture the load frequency in the fatigue test of storage condition D where increased to a load frequency of 6 Hz during the test.

An additional fatigue test series under submerged conditions WST with different load frequencies (0.35, 1.0, 5.0 and 10.0 Hz) was carried out to examine a possible frequency effect. Note that these tests were carried out on prefabricated specimens of HPC-B. The compressive strengths of both high-strength concretes were determined immediately before conducting the fatigue tests, using three specimens from the same batch having the same geometry as the specimens used in the fatigue tests. The compressive reference strength which is required to determine the axial forces in the fatigue tests was calculated for each concrete and storage condition as the mean value of the compressive strengths. The static tests were performed using a monotonically increasing loading of 0.5 MPa/s.

![Figure 1. Experimental set-up (left) and measurement equipment (right)](image)

Different damage indicators were measured during the fatigue tests to investigate how the moisture content in the microstructure influences the fatigue resistance of the concrete and which additional water-induced damage mechanisms are involved in the degradation process. The axial deformations of
the test specimens were measured continuously with a constant sample rate of 300 Hz using three laser distance sensors positioned around each specimen at 0°, 120° and 240°. In addition, the axial force and the surface temperature of the specimens were measured. An acoustic emission analyses was used to characterise the water-induced degradation mechanisms. Six acoustic emission sensors with a frequency response of 250 – 1600 kHz were attached to each test specimen. The sensors were positioned with an angle offset of 60° to each other, alternating in the upper and lower third of the specimen’s height. The measurement equipment used is illustrated on the right-hand side of Figure 1.

3. Results and discussion

3.1. Moisture content and material properties

In a first step, the characteristic moisture content, the characteristic dynamic Young’s modulus and the average compressive strength were determined to classify the influence of different concretes and storage conditions. The test results of HPC-A and HPC-B are shown in Table 3 as mean values. As expected, the average moisture content of HPC-A shows an increasing trend over the different storage conditions. The highest moisture content was determined in the specimens of the storage condition WST with a value of 5.0 mass-%.

Table 3: Material properties of the high-strength concretes HPC-A and HPC-B

<table>
<thead>
<tr>
<th>acronym</th>
<th>moisture content [mass-%]</th>
<th>dynamic Young’s modulus [GPa]</th>
<th>compressive strength [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HPC-A</td>
<td>HPC-A</td>
<td>HPC-A</td>
</tr>
<tr>
<td>D</td>
<td>~ 0</td>
<td>41.7</td>
<td>108</td>
</tr>
<tr>
<td>C</td>
<td>3.5</td>
<td>47.1</td>
<td>97</td>
</tr>
<tr>
<td>M</td>
<td>4.3</td>
<td>52.4</td>
<td>-</td>
</tr>
<tr>
<td>WS/WST</td>
<td>5.0</td>
<td>53.3</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>53.2</td>
<td>107</td>
</tr>
</tbody>
</table>

The average dynamic Young’s modulus of HPC-A shows values between 53.3 GPa (WS/ WST) and 41.7 GPa (D). Furthermore, the dynamic Young’s modulus is decreasing with a decreasing moisture content. These results correspond to those from Huenme (2018) and Winkler (2010). Huenme (2018) determined differences in the dynamic Young’s modulus of about 5 – 15 % between specimens which were stored in a climate chamber and underwater. Winkler (2010) explains this phenomenon by an increasing moisture content of the pore structure, which leads to a higher stiffness of the concrete. The mean compressive strength of storage condition C is the lowest value of all storage conditions, whereas the other results were very similar, between 107 and 110 MPa. The biggest deviation is determined between the storage conditions C and WS/WST with a relative deviation of 10.2 %. A comparison of the results of HPC-A and HPC-B for the storage condition WST shows similar values between the high-strength concretes tested. Only the moisture content in the microstructure of HPC-B is a little lower with a value of 4.0 mass-%. The results of the compressive strength generally show only a slightly influence of the moisture content in the microstructure under a slowly monotonically increasing loading. These results correspond to those from Huenme (2018). He also detects no significant differences in the compressive strength between test specimens stored a climate chamber or underwater.

3.2. Number of cycles to failure

Figure 2 demonstrates the correlation between the maximum compressive stress level S_{max} and the numbers of cycles to failure N for the concrete HPC-A. The numbers of cycles to failure are plotted in a logarithmic scale. The test results are presented as single values and mean values for each storage condition (D, C, M, WS and WST). The S-N curve for pure compressive fatigue loading of fib Model Code 2010 in dry environmental conditions and the DNV S-N curve for wet environmental conditions are shown additionally in Figure 2 for a better classification of the results. It can be seen that the test specimens of all storage conditions exceed the requirements of the DNV. Furthermore, the results
show that the numbers of cycles to failure of the storage condition C are located very close to the expected values according to fib Model Code 2010. Therefore, the high-strength concrete (HPC-A) used shows basically a fatigue resistance which is typical for concrete.

The numbers of cycles to failure illustrated in Figure 2 show a decreasing fatigue resistance with an increasing moisture content in the microstructure of the concrete. This trend coincides with the few investigations documented in literature (see e.g. Huemme 2018 and Sørensen et al. 2011), assuming the decreasing fatigue resistance with a possible pore-water pressure which leads to additional tensile stresses acting in the microstructure of the concrete. The biggest deviation of the average number of cycles to failure of this investigation can be found with a value of 2.5 orders of magnitude between the storage conditions WST and D. Note that the result of the storage condition D refers to one fatigue-tested specimen without rupture (marked by an arrow). The actual number of cycles to failure is not known, but it is, in any case, higher than the value marked. The results of the storage conditions C and M are logically arranged between the storage conditions WST and D. In addition, Figure 2 shows that the values of the storage condition WS (log $N = 4.30$) are located quite close to the values of the storage condition WST (log $N = 4.17$). This fact shows that not the wet environment but the moisture in the microstructure of the concrete is substantially responsible for the reduction of the fatigue resistance of the concrete. External surrounding water reduces the fatigue resistance of the concrete further, but only a small amount. The results of the number of cycles to failure depending on the storage conditions generally show that the moisture content affects the resistance of concrete against fatigue deterioration dramatically.

3.3. Damage indicators

As first damage indicator, the development of stiffness is analysed. For this, the secant modulus ($E_S$) in the decreasing branch was calculated for each load cycle using the strains at maximum and
minimum stresses. Similar to Oneschkow 2016, the gradient of the development of stiffness in phase II of the strain development is calculated in accordance with equation (1). The gradient \( \text{grad } E_S^{0.2-0.8} \) is determined between 20 % and 80 % of the numbers of load cycles to failure. Damage indicator \( \text{grad } E_S^{0.2-0.8} \) is used in the following to detect differences within the degradation process between the moisture contents investigated.

\[
\text{grad } E_S^{0.2-0.8} = \left( \frac{\Delta E_S^{0.2-0.8}}{\Delta N^{0.2-0.8}} \right)
\]  

(1)

Acoustic emission signals during the fatigue degradation process are additionally analysed to obtain detailed information about the development of damages. The following analysis is based on the results for the HPC-A.

Figure 4 shows the results of the gradient of stiffness depending on the moisture content. It can be seen that \( \text{grad } E_S^{0.2-0.8} \) generally increases with increasing moisture content. The results of the storage condition WS and WST show the highest and results of D and C the lowest values. The lower values of \( \text{grad } E_S^{0.2-0.8} \) for the specimens of the storage conditions D and C indicate a slower damage evolution per load cycle. However, \( \text{grad } E_S^{0.2-0.8} \) increases rapidly from a value of -7 kPa for condition C to a value of -240 kPa for condition WS. Consequently, the results indicate a critical value of moisture content from which additional water-induced damage mechanisms are acting dramatically. The critical value of the concrete examined here is approximately close to a moisture content of 3.5 mass-%. If this critical value is exceeded, \( \text{grad } E_S^{0.2-0.8} \) increases fast, which leads to a decreasing fatigue resistance of the concrete.

![Figure 4. Gradient of the development of stiffness in phase II (HPC-A)](image1)

![Figure 5. Acoustic emission activity per cycle (HPC-A)](image2)

Figure 5 illustrates the acoustic emission activity depending on the storage conditions. The hits per load cycle are demonstrated on the y-axis, which gives additional information about the development of damage, assuming that only the damage occurring produces these emissions. The results show a correlation between the acoustic emission activity and the storage condition. It can be seen that the acoustic emission activity increases with an increasing moisture content. The specimens especially of the storage conditions WS and WST show more acoustic emission activity, with values of about 0.9 to 1.4 hits per cycle, compared to the other storage conditions. These observations correspond to the results of the development of stiffness illustrated above.

Overall, the results indicate that the gradient of development of stiffness and the acoustic emission activity increases quickly after reaching a critical moisture content in the microstructure of the concrete.
4. Computational model and representative numerical example

A microscale model leads to accurate material descriptions and a better understanding of the failure mechanism. Consequently, a micromechanical framework for modelling water-induced damage mechanism of high-performance concrete is investigated within this section. Concrete has a highly heterogeneous microstructure and its composite behaviour is very complex, as discussed in the experimental observation above. Due to that, a variety of effects must be considered for analysing the failure response at the microscale, such as modelling the solid skeleton, fluid bulk phases and their interactions. In order to obtain a deeper understanding of the water influence on the concrete at the micro-level a microcomputed tomography (micro-CT) scan was performed to illustrate the microstructure geometry and concrete content which are required to build up the constitutive model and design the numerical simulation. Based on the experimental data, a micromechanical model has been developed for the coupled problem of fluid-saturated heterogeneous porous media at fracture. The modelling of microscopic cracks in porous heterogeneous media can be achieved in a convenient way by recently developed continuum phase field approaches to fractures which are based on the regularization of sharp crack discontinuities, as outlined in Aldakheel (2016). This avoids the use of complex discretization methods for crack discontinuities and can account for complex crack patterns. The numerical example proposed here stems from a conjoint project of the priority program SPP 2020. The three-dimensional microstructure geometry of the high-performance concrete and the finite element representation are depicted in Figure 6.

![Figure 6. Three-dimensional microstructure of HPC. Left: Geometry based on a microcomputed tomography scan and the finite element discretization (right).](image)

Hereby, blue areas correspond to the saturated pores and grey zones represent the cement matrix. Note that we consider the pores to be full of water in the simulations. Material properties of the cement matrix are obtained through nano-indentation techniques.

![Figure 7. Contour plots of the crack phase-field $d$ at the final failure. Blue and Red contour colours correspond to the unbroken state ($d = 0$) and fully broken state ($d = 1$) of the material, respectively.](image)

Figure 7 demonstrates contour plots of the fracture phase-field $d$ at the final deformation state. The cracks start to initiate from the pores when a threshold energy is reached. Thereafter, they propagate in random directions inside the cement matrix and join other cracks till final rupture. We used a
transparency effect for the crack phase-field with $d = 1$, as plotted in Figure 7 (right), to illustrate the failure surface inside the cement paste. Furthermore, it has been observed that concrete tested underwater shows earlier damage behaviour compared to a dry concrete.

5. Conclusion and outlook

Well-instrumented fatigue tests on high-strength concrete specimens were conducted to investigate how the moisture content in the microstructure and a wet environmental condition influences the fatigue resistance of a high strength concrete.

It is shown that the number of cycles to failure decreases dramatically with an increasing moisture content. Furthermore, it is demonstrated that not the wet environment but the moisture content in the microstructure is substantially responsible for the reduced fatigue resistance.

In addition, the damage indicators analysed show a strong dependency on the moisture content in the microstructure. The results of the development of stiffness and the acoustic emission show quickly increasing values for specimens with a moisture content higher than a particular value. Consequently, the results indicate the existence of a critical moisture content from which water-induced damage mechanisms are acting.

In addition, the results show an increasing impact of water-induced damage mechanisms with a decreasing load frequency.

Based on these experimental observation, a micro-mechanical model for the coupled problem of Darcy-Biot-type fluid-saturated heterogeneous porous media at fracture was proposed.

High-resolution imaging techniques, such as SEM and CT, and additional NMR measurements are planned to obtain more information about the occurrence and quality of moisture-induced damage in relation to the pore system of the concrete.

Acknowledgements

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