Received: 8 October 2022 | Accepted: 3 November 2022

DOI: 10.1002/pamm.202200221

The high cycle fatigue testing of High-Performance Concretes using high frequency excitation

Hamid Madadi[1,*] and **Holger Steeb**[1,2]

[1] Institute of Applied Mechanics (CE),University of Stuttgart, Stuttgart, Germany
[2] SC SimTech, University of Stuttgart,Stuttgart, Germany

The effect of fatigue failure in brittle materials like (ultra) High Performance Concrete (UHPC) due to cyclic loading causes unexpected failure that consequently results in heavy costs in marine and civil structures. To characterize the effect of fatigue, cyclic loading tests are performed, and "the number of cycles to failure" are experimentally determined. One problem with these kinds of tests is that such experimental investigations are potentially expensive, i.e., time-consuming process since the number of loading cycles could be extremely high. Further, within the different damage phases of the cycling tests, one has no access to the small-scale, i.e., microscopical evolution of (micro-)cracks. Additionally, a full characterization of the small-strain stiffness evolution of the material is challenging. The goal of the research investigation is to combine a (large amplitude) High Cycle Fatigue experiment with a (low amplitude) Dynamic Mechanical Analysis (DMA). Using a setup based on the piezoelectric actuator, the (rate-dependent) mechanical properties of the material in tangential space, and the failure modes of the material will be examined accurately. The excitation frequency is between 0.01 Hz to 1000 Hz which allows for reducing the experimental investigation time to failure. Further, it allows investigating the effect of frequency on the number of cycles to failure. Firstly, experimental results for HPC and berea sandstone samples will be presented. Harmonic experimental data include (direct) strain measurements in axial and circumferential directions as well as forces in axial directions. In addition, the resulting complex Young's modulus and evolving damage-like "history" of HPC and berea sandstone specimens will be shown.

1 Introduction

Concrete technological advancements currently allow the use of concrete compositions with ever-increasing compressive strengths and makes the construction of increasingly thin and filigree structures possible [1]. Because of a lower ratio of deadweight to non-static loads, these structures are subjected to more fatigue-relevant stresses than massive structures. Thus, the fatigue resistance of the concrete becomes critical for the design of these structures.

In the recent decades, there has been a significantly increasing demand for structures in which fatigue-related stresses are dominant, such as wind turbines or narrow bridges composed of high-strength or ultra-high-strength concrete. As a result, many studies in recent decades have focused on fatigue testing and particularly on the concretes' fatigue behaviour [2–4].

High-performance concrete (HPC) and ultra-high-performance concrete (UHPC) are among the modern types of concretes and a wide range of concrete admixtures and additives are now available for their production [5]. Even after many years of research, the fatigue behavior of these concretes is quite complicated and not entirely understood. Due to a lack of understanding on the fatigue damage processes, the corresponding safety design elements have been chosen in a conservative manner [6]. Constructions using these concretes must be built extremely cautiously since the fatigue behavior of HPC and UHPC is particularly relevant to the service life of design equations [7, 8]. So far, research has been focused mostly on the frequency and amplitude effects of external fatigue stresses. Since simple ultra-high-performance concretes have only lately become popular, currently, a small number of fatigue research on them is available in the literature [9, 10]. Regarding the impact of loading frequency on the concrete's fatigue behavior, there aren't many studies reported in the literature. High-strength concrete specimens were tested in the air and under water for compressive fatigue testing in Hohberg [2] Hümme et al. [11], and Oneschkow et al. [12] works. The results of these works have shown that higher loading frequencies result in more cycles to failure than lower frequencies for specimens kept and tested in air. Oneschkow [3] examined compressive fatigue on a high-strength concrete that had been kept and tested in air and his work's findings demonstrated that greater loading frequencies result in a reduction in the gradient of the stiffness development for phase II. Furthermore, by increasing the loading frequencies, the calculated stiffness degradation increased. However, the speed of the test or loading frequency for the fatigue test for these materials was always low, and finally, the fatigue test was performed with a frequency of 10 Hz [13].

In this article, on the one side, it has been tried to check the behaviour of materials during the fatigue test with the help of dynamic mechanical analysis (DMA), and on the other side, it is possible to perform a high-frequency fatigue test by changing this method.DMA is a method of identifying material properties that works under different mechanical and environmental conditions [14]. Here, concrete materials are examined using DMA to characterize the consequences of material behavior on an effective scale. DMA probes the samples with modest amplitudes and is sensitive to the intrinsic stiffness changes [15]. Both the undamaged and the particularly damaged states of the HPC mixture were examined and compared.This demonstrated

---

[*] Corresponding author: e-mail hamid.madadi@mib.uni-stuttgart.de, phone +49 711 685-66348,fax +49 711 685-66347

that DMA could be used to identify and explain damage progression when the Young's modulus changes. In the following, it is tried to combine the DMA method as a high-speed fatigue testing method with the DMT fatigue test method.

2 Methods and relations

This paper describes experimental results obtained by well-established high cycle fatigue experiments using high frequency loading and a novel low-amplitude high-frequency characterization approach.

2.1 Description of the Dynamic Mechanical Analysis

Figure 1 shows the DMA setup schematically. Besides, there are detailed descriptions of this setup and other DMA setups used in geophysics in [14–16]. As shown in Figure 1 setup, to measure the force, a pre-calibrated aluminum cylinder is used. In addition, high-voltage version of piezoelectric actuators (Physik Instrumente P-235.2s) were used for harmonic excitations. For this setup, a static area preload was applied to the sample using a metallic stamp in a static universal testing machine (Figure 1). Then, a piezoelectric actuator was placed on top of the sample. The actuator used in this test transforms voltages ranging from 1 to 1000 V and makes displacements that reach 40 µm of amplitude. Basically, the displacements' amplitude depends on the excitation frequency, the static pre-load and the cumulative stiffness of the setup. Generally, it can be assumed that the actuator displacements change highly nonlinear receiving input voltage. After being offset by 500 volts, the actuator input was sinusoidally excited. Consequently, two models of arbitrary waveform generators generator (Physik Instrumente P-517) were used to make a sinusoidal voltage signal that later was amplified by a high-voltage "Physik Instrumente E-482" amplifier. For this harmonic signal the maximum peak to peak amplitude is 10 Vpp that technically corresponds to 1000 volts on a piezoelectric actuator with 40 dB amplification. The aluminum samples are equipped with two strain gauges biaxially and besides both the transversal and longitudinal gauges are wired a diagonal full-bridge Wheatstone. In order to enhance the signal-to-noise ratio (SNR), longitudinal and transversal strains were averaged. In addition, a PT1000 (Resistance Temperature Detectors, RTD) temperature sensor is also used to measure the surrounding temperature. The standard aluminum sample was calibrated at low frequencies and utilized for high-frequency force measurements. Universal measuring amplifiers (HBM Genesis GEN2tb) were used to amplify and minimize the signals for strain, force, and temperature. By using MATLAB scripts, the AWG and the measurement amplifiers were controlled by computer. Next, the complex coefficients of the force and strain signals were calculated in the postprocessing stage by averaging the outcomes of a sliding-window fast Fourier transformation (FFT). The frequency-dependent complex young's modulus (E) is calculated using the extracted complex coefficients.

It was necessary to first choose an adequate preload and excitation amplitude from pretests, which are sometimes referred to as amplitude sweeps, in order to assess the frequency-dependent properties using frequency sweeps. Because this setup is a nondestructive test, the preload strain is chosen to be both strong enough to provide a suitable SNR and low enough to prevent (additional) damage. To attain an appropriate SNR and reduce the amplitude dependency at the same time, the optimal excitation amplitude is selected based on the outcomes of earlier amplitude sweeps; it means, the observed viscoelastic properties should be kept in the linear regime. Following that, the obtained effective material properties are assessed over the axial strain amplitude of the samples. For the properties' characterization test, samples with a length of 75 mm and 30 mm thickness are selected.

Afterwards, the complex signals are used to determine the Young's modulus and Poisson's ratio in a same method like to the static case. Figure 2 illustrates the sample's axial strain, axial stress and lateral strain signals as recorded in the time domain. It is obvious that the lateral strains are much smaller than the axial ones by one order of magnitude. However, the signal-to-noise ratio is still high enough to produce accurate data. The setup's inherent load cells should be calibrated before the force measurement. As a result, the setup includes two load cells that allow for redundant axial force measurement. The second load cell, which consists of a standard aluminum (Al) sample situated directly below the sample, is calibrated using the machine's load cell, which has a maximum force capacity of 50 kN, for frequencies up to 1 Hz. The Al standard sample is then utilized to measure high(er) frequency regarding this low frequency calibration. It is worth mentioning that the Al standard sample is positioned exactly beneath the sample in this instance in order to evaluate the axial stress. An illustration of the unprocessed axial strain, axial stress, and lateral strain signals collected at 0.1 Hz is shown in Fig. 2.

2.2 Description of the Dynamic Mechanical Testing

The DMA method is a non-destructive test in which the preload for the test is about 5 percent of the failure strength. But in the DMT method, which is a destructive method, the loading ranges from 40 to 85 percent of the failure strength. The DMT test method can be used to perform a fatigue test with applying some changes in the DMA test setup, but it should be noticed that the classic fatigue tests have a test speed between 0.1 Hz and 10 Hz. Using this method, it is possible to run tests with speeds range from 0.1 cycles per second to 1000 cycles per second. Therefore, it takes days to weeks to perform a fatigue test using the classic method, but with the help of the DMT method, a fatigue test with high accuracy can be performed just in few minutes. However, still there are limitations using this fatigue testing method, since the periodic loading is dependent on the voltage change in the actuator and the maximum displacement of the actuator used in this paper is 40 μm. Therefore, there is a limit in the sample size. Two types of samples have been used for fatigue testing by the high frequency stimulation method. Sandstone with a diameter of 11 mm and HPC with a diameter of a quarter inch were used. The voltage applied to the driver was equal to 950 volts.

3 Results and discussion

3.1 Determination of the material properties

Here, Fig. 3 shows the frequency-dependent Young's modulus that its Young's modulus magnitude grows linearly with frequency up to 250 Hz and above this frequency, the values increase more. The dispersion of the material may account for the rise in frequency over 250 Hz. Between 200 and 300 Hz, a resonance effect can be seen in HPC. Actually, it is the resonance of the setup and its effect is obvious.

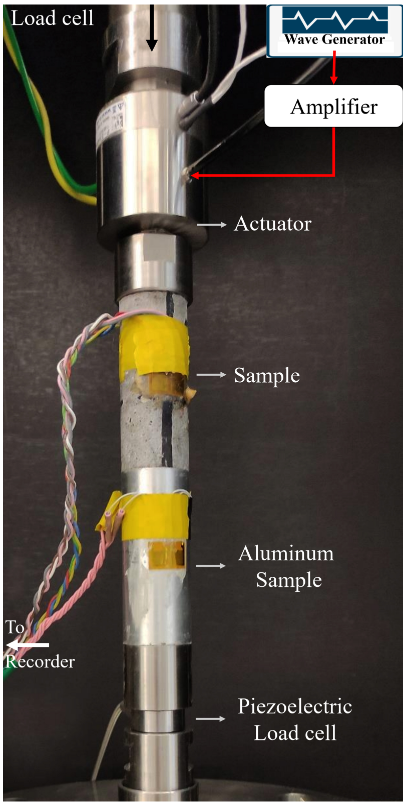


Fig. 1: The DMA setup.

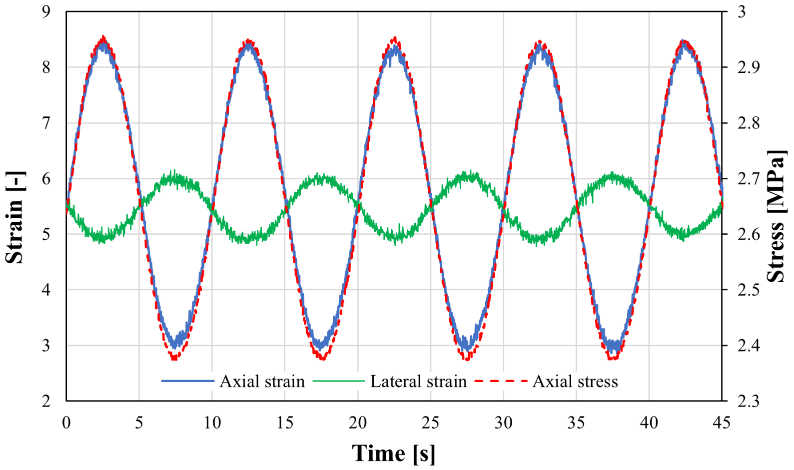


Fig. 2: A time-domain example of axial-lateral strain signals and axial stress.

In Figure 3, the results of Young's modulus based on frequency are reported for 3 materials, for HPC in two states, undamaged and damaged, and for the sandstone sample. As shown in Figure 3, the properties of the material in the undamaged state for the HPC are higher than the damaged model. In the undamaged sample after the failure caused by fatigue failure, the Young's modulus has dropped by about 10 percent. Also, the amount of Young's modulus under the effect of frequency for Sandstone, which is equal to 18 GPa in the static state, increases by about 20 percent by increasing the frequency up to 1000 Hz. Due to the homogeneity of the sandstone in comparison to HPC, the behavior of this material is more linear under frequency, but still the resonance effect is seen between 200 and 300 Hz.

3.2 Results of Fatigue test with DMT

In this section, the results of the fatigue test using the DMT method are given. At first, the DMT setup was evaluated using sandstone samples, and then HPC samples were tested.

Sandstone samples were selected for fatigue testing because the Young's modulus of sandstone was about half of HPC, however, the diameter of sandstone samples was twice of HPC samples. In addition, the sandstone samples are mechanically more homogeneous than HPC, since the HPC samples contain some imperfections like aggregates, bubbles, etc.

The fatigue test results of sandstone samples under different test frequencies from 20 cycles/s to 200 cycles/s are shown in Figure 4.As shown in this figure, the samples failed in the form of shear failure. The crack initiates from the central part of the upper edge of the sample and then continues to propagate transversely at an angle of 60 degrees, and next it grows longitudinally in the sample. Due to the homogenous nature of sandstone, the failure behavior of this material is similar in all samples.

In Figure 4, the results of sandstone samples under different loading frequencies are reported. The initial loading on the samples was equal to 70 percent of the failure strength, and the applied amplitude was about 30 percent of the failure strength.

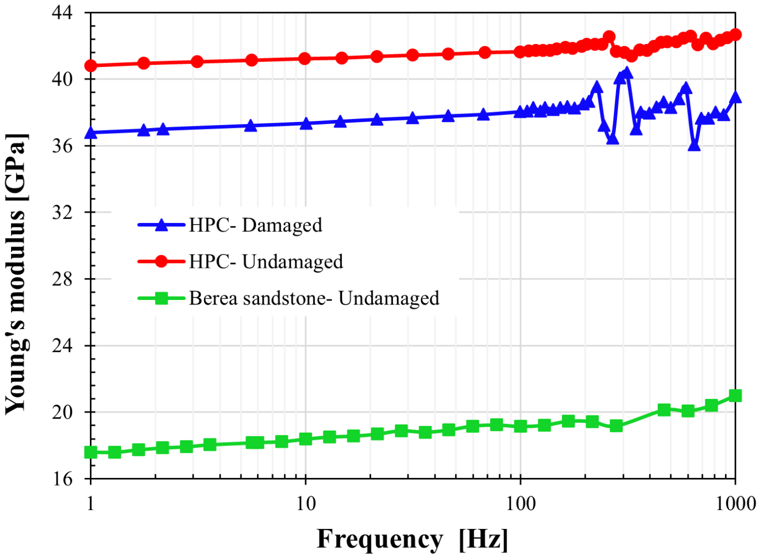


Fig. 3: Frequency-dependent young's modulus of HPC and berea sandstone

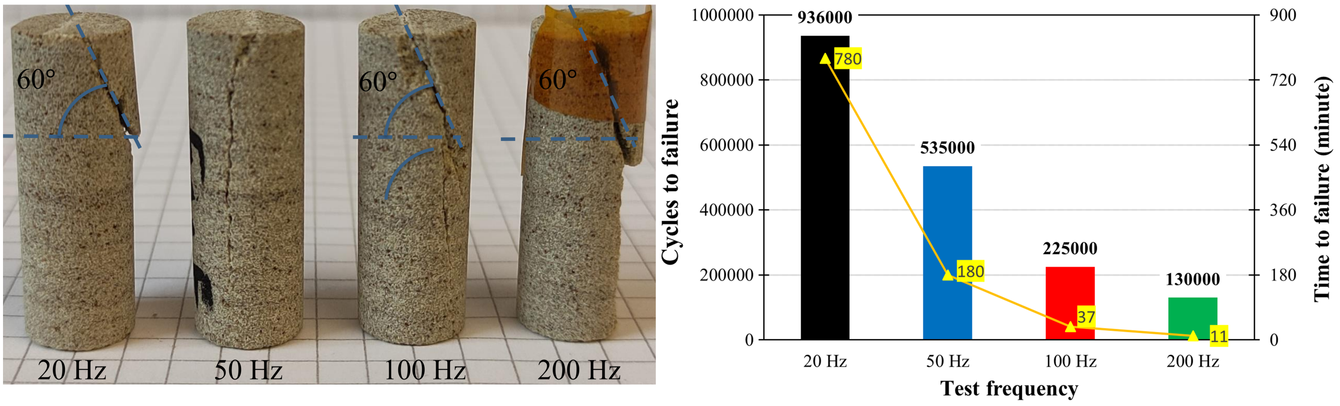
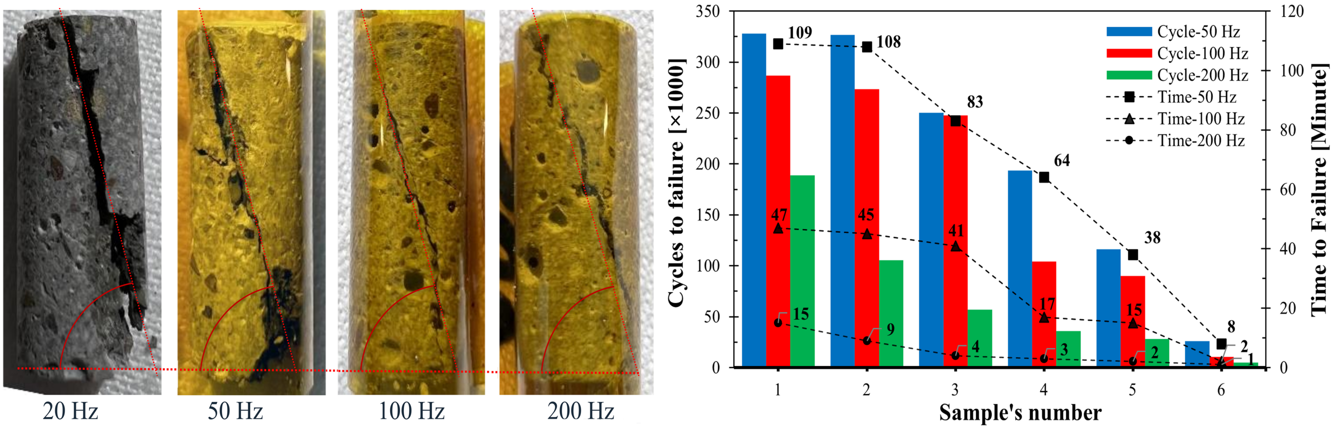


Fig. 4: Results of Berea sandstone samples under high frequency fatigue test

In other words, the maximum applied load was equal to 85 percent and the minimum applied load was 55 percent of the failure strength. It was observed that in the samples with a loading frequency of 20 cycles/second, the sample failed at around 1 million cycles and the overall the fatigue test took 780 minutes. For a loading frequency of 50 cycles/second, the sample failed after half a million cycles, which took about 3 hours. For a testing frequency of 100 cycles per second, the sample suffered fatigue after about 200 thousand cycles, which took only 37 minutes of testing time and finally, for loading at 200 cycles per second, the sample failed after about 130 thousand cycles, which took only 11 minutes of loading.
As shown in Figure 4, by increasing the loading frequency, the number of cycles to failure decreases linearly, but the test time is reduced exponentially, because on the one hand, with increasing the loading frequency, the number of cycles to failure decreases, and on the other hand, because the loading frequency is higher, it takes less time to reach that number of cycles for failure. For instance, it takes 83 minutes to reach 100 thousand cycles under a frequency of 20 cycles per second, but it takes only 8 minutes for the loading frequency of 200 cycles per second.

In Figure 5, the results of shear failure due to fatigue test in HPC samples under loading with frequencies ranging from 20 cycles/s to 200 cycles/s are reported. In these samples, the initial crack starts from the top side of the sample and propagates at an angle of 60 degrees. Because of the brittle nature of the samples, most of the fatigue test time is spent on creating the initial crack. Once the initial crack is created, the crack growth time until the complete failure of the sample is just few seconds.

In Figure 5, the results of HPC samples under different loading frequencies are reported. The initial loading on the samples was equal to 40 percent of the failure strength, and the applied amplitude was about 40 percent of the failure strength, in other words, the maximum applied load was equal to 60 percent and the minimum applied load was 20 percent of the failure strength. For each loading frequency 6 samples were tested and results in are arranged Figure 5 according to the number of cycles required for failure.
It was observed that the samples under the loading frequency of 50 cycles/second had the highest number of cycles to failure, which was about 325 thousand cycles. Up to the loading frequency of 200 cycles/second, which had the lowest number of cycles to failure and correspondingly the lowest number of cycles for the samples' failure was 10 thousand. These wide ranges are due to the nature of HPC, which is an Orthotropic material. Besides, each sample has a different tomography from another sample, since the size of the aggregates and the bubbles, as well as their location, are also different.
For the first series of samples, for a loading frequency of 50 cycles/second, the test time took about 2 hours. For loading frequency of 100 cycles/second, the test was completed in about 50 minutes, and for the loading frequency of 200 cycles/second, 15 minutes were needed to perform the test. As shown in Figure 5, the number of cycles to failure decreases with the increase in loading frequency, and consequently, due to this decrease in the number of cycles and also the increase in loading frequency, the time to failure decreases by a greater amount.
As shown in Figures 4 and 5, for a same type of material, the number of cycles to failure decreases with increasing loading frequency. This reduction in cycles is due to the fact that at low frequencies and after loading there is more time for unloading. For this reason, there is time for stress relaxation. Likewise, at a higher frequency, because the loading speed is also higher, the sample has less time for stress relaxation. This relaxation stress leaves a cumulative effect on the sample, which causes less remained stress on the sample in each cycle at low frequency, but the amount of stress increases as the frequency increases. The speed of stress accumulation is higher at higher frequencies, this issue results in sample failure fewer cycles at higher frequencies. On the other hand, with increasing frequency, it was observed that the temperature of the sample also increases during the test, which is another reason for reducing the loading frequency to postpone the failure and it is in a good agreement with the results of a previous research [17].



20 Hz 50 Hz 100 Hz 200 Hz

Fig. 5: Fatigue failure of HPC samples under different loading frequencies

3.3 Conclusions

Using DMA method, mechanical properties can be extracted under different mechanical, thermal and environmental conditions with very high accuracy. In addition, DMA is a non-destructive testing method that takes into account the behavior of viscoelastic materials under different loading frequencies and even under the effect of temperature it is able to accurately measure the behavior of these materials. With applying few changes in the DMA setup, its analytical setup can be changed into a test setup for fatigue testing with high loading frequencies.

Since the classical fatigue tests are limited in frequency and at the maximum can apply a load up to 10 cycles per second, the time cost of each test is high and may take several weeks. Using the DMT method, the test frequency can range from 0.1 cycles per second to 1000 cycles per second. On the one hand, fatigue testing can be done at high frequencies and on the other hand, the behavior of the materials under such loading frequencies can be investigated as well. In addition, the effect of temperature on the material can be measured.

Due to the use of piezoelectric actuators which are controlled based on voltage and the usage of accurate sensors, the accuracy of DMA fatigue tests is higher than classical fatigue tests and high-resolution stiffness reduction can be obtained too. The presented setup has the ability to be coupled with different types of sensors and recorders with high sample rates and can measure the sensitivity of various types of tests under environmental conditions such as temperature, humidity, etc. This research aims to measure the properties of materials before and after the failure. Furthermore, it shows the efficiency of DMA fatigue tests with high loading frequencies, which reduces the time of a fatigue test from weekly periods to few minutes.

Data availability statement The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Acknowledgements Financial support for this work was provided by the German Science Foundation (DFG) as a part of the project “Temperature and humidity induced damage processes in concrete due to pure compressive fatigue loading” of the DFG priority program SPP 2020 through grant number STE969-12/1. The support provided by this organization is acknowledged with gratitude. Open access funding enabled and organized by Projekt DEAL.

References

[1] Menna C, Mata-Falcón J, Bos FP, Vantyghem G, Ferrara L, Asprone D, et al. Opportunities and challenges for structural engineering of digitally fabricated concrete. Cem Concr Res 2020;133:106079. https://doi.org/10.1016/J.CEMCONRES.2020.106079.

[2] Vi F, Geowissenschaften BUA. Zum Ermüdungsverhalten von Beton 2004. https://doi.org/10.14279/DEPOSITONCE-815.

[3] Oneschkow N. Fatigue behaviour of high-strength concrete with respect to strain and stiffness. Int J Fatigue 2016;87:38–49. https://doi.org/10.1016/J.IJFATIGUE.2016.01.008.

[4] Viswanath S, LaFave JM, Kuchma DA. Concrete compressive strain behavior and magnitudes under uniaxial fatigue loading. Constr Build Mater 2021;296:123718. https://doi.org/10.1016/J.CONBUILDMAT.2021.123718.

[5] Xue J, Briseghella B, Huang F, Nuti C, Tabatabai H, Chen B. Review of ultra-high performance concrete and its application in bridge engineering. Constr Build Mater 2020;260:119844. https://doi.org/10.1016/J.CONBUILDMAT.2020.119844.

[6] Minh-Tan Do B, Chaallal mar, ARcin P-C. Fatigue Behavior of HighPerformance Concrete. J Mater Civ Eng 1993;5:96–111. https://doi.org/10.1061/(ASCE)0899-1561(1993)5:1(96).

[7] [1] Oneschkow N, Lohaus L. Zum Ermüdungsnachweis von druckschwellbeanspruchtem Beton. Beton- Und Stahlbetonbau 2017;112:530–40. https://doi.org/10.1002/BEST.201700024.

[8] Oneschkow N, Lohaus L. Zum Ermüdungsnachweis von druckschwellbeanspruchtem Beton: Teil 2: Sicherheitsüberlegungen und Potenzial für Weiterentwicklungen.

[9] Kono, S.; Hasegawa, H.; Mori, K.; Ichioka, Y.; Sakashita, M.; Watanabe F. S2-8-5 Low Cycle Fatigue Characteristics. 8th Int Symp Util High-Strength High-Performance Concrete 2008:616–21.

[10] Deutscher M, Tran NL, Scheerer S. Experimental Investigations on the Temperature Increase of Ultra-High Performance Concrete under Fatigue Loading. Appl Sci 2019, Vol 9, Page 4087 2019;9:4087. https://doi.org/10.3390/APP9194087.

[11] Hümme J, von der Haar C, Lohaus L, Marx S. Fatigue behaviour of a normal-strength concrete – number of cycles to failure and strain development. Struct Concr 2016;17:637–45. https://doi.org/10.1002/SUCO.201500139.

[12] Oneschkow N, Hümme J, Lohaus L. Compressive fatigue behaviour of high-strength concrete in a dry and wet environment. Constr Build Mater 2020;262. https://doi.org/10.1016/J.CONBUILDMAT.2020.119700.

[13] Ali MA, Oneschkow N, Lohaus L, Haist M. Influence of loading frequency on the compressive fatigue behaviour of high-strength concrete with different moisture contents. Curr Perspect New Dir Mech Model Des Struct Syst 2022:465–6. https://doi.org/10.1201/9781003348450-219.

[14] Batzle ML, Han DH, Hofmann R. Fluid mobility and frequency-dependent seismic velocity — Direct measurements. Http://DxDoiOrg/101190/12159053 2006;71. https://doi.org/10.1190/1.2159053.

[15] Pimienta L, Fortin J, Guéguen Y. Experimental study of Young’s modulus dispersion and attenuation in fully saturated sandstones. Http://DxDoiOrg/101190/Geo2014-05321 2015;80:L57–72. https://doi.org/10.1190/GEO2014-0532.1.

[16] Markert M, Katzmann J, Birtel V, Garrecht H, Steeb H. Investigation of the Influence of Moisture Content on Fatigue Behaviour of HPC by Using DMA and XRCT. Mater (Basel, Switzerland) 2021;15. https://doi.org/10.3390/MA15010091.

[17] Ali MA, Oneschkow N, Lohaus L, Haist M. Influence of loading frequency on the compressive fatigue behaviour of high-strength concrete with different moisture contents. Curr Perspect New Dir Mech Model Des Struct Syst 2022:465–6. https://doi.org/10.1201/9781003348450-219.