ESTIMATION OF STATIC COMPRESSIVE STRENGTH AND NUMBER OF CYCLES TO FAILURE OF HIGH-PERFORMANCE CONCRETE (HPC) WITH RECYCLED (RC)-AGGREGATES USING RESONANCE ANALYSIS

ABSCHÄTZUNG DER STATISCHEN DRUCKFESTIGKEIT UND BRUCHLASTWECHSELZAHLEN VON HOCHFESTEM BETON (HPC) MIT RECYCLING (RC)-GESTEINSKÖRNUNG MIT DER RESONANZANALYSE

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SUMMARY

Resonance analysis is a non-destructive testing method that can be used, as an example, to analyse internal concrete structures. The purpose of this study was to determine if the resonance frequency and velocity of sound could be used to predict fatigue strength and static compressive strength. A concrete containing basalt was used as the reference concrete, while for the three recycled concretes that were tested, the basalt was replaced by aggregates consisting of brick chippings, concrete rubble or a mixture of concrete rubble and building rubble. The concretes with recycled aggregates showed a static compressive strength that was approximately 30 MPa lower than the static compressive strength of the reference concrete, although the compressive strengths of the recycled concretes were comparable. The fatigue tests were all performed load controlled at a frequency of 10 Hz. It was observed that the specimens with higher resonance frequencies and sound velocities measured in the resonance analysis also showed higher static compressive and fatigue strengths. However, the results must be analysed separately for each concrete composition. The recycled concretes generally showed lower resonance frequencies and sound velocities than the reference concrete, with the brick chippings concrete showing the lowest values.

ZUSAMMENFASSUNG

Die Resonanzanalyse ist eine zerstörungsfreie Prüfmethode die beispielsweise zur Analyse von inneren Betonstrukturen verwendet werden kann. In diesen Untersuchungen wurde geprüft, ob auf Grundlage der Resonanzfrequenz und der Schallgeschwindigkeit Rückschlüsse auf die Ermüdungsfestigkeit und die statische Druckfestigkeit geschlossen werden können. Als Referenzbeton diente ein Beton mit Basalt, während für die drei untersuchten Recyclingbetone der Basalt mit einer Gesteinskörnung aus Ziegelsplitt, Betonbruch oder eine Mischung aus Betonbruch und Bauschutt ersetzt wurde. Die Betone mit rezyklierter Gesteinskörnung zeigten eine um circa 30 MPa geringere statische Druckfestigkeit als der Referenzbeton, wobei die Druckfestigkeiten der Recyclingbetone vergleichbar waren. Die Ermüdungsversuche wurden alle kraftgeregelt mit einer Frequenz von 10 Hz durchgeführt. Es konnte festgestellt werden, dass die Prüfkörper bei denen höhere Resonanzfrequenzen und Schallgeschwindigkeiten in der Resonanzprüfung gemessen wurden, auch höhere statische Druckfestigkeiten und Ermüdungsfestigkeiten zeigten. Die Ergebnisse müssen jedoch für jede Betonzusammensetzung getrennt betrachtet werden. Die Recyclingbetone wiesen dabei grundsätzlich geringere Resonanzfrequenzen und Schallgeschwindigkeiten auf, wobei der Beton mit Ziegelsplitt die niedrigsten Werte hatte.

1. INDRODUCTION

The fatigue strength of high-performance concretes (HPC) is a determining factor for the durability and reliability of structures exposed to high cyclic loads. The increasing environmental impact of the construction industry, particularly through the emission of greenhouse gases in the form of CO_2, requires a rethink of existing construction methods and building material compositions. High CO_2 emissions are mainly caused by the energy-intensive production of cement and concrete steel. In addition, due to the high consumption of resources, the construction sector produces a lot of waste that needs to be returned to the material cycle.

The use of recycled materials as an environmentally friendly alternative to natural aggregates in high-performance concretes is now increasingly coming into focus. Concrete with recycled aggregates offers the possibility of avoiding waste and conserving resources, but affects the mechanical properties and durability of the concrete, including its fatigue behaviour. As the aggregate is the main component of the concrete, the substitute has a major influence on the strength. In this series of tests, resonance testing is used to investigate whether a prediction can be made regarding the static compressive strength and fatigue resistance based on the measured resonance frequency and sound velocity in the resonance analysis. These tests are based on the fatigue tests carried out by [1] and the creep tests by [2]

2. COMPOSITION AND MATERIAL

2.1 Material und Geometry

Four different concretes were analysed for the fatigue tests and the resonance analysis. The HPC from the Priority Programme 2020 (SPP2020) was used as the reference concrete [3]. For the other three concretes, the basalt was replaced with different recycled aggregates (see Table 1). For the substitution, only the mass of the basalt (920 kg/m³) was replaced by the respective recycled aggregate with a grain size of 2/8 and no volume calculation was made. The compositions can be found in Table 2.

Table 1: Concrete compositions

CONCRETE	COMPOSITION
Ref. 100 Ba	100 % Basalt
100 BC	100 % Brick chippings
100 CR	100 % Concrete rubble
70 CR 30 BR	70 % Concrete rubble; 30 % Building rubble

Table 2: Composition of Ref 100 Ba

COMPONENT [-]	REF 100 BA	
	Density [kg/dm³]	Amount [kg/m³]
CEM I 52,5 R-SR3 (na)	3.094	500
Quartz Sand H33 (0/0.5 mm)	2.70	75
Sand 0/2	2.64	850
Basalt 2/5	3.06	350
Basalt 5/8	3.06	570
Superplasticizer	1.05	4.25
Stabilizer	1.10	2.42
Water	1.00	176

The three recycled aggregates are shown in Table 1 and the structures of the four different compositions are represented in Fig. 1. The aggregate of concrete

100 BC consists of pure brick chippings from roof tiles. The aggregate of the concrete 100 CR consists of pure concrete rubble and the third aggregate 70 CR 30 BR consists of 70 % concrete rubble and 30 % building rubble. This ratio was selected in accordance with DIN 4226-101 [4]. All samples were stored at 20°C and 65 % relative humidity until testing, after being stored in the formework for one day and then under water for 7 days. The cylinders were cut to the appropriate length and the tops were ground plane-parallel for the static and dynamic tests.

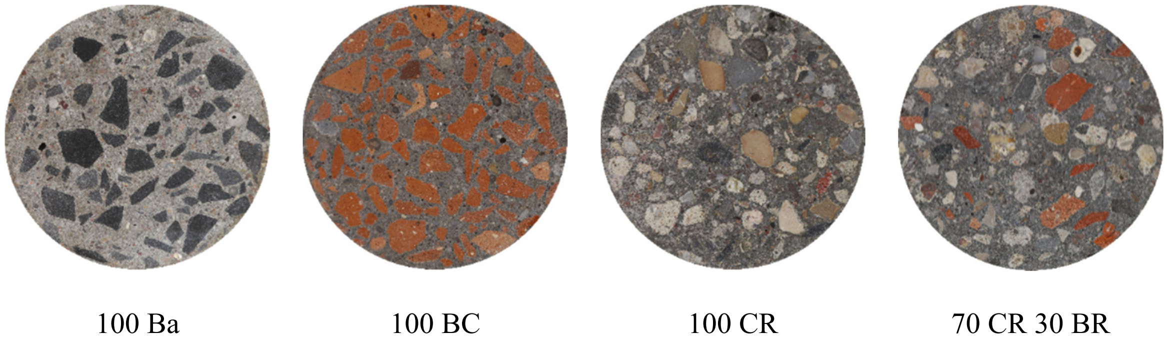
100 Ba 100 BC 100 CR 70 CR 30 BR

Fig. 1: Concrete structures

3. TEST SETUP AND EXPERIMENTAL PROGRAMM

3.1 Test Setup

3.1.1 Static testing

The static compressive strengths were determined in a compression testing machine from Toni Technik Baustoffprüfsysteme GmbH with a load limit of 5000 kN. The samples were tested at a load velocity of 0.6 MPa/s. The results of the static compressive strength are shown in Table 4 and Fig. 2 in Chapter 3.3.1.

3.1.2 Fatigue testing

All fatigue tests were carried out using a 4-column testing frame from FORM+TEST Seidner & Co. GmbH. The test frame was instrumented with a servo-hydraulic cylinder from Schenk with a maximum force of 630 kN. All tests were carried out at a test frequency of 10 Hz. The test setup with the servo-hydraulic cylinder is similar to the test setup in [5]. The test specimens were wrapped in a vapour-tight aluminium composite foil from ProfiTherm for the entire duration of the test, so that water loss during the test was more or less eliminated.

3.2 Experimental programme

All tests were carried out with a sinusoidal loading. The lower stress was defined as $S_u = \sigma_u/f_{c,cyl} = 0.05$ and the upper stress $S_o = \sigma_o/f_{c,cyl}$ was varied ($S_o = 0.70/0.75/0.80$). Table 3 shows an overview of the test programme and the number of samples in each case

Table 3: Overview of the test programme and the number of samples

	100 BA	**100 BC**	**100 CR**	**70 CR 30 BR**
Static compressive strength	3	3	3	3
$S_o = 0.70$; $S_u = 0.05$; $f_p = 10$ Hz	2	2	2	2
$S_o = 0.75$; $S_u = 0.05$; $f_p = 10$ Hz	2	2	3	2
$S_o = 0.80$; $S_u = 0.05$; $f_p = 10$ Hz	2	2	2	2

3.3 Results

3.3.1 Static compressive strength

The results of the static tests are shown in Fig. 2. The average values $f_{c,cyl}$ from three cylindrical samples are shown in Table 4.

Table 4: Compressive strengths of the different concrete compositions

CONCRETE VARIATION	**100 BA**	**100 BC**	**100 CR**	**70 CR 30 BR**
Static compressive strength fc,cyl [MPa]	94.8	66.8	68.0	71.2
Standard deviation [MPa]	3.55	1.04	3.29	2.31

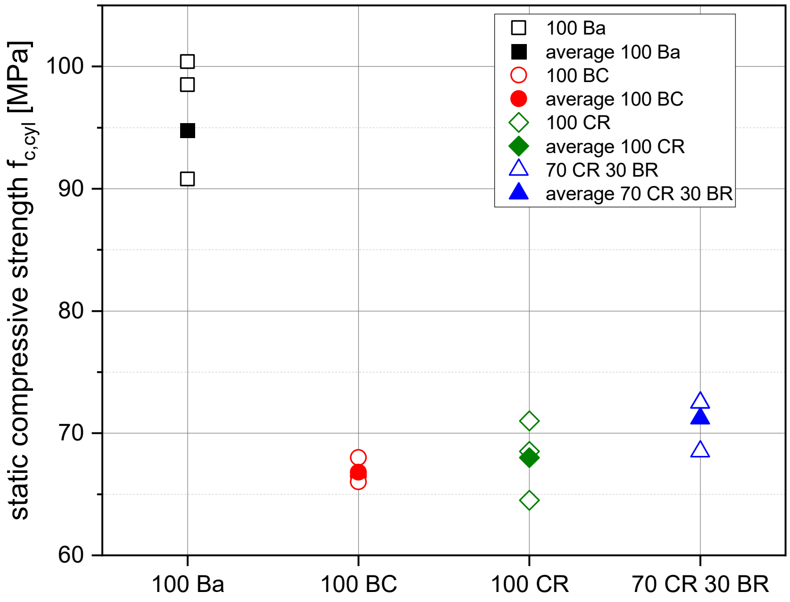

Fig. 2: Static compressive strength of the different concretes

It can be clearly seen that the static compressive strength of the reference concrete (100 Ba) with 94.8 MPa is significantly higher than the strengths of the concretes with recycled aggregates. The concretes with recycled aggregates achieve comparable compressive strengths which are around 30 MPa below the static compressive strength of the reference concrete 100 Ba. The static compressive strength of the 100 BC concrete was the lowest with 66.8 MPa. When analysing the standard deviation, no correlation with the recycled material can be determined.

3.3.2 Fatigue testing

In order to gain a first overview of the behaviour of the concretes with recycled aggregates, two tests (three tests for 100 CR, $S_o = 0.75$) were carried out at each stress level. The results of the fatigue tests are shown in Fig. 3 and Fig. 4. These results have already been analysed in detail in [1]. All tests were performed with a lower stress level of $S_u = 0.05$. Fig. 3 shows the number of cycles to failure of the different concretes at different upper stress levels. It is clearly recognisable that the scatter of the individual values of the different concrete compositions is lower at a low upper stress level ($S_o = 0.70$) than at the higher stress levels ($S_o = 0.75$; $S_o = 0.80$). It can also be observed that the values of the concrete with 100 % concrete rubble (green; diamond) show the greatest scatter, while the values of the concrete with brick chippings (red; circle) are closer together and therefore show less scatter. The concrete with 70 % concrete rubble and 30 % building rubble (blue; triangle) shows the highest number of cycles to failure at an upper stress level of $S_o = 0.70$ and $S_o = 0.80$.

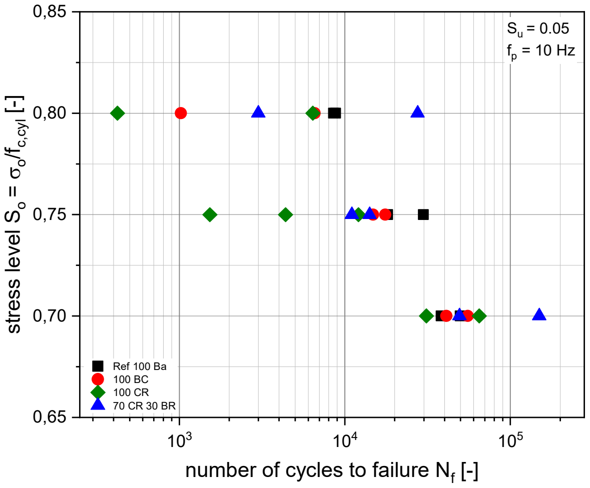

Fig. 3: Number of cycles to failure depending on the stress level

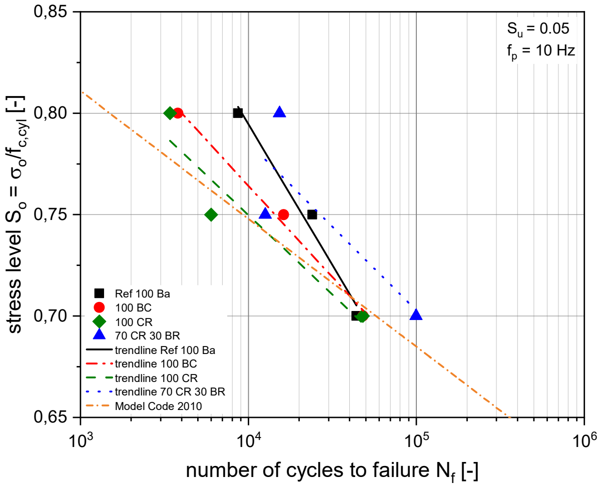

Fig. 4: Average values of the number of cycles to failure and the corresponding trendlines

Fig. 4 shows the mean values of the number of cycles to failure of all tests carried out with their respective trend lines. The trend lines were calculated with a linear regression function $f = m \times \log(N) + b$ in order to be able to represent the fatigue behaviour. The parallel courses of the three trend lines of the concretes with recycled aggregates can be recognised, whereby the concrete with 100 CR has the lowest number of cycles to failure at the same stress level. The reference concrete (100 Ba) shows lower values at an upper stress level of $S_o = 0.70$, so that the trend line does not run parallel to the three concretes with RC aggregates. The values of the Model Code 2010 are also shown in orange. With the exception of the values of the concrete with 100 % concrete rubble at the upper stress levels of 0.75 and 0.70 and the values of the reference concrete and the concrete with brick chippings at an upper stress level of 0.70, all other values lie to the right of the line of the Model Code 2010, which means that they are underestimated by the Model Code 2010.

3.3.3 Density

In addition to analysing the static compressive strength of the concretes and the number of cycles to failure at different stress levels, tendencies can be identified from the density values of the individual test specimens. The density is determined from the dimensions and mass of the test specimens before the test. In both the static tests and the dynamic tests, a correlation can be recognised between the density and the breaking load or the number of cycles to failure. The results are shown in Fig. 5 and Fig. 6.

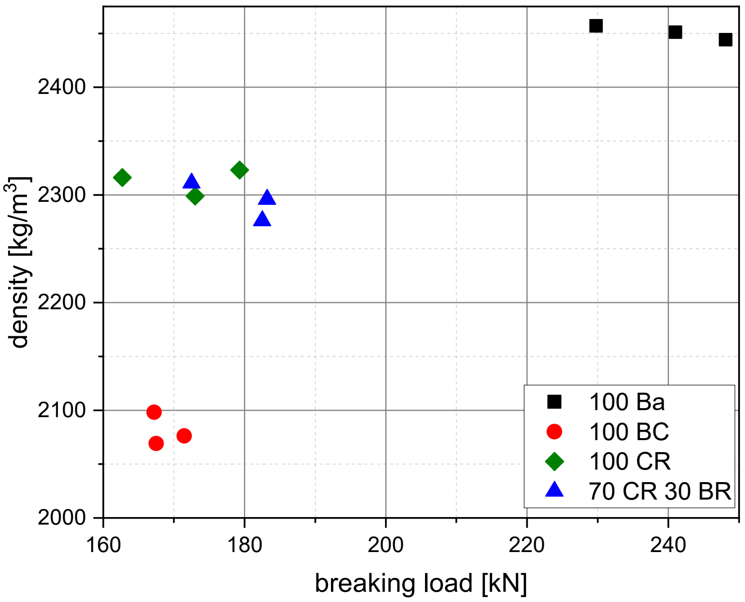

Fig. 5: Density of the different concretes with their breaking load

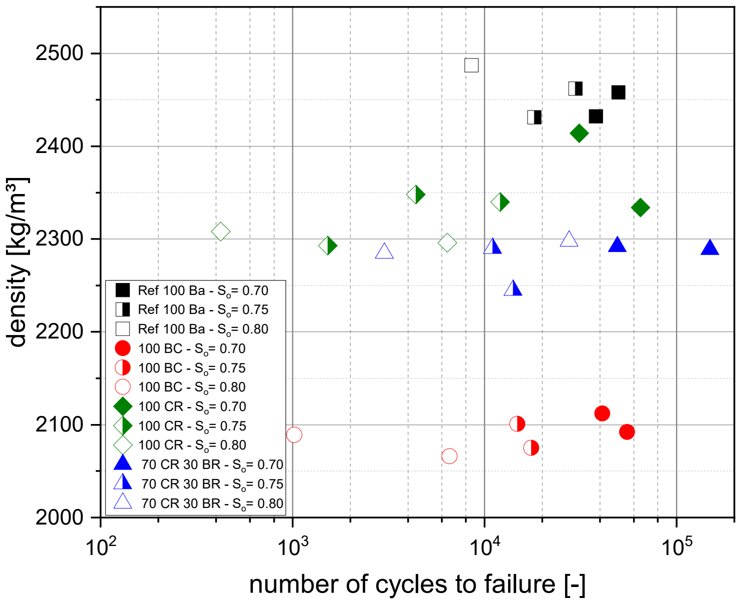

Fig. 6: Density of the different concretes with the corresponding number of cycles to failure

It can be seen that the values of the different concretes are either clustered closely together or lie on a line. The results of the static compressive strength in Fig. 5 show that there is a correlation between the density and the static compressive strength, as a higher density is very often linked to a higher static compressive strength. A similar effect can be seen in the fatigue tests in Fig. 6, where two samples were analysed for each concrete and stress level. In the case of concrete 100 BC, a lower density at the same related upper stress level results in higher number of cycles to failure. Concrete 100 CR shows a similar behaviour. Concrete

70 CR 30 BR tends to achieve higher number of cycles to failure with a higher density. This is the same for concrete 100 Ba across all upper stress levels. The results in Fig. 5 and Fig. 6 show a correlation between density and static compressive strength or number of cycles to failure. However, this possible correlation appears to be very sensitive to the concreting circumstances of the test specimens. Possible air inclusions influence the density very easily. Further correlations therefore need to be identified and further data collected.

4. RESONANCE TESTING

4.1 Resonance testing principle

Resonance testing is a non-destructive testing method for analysing the internal structures of various test specimens. This analysis is carried out by analysing the frequency. Each test specimen is stimulated by a mechanical impulse caused by the fall of a steel ball. The setup used for this is illustrated in Fig. 7 (Chapter 4.2) The generated sound is called structure-borne sound and is a mechanical vibration that expands as a wave in an elastic medium. In solids, sound expands in the form of transverse as well as longitudinal waves. In concrete test specimens, the velocity of sound depends on the modulus of elasticity, density and temperature (see Formula 1, Chapter 4.3). This sound is then recorded without direct connection using a microphone and evaluated after being digitised. The frequency determination is more accurate than 0.1 % [6]. In addition, the frequencies are more accurate than ultrasonic transit time measurements, as the results are averaged over the entire sample volume [6]. Samples that are protected against moisture loss by foil can also be measured without any problems.

4.2 Test Setup Resonance testing

The set-up used (RA100 Concrete measuring instrument from Lang Sensorik) is shown in Fig. 7. Concrete specimens whose dimensions are not less than 100 mm and whose shape corresponds to a cube, prism or cylinder are particularly suitable for measurement in this set-up. The specimens to be analysed can either be placed on adjustable rubber feet as a specimen support or held by a centre support. The specimens should not exceed a maximum weight of 100 kg.

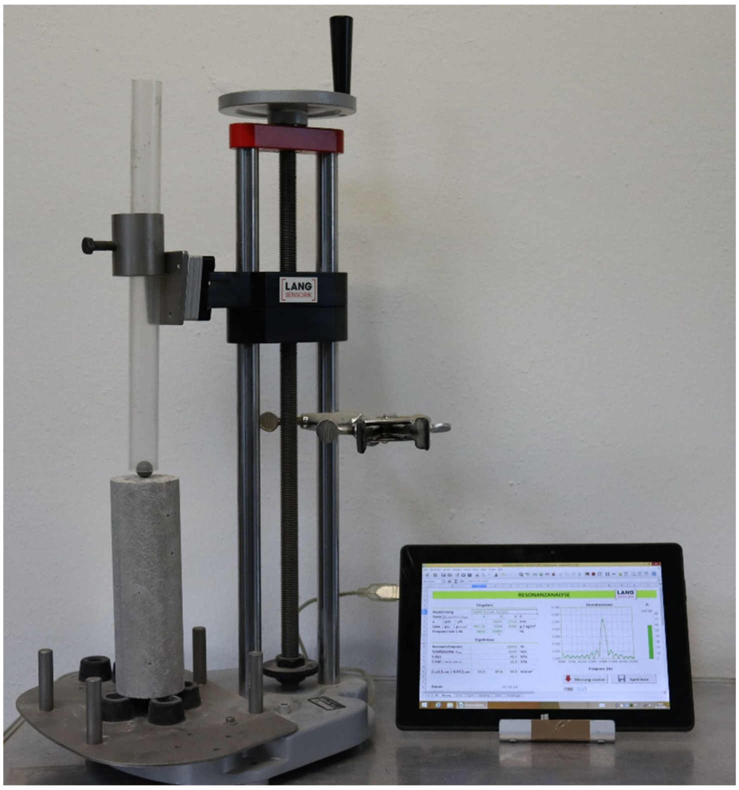

Fig. 7: Test-setup for resonance analysis (RA100 Concrete from Lang Sensorik)

4.3 Results Resonance testing

Firstly, the results from the resonance test of the static tests will be analysed. In the following two figures (Fig. 8 and Fig. 9), the breaking load is compared with the resonance frequency (Fig. 8) and the sound velocity (Fig. 9).

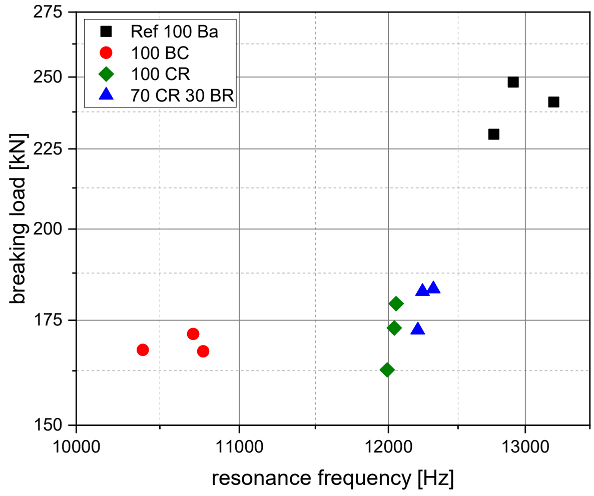

Fig. 8: Resonance frequencies of the different concretes with the corresponding breaking loads

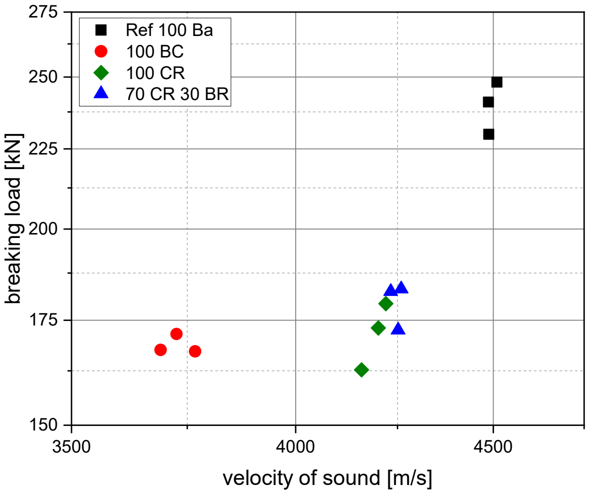

Fig. 9: Sound velocities of the different concretes with the corresponding breaking loads

When looking at the two diagrams, a similar picture can be recognised. It can be seen that the values of the different concretes are quite close to each other and do not show a large scatter. As the concretes are made of different aggregates, they have different densities and moduli of elasticity, which results in different sound velocities according to formula (1).

$$c = \sqrt{\frac{E}{\rho}}\ \text{[m/s]}\ \ with\, E = Modulus\ of\ elasticity;\ \rho = Density \tag{1}$$

The results in Fig. 8 and Fig. 9 show a strong tendency for the velocity of sound and resonance frequency to increase with increasing breaking load, regardless of the concrete composition. The reference concrete with basalt also shows significantly higher resonance frequencies and sound velocities at significantly higher breaking loads. The values for the concrete with 100 % concrete rubble and those for the concrete with 70 % concrete rubble and 30 % building rubble are comparatively close to each other, as the mix design is identical except for the 30 % building rubble. The values for the breaking load of the brick chippings are only slightly lower than the values for the other concretes with recycled aggregate, but the resonance frequencies and sound velocities are significantly lower. It can be concluded from this that further statements can only be made within one type of concrete.

Fig. 10 and Fig. 11 compare the resonance frequencies and sound velocities of the respective concretes with the corresponding number of cycles to failure. It should be noted that three stress levels were investigated for each concrete, see Chapter 3.2.2. Only the values that were investigated with the resonance analysis before the fatigue loading are presented.

The results in Fig. 10 and Fig. 11 show different sound velocities and resonance frequencies depending on the concrete composition. It can be seen that strong tendencies appear within the respective concrete compositions and stress levels. These tendencies show increasing resonance frequencies and sound velocities with increasing numbers of cycles to failure. The values of the reference concrete are once again higher than the values of the concretes with the recycled aggregates. However, the difference is no longer as significant as in the static tests. The values for the concrete with brick chippings are again the lowest, although the values for the other concrete compositions are closer together. Fig. 11 shows values that are closer together than those in Fig. 10.

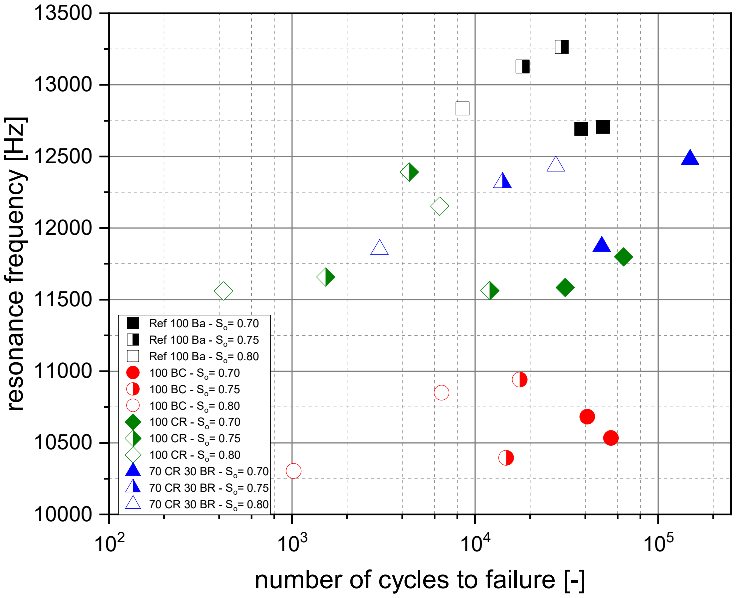

Fig. 10: Resonance frequencies of the different concretes with the corresponding number of cycles to failure

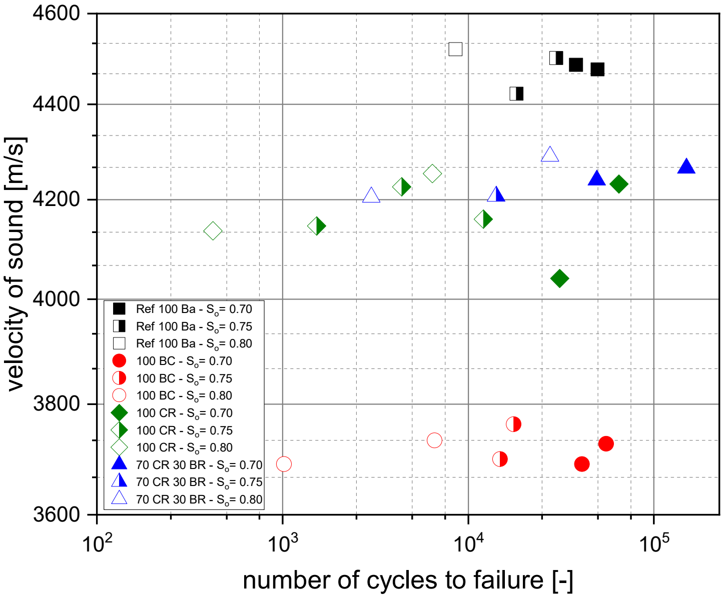

Fig. 11: Sound velocities of the different concretes with the corresponding number of cycles to failure

5. CONCLUSION AND OUTLOOK

The results shown here demonstrate that the velocity of sound and the resonance frequency measured in the resonance analysis as well as the density of the specimens are possible indicators for predicting the static compressive strength and the number of cycles to failure in a fatigue test. The differences in the concrete composition are clearly reflected in the results. Therefore, the test method must be used for each concrete composition. With increasing density, sound velocity or resonance frequency, the compressive strength or the number of cycles to failure increases. The velocity of sound and the resonance frequency show a clearer tendency than the density of the concrete test specimens. The extent to which predictive reliability can be ensured at different stress levels must be investigated in further fatigue tests. A possible further damage indicator such as the gradient of the strain in damage phase 2 [7] could, in combination with the method used here, give a prediction of the number of cycles to failure. In order to support this thesis, further data is to be gained in a large concrete testing in order to further investigate the prediction of the resonance analysis. For example, a test technique could be developed on the basis of previously obtained data, which could be used to predict the number of cycles to failure of individual test specimens. Furthermore, different test specimen geometries and sizes are to be investigated in order to be able to make a general statement.

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