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Can microsilica improve concrete in terms of fatigue behavior?

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ABSTRACT: Cement-based composites display several attractive characteristics for application in civil structures like bridges, concrete pavements, cooling and wind tower buildings and also for strengthening existing structures. This paper introduces values of the basic mechanical parameters of concrete for prestressed elements prepared as new potential material for bridge elements developed by ZPSV, a.s. a company producing bridge structures. The concrete mixtures have the same composition and the main differential lies in using microsilica admixture. To this aim specimens were prepared and tested under static (compressive strength and modulus of elasticity) and cyclic loading (fatigue parameters Wöhler curve). The experimentally obtained results (both mechanical and fatigue) of both concretes for prestressed elements are compared and the suitability of these types of composites for its application is discussed.

1 INTRODUCTION

Concretes – especially prestressed ones – with increasingly higher and higher strengths are used for construction – especially presteressed – at the present time. This is the consequence of the application of new chemical admixtures, especially superplasticizers, which allow reaching a very low water to cement ratio. Due to the higher strength, some new problems arise. One of these problems is the value of the modulus of elasticity of concretes with a very low water to cement ratio.

The Czech Code (CSN 73 6207) recommends very high values of the modulus of elasticity for the concrete for prestressed structures (bridges, sleepers, etc.). These values are not easy to reach. They were probably derived from the relationships between the compressive strength and the modulus of elasticity. But these relationships (see e.g. Aitcin 1998, Collepardi 2006) do not work for high strength concrete. To enhance the modulus, some other ways were considered – like the application of microsilica or metakaoline. From this point of view, fatigue properties are interesting too. The limited knowledge about the long-term behavior or the effects of repeated loading on the properties of these materials has caused a growing interest in the fatigue performance of concrete. Additionally, reliable data are needed for the calibration of accurate models capable of predicting the fatigue behavior of silicate-based composites.

During the past three decades, a number of works pertaining to experimental and analytical methods of evaluating the strength characteristics of concrete have been published under varied specimen types, curing time, testing methods, etc. (Lee & Barr 2004).

Fatigue failure occurs when a concrete structure fails at less than design load after being exposed to a large number of stress cycles. Fatigue may be defined as a process of progressive and permanent internal damage in a material subjected to repeated loading. Fatigue loading is usually divided into three categories: low-cycle and high-cycle loading and super-high-cycle fatigue (Lee & Barr 2004).

In general, parameters such as loading conditions, load frequency, boundary conditions, stress level (stress ratio), number of cycles, matrix composition, environmental conditions and mechanical properties will influence the fatigue performance of concrete (Kim & Kim 1996, Lee & Barr 2004).

Kleiber and Lee (Kleiber & Lee 1982) reported that the flexural fatigue behaviour of plain concrete was somewhat affected by the water to cement ratio of concrete, and the fatigue strength was decreased for a low water to cement ratio. Oh (Oh 1991) demonstrated that the probabilistic distribution of fatigue life of concrete depends on the level of applied stress. Most researchers have found that the inclusion of fibers can benefit the fatigue performance of concrete (Lee & Barr 2004, Seitl et al. 2009a). For flexural fatigue tests, it appears that only a marginal benefit comes from fiber addition, because the additional flaws introduced by fiber outweigh the benefits (Lee & Barr 2004).

In recent years, more attention has been paid by researchers to the fatigue behaviour of concrete for prestressed elements. On the one hand, a heavy traffic flow and heavy vehicles make the prestressed element to increased magnitude and cycles of fatigue stresses. On the other hand, new types of materials such as concrete containing mikrosilica are expected to improve the fatigue performance, but little is known of their long-term performance.

The paper continues and develops the previous study of the co-authors (Seitl et al 2008, Seitl et al. 2009a, Seitl et al. 2010).

The aim of the paper is to present selected fatigue and mechanical parameters of normal concrete and concrete with microsilica content – concrete prepared as a new potential material for a bridge element developed by ZPSV, a.s. The experimental measurements were made at two levels. The first one was a static measurement and its results are represented by values of compressive strength and the modulus of elasticity of the materials. The second level is connected with high-cycle fatigue – Wöhler curves of both study concretes were determined. The obtained experimental results are compared with literature data.

2 EXPERIMENTAL BACKGROUND

The experimental test program was carried out at the Laboratory of Civil Engineering Faculty of Brno University of Technology in the Czech Republic and the ZPSV, a.s. laboratory. Both static and fatigue tests were carried out in laboratories where temperature and relative humidity values did not undergo significant fluctuations. The controlled values for temperature and relative humidity were 22±2 °C and 50%, respectively.

2.1 *Prestressed concrete and specimen preparation*

The tested specimens were prepared from mixtures whose composition is presented in Table 1. The mixtures were marked here with respect to the day of their production 200109 and 010409.

Trial batching was mixed in the laboratory mixer in the volume of 35 litres. Cubes 150 mm and beams 100×100×400 mm were made from the concrete for the testing of compressive strength, the modulus of elasticity and the fatigue properties.

The fatigue experimental data are carried out from the three-point bending (3PB) tests. Figure 1 shows the geometry of the 3PB specimens; their dimensions were L=400, S=300, W=100 and the thickness

Table 1. Composition of mixtures (kg/m^3).

	200109	010409
Cement CEM I 42.5 R	455	420
Microsilica	0	35
PC superplasticizer	150	150
Water	7.5	7.5
Sand 4/8 mm	625	625
Crushed aggregates 4/8 and 8/16	1220	1220

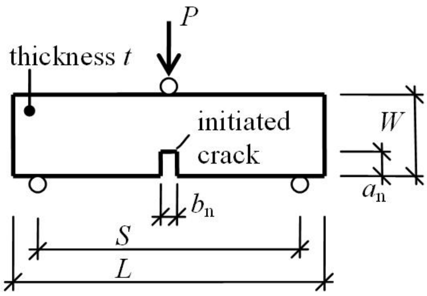

Figure 1. Schematic of three-point bend (3PB) specimen geometry.

=100 mm. The initial notch was made by a diamond saw that fabricated the 2–2.5 mm wide notches with controlled notch profiles and orientation.

Note that the numerical study of the influence of the shape of a saw-cut notch on the experimental results is shown in (Seitl et al 2008b). In this study 3PB specimens with notch to width a_n/W ratios of about 0.10 were produced for subsequent fatigue crack growth testing.

2.2 *Equipment*

Tests of compressive strength and the modulus of elasticity of both concretes were carried out in the experimental laboratory of ZPSV, a.s. in accordance to *EN ISO 4012 and ISO 6784 (FORM+TESTS Prufsysteme, Alpha 3-3000).*

The fatigue crack growth experiments (Wöhler curves) were carried out in a computer-controlled servo hydraulic testing machine (INOVA–U2).

Fatigue testing was conducted under load control. The stress ratio $R=P_{max}/P_{min}$=0.1, where P_{max} and P_{min} refer to the maximum and minimum load of a sinusoidal wave in each cycle, was selected to avoid shifting the beams with cycling while generating stresses that could be considered representative of dead loads in beams. The load frequency used for all repeated-load tests was approximately 10 Hz. The fatigue failure numbers of specimens are recorded.

Along with data points, the analytical expressions for the S-N curves in the following form were obtained by using the power function

$$\sigma_f = aN^b \qquad (1)$$

where σ_f is the stress amplitude, N is the number of cycles and a, b are the material parameters. The parameter a reflects the height of the S-N curve. The parameter b reflects the steep degree of fatigue curve.

As the second possibilities S-N curves may be represented by a straight line in a normalized and logarithmic scale by using linear regression

$$S_n = k\log N + l \quad (2)$$

where S_n is the dimensionless stress amplitude ($S_n=\sigma_f/\sigma_{st}$ – by relating the fracture stress to static stress), N is the number of cycles and k, l are the material parameters.

Both types of fatigue equations are used to analyze the fatigue performance of concrete in this study.

3 RESULTS

3.1 *Static results*

As a first step the experimental measurement of compressive strength and the static modulus of elasticity was done. The results obtained from the measurement are shown in Table 2. The measurement was done according the *EN ISO 4012 and ISO 6784* after 28 days. It is evident that the mixture 010409 has better mechanical parameters than the mixture 200109. The increase is significant for the static modulus of elasticity and its value is about 6%.

Table 2. Properties of hardened concrete at the age 28 days.

	200109	010409
Compressive strength [MPa]	92.7	94.4
Static modulus of elasticity E_s[GPa]	36.0	38.3

Note that the mixtures were designed for concrete C 60/75 (EN 206) for the production of prestressed elements – bridge beams. CSN 73 6207 requires the value of 43.5 GPa for this class of concrete

3.2 *Fatigue parameters*

The results of the fatigue tests for study materials are presented in Figures. 2 and 5. The tested materials are loaded in the range of high-cycle fatigue; therefore, an upper limit to the number of cycles to be applied was selected as 2 million cycles. The test was terminated when the failure of the specimen occurred or the upper limit of loading cycles was reached, whichever occurred first.

The results of the fatigue tests under a varying maximum bending stress level are summarized in Figure 2 where maximum bending stress in the fatigue experiment is plotted against the logarithm of the number of cycles to failure. Along with data points, the analytical expressions for the curves in the form $\sigma_f=aN^b$ were obtained. In an ideal world, all specimens would fail in the same cycle group and after the same number of cycles. But fatigue behaviour of material like concrete (the heterogeneous material) is far from being ideal and the results are usually highly scattered, therefore, not only the analytical expression but also the index of dispersion was determined.

The power function and the coefficient (R^2 is index of dispersion) for the present tested materials are as follows:

200109 $\sigma_f=4.22N^{-0.0335}$ and $R^2=0.85$,
010409 $\sigma_f=4.27N^{-0.0347}$ and $R^2=0.95$.

The Wöhler curve is rather flat, confirming the tendency of silicate-based composites and metal alloys. In general, S–N curves realized on silicate-base materials are relatively flat up to the fatigue limit, due to the brittle character of their failure.

The fatigue strength with 2 million repeated loading cycles in 200109 and 010409 shows about 61% and 59% to the first static flexural strength, respectively.

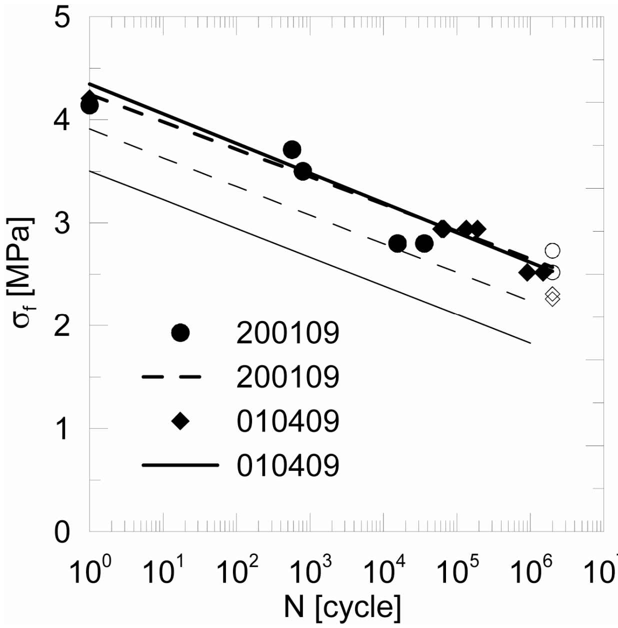

Figure 2. σ_f–N diagrams for 200109 and 010409 materials (black symbol: broken specimen; white symbol: unbroken specimen).

4 DISCUSSION OF RESULTS AND FRACTURE SURFACES

Finally, let's compare the linear regression lines for the present and the literature results taken from (Lee & Barr, 2004), where the authors provide an overview of recent developments in the study of the fatigue behavior of plain and fiber reinforced concrete. For our studied materials, it is interesting to compare the obtained results with the data for the plain concrete, because there were no added fibers in the studied mixtures – see 2.1.

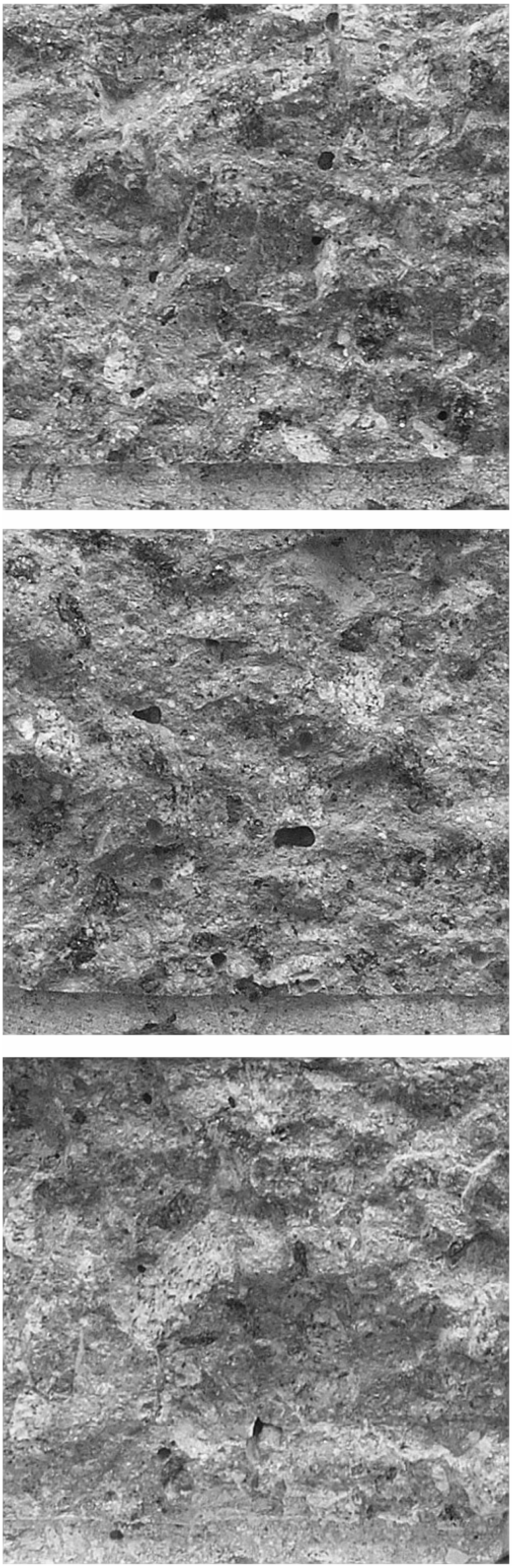

Figure 3. Fracture surface of specimens marked 200109 after the tests (A-static, B-low cycles and C-high cycles 10^6 loading).

Figure 4. Fracture surface of specimens marked 010409 after the tests (A-static, B-low cycles and C-high cycles 10^6 loading).

The results of the test are recorded in a normalized Wöhler diagram, see Figure 5 where on one axis the normalized stresses ($S_n=\sigma_f/\sigma_s$; σ_f–the values of fatigue loading stress and σ_s–values of static maximal stress) is given and on the other axis the numbers of cycles until failure on a log scale are presented. The Wöhler curves coefficients for analytical expression in the form $S_n=k\log N+l$ are presented in Table 3; the last column are values of indexes of dispersion R^2.

Table 3. Regression parameters of fatigue equations and index of dispersion.

Material	k	l	R^2
Concrete – Lee & Barr (2004)	-0.0606	1.0327	0.72
Concrete 200109	-0.0629	1.0087	0.85
Concrete 010409 (microsilica)	-0.0667	1.0137	0.95

It can be seen that for small values of N, the σ_f–N curves tend to converge to σ_f values that are greater than the static value N=1. This is mainly because the compressive strength used as a reference was obtained from the static tests in which the loading rate is much lower than that of the fatigue tests.

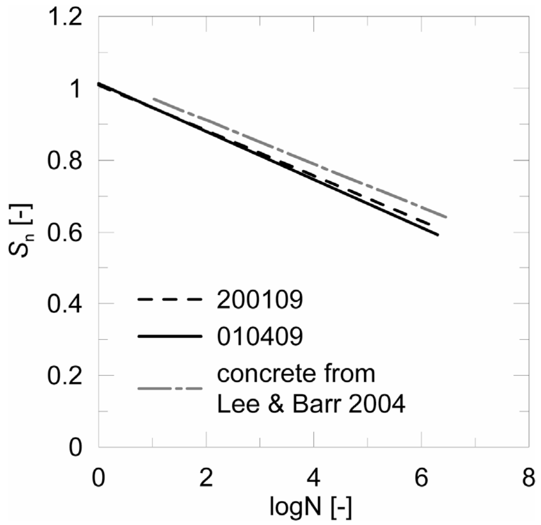

Figure 5. Comparison between S_n–*logN* diagrams for 200109, 010409 materials and literature data Lee & Barr (2004).

After the experimental tests the crack surfaces of both mixtures were studied visually and compared. The specimens were chosen to cover three stages of experimental loading. (A-static, B-low cycles typically around 10^4 cycles and C-high cycles typically around 10^6 loading). The obtained surfaces for selected specimens are shown in Figures 3 and 4. Figure 3 shows the crack surface of the material 200109 and Figure 4 shows the crack surface of the material 010409.

Note that adding the microsilica to the mixture 0104009 has changed the color of the matrix to darkness.

Only small differences were observed between the visual appearances of these concrete mixtures. It can be written the following notes:

Various types of loading influence the crack surface. Fatigue loading leads to noticeable damage of the cement base.

Adding the microsilica to the mixture 0104009 has an influence on mechanisms of rupture, it can be seen that most aggregates on the crack surface of mixture 010409 had been fractured during the crack growth through the specimen as opposed to the crack surface of mixture 200109.

It can be assumed that a different type of fracture can be connected with lower scatter of the presented fatigue results of both mixtures, see 3.2.

5 CONCLUSIONS

The following conclusions can be drawn based on the tests results presented in this paper:

Admixture of microsilica helped increase slightly the value of the modulus of elasticity of high strength concrete.

The fatigue parameters of the two concrete samples were almost identical.

The concrete with microsilica has a higher value of the index of dispersion than the concrete without microsilica, i.e. the results of these fatigue tests are more balanced.

The fatigue life of studied concrete is more sensitive to the change of stress; the Wöhler's curves are rather flat.

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