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# Cement based composites for thin building elements: Fracture and fatigue parameters

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**Abstract**

For application in civil engineering structures and also for strengthening existing structures cement-based composites are one of the most frequently used materials. Although many studies have been conducted on the mechanical properties of concrete from static tests, very little research has been reported on concrete fatigue properties. The purpose of this paper is to investigate the static and fatigue behavior of new cement-based composites, developed by ZPSV, a.s. a company producing bridge/train/building structures, are presented. To this end specimens were prepared and tested under static (compressive strength, bending strength, volume density and freezing and thawing resistance index) and cyclic loading (fatigue parameters – Wöhler/*S*–*N* curve). The experimentally obtained results (both static and fatigue) of cement-based composites are compared and the suitability of the composites in terms of their application for thin building elements is discussed.

*Keywords*: Cement-based composites, Fatigue concrete, Wöhler curve, fibers

## 1. Introduction

In recent years, the condition monitoring, repair, and retrofitting of existing structures, such as buildings and bridges, have been among the most important challenges in civil engineering. The primary reasons for the condition assessment and consequent maintenance and strengthening of structures include enhancement of resistance to withstand underestimated loads, increase in the load-carrying capacity for higher permit loads, restoration of lost carrying capacity due to corrosion of structural steel or reinforcing bars, and cracking of concrete or other types of degradation caused by ageing. The knowledge gained needs to be applied conceptually to new cement-based composites. 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 [1–4]. In addition, reliable data are needed for the calibration of accurate models capable of predicting the fatigue behavior of structural concrete.

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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. [1, 14]. 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 [1].

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 [5, 1].

Kleiber and Lee [6] 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 [7] demonstrated that the probabilistic distribution of the 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 [1, 8]. 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 [1].

In recent years, more attention has been paid by researchers to the fatigue behaviour of concrete. On the one hand, a heavy traffic flow and heavy vehicles expose structures built from concrete to an increase in the magnitude of fatigue stress cycles. On the other hand, new types of materials such as concrete containing metakaolin are expected to improve the material parameters, but little is known about their long-term performance. This paper continues and develops the previous study of the co-authors [9, 8, and 4].

The aim of the paper is to present selected material parameters of cement-based composites marked here 230709, 210909 and 081009, which are prepared as a new mixtures for thin building elements. The experimental measurements were made at two levels. The first one was a static measurement done by the ZPSV, a.s. and these results are represented by values of the compressive strength, bending strength, volume density and freezing and thawing resistance index of the materials. The second level is connected with high-cycle fatigue – Wöhler curves of all study concretes were determined. The obtained experimental results are discussed and related to decisions regarding practical use.

## 2. Materials, equipment and test procedure

The experimental test program was carried out the ZPSV, a.s. laboratory and at the Laboratory of Civil Engineering Faculty of Brno University of Technology in the Czech Republic. 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. The concrete compositions are summarized in Table 1. The mixtures were marked here with respect to the day of their production 230709, 210909 and 081009. The concretes were designed on the basis of preliminary tests in laboratory for production of thin building elements (dimensions approximately 3500 × 1050 × 40 mm). Condensed Silica Fume (Chryso®Silica) or metakaolin (Metaver I) were used for enhancing the stability of a self-compacting mixture with low water to cement ratio. It is not possible to use obvious reinforcement (e.g. steel bar) in the elements and for this reason a fibre–reinforced form of concrete was designed. Trial batching was mixed in the concrete plant in the 400 litres-mixer in the volume of 100 litres. All mixtures show good workability – they were self-compacting. Beams 40 × 40 × 160 mm were made from the studied mixtures for the testing of compressive strength, bending strength, volume density, freezing and thawing resistance and the fatigue properties.

Table 1. Material characteristics and composition of mixtures (kg/m$^3$)

| Concrete | 230709 | 210909 | 081009 |
|---|---|---|---|
| CEM I 42.5 R Mokra | 690 | 770 | 730 |
| Chryso®Silica | 60 | – | 62 |
| Metakaolin Metaver I | – | 32 | – |
| water | 250 | 250 | 250 |
| PCC superplasticizer | 12 | 8 | 10 |
| sand 0/4 mm | 1320 | 1250 | 1250 |
| fibers – 25 mm | 3.2 | 2.5 | 5.0 |

Tests of the compressive strength, bending strength and volume density of concrete beams were carried out in the experimental laboratory of ZPSV, a.s. in accordance to EN ISO 4012 [10] and ISO 6784 (FORM+TESTS Prufsysteme, Alpha 3-3000) [11]. Freezing and thawing resistance were tested in accordance with Czech Norm CSN 73 1322 [12]. Study beams were frozen in a freezer where a temperature of -20°C was maintained for 4 hours. After this time the beams were put into water +20°C for 2 hours. During preliminary tests, 125 cycles were often required. To qualify the concrete as frost resistant, the freezing and thawing index (ratio of strength of frosted beams/strength of reference beams) had to be higher than 0.75.

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 10 Hz [13]. 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:

$$\sigma_f = a\,N^b\,, \tag{1}$$

where $\sigma_f$ 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.

Note that the static tests were done on the specimens without specific preparation. On the other hand the fatigue experimental data are carried out from the three-point bending (3PB) tests. Fig. 1 shows the geometry of the 3PB specimens; their dimensions were $L$ = 160, $S$ = 120, $W$ = 40 and the thickness = 40 mm, the thickness is the same the minimal dimension of thin building elements. 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 [9]. In this study 3PB specimens with notch to width $a_n/W$ ratios of about 0.10 were used for all specimens tested on fatigue.

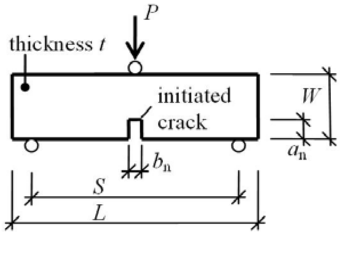


Fig. 1. Schematic of three-point bend (3PB) specimen geometry

## 3. Results of the tests

### *3.1. Static experiments results*

As a first step, the experimental measurements of compressive strength, bending strength, volume density, and freezing and thawing resistance index were made. The results obtained from the measurement are shown in Table 2. Note that the experimental measurements were carried out according the EN ISO 4012 [10] and ISO 6784 [11] after 28 days along the mixture preparation.

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

| Concrete | Unit | 230709 | 210909 | 081009 |
|---|---|---|---|---|
| Compressive strength | [MPa] | 75.9 ± 2.5 | 93.1 ± 0.1 | 93.4 ± 2.0 |
| Bending strength | [MPa] | 11.1 ± 0.5 | 11.3 ± 0.3 | 10.8 ± 0.5 |
| Volume density | [kg/m3] | 2136 ± 10 | 2255 ± 20 | 2264 ± 30 |
| Freezing and thawing resistance index | [–] | – | 0.89 | 0.76 |

### *3.2. Fatigue experiments results*

Plotting the stress versus the number of cycles until failure (known as *S–N* diagrams or Wöhler diagrams) an assessment of the influence of the stress level on the fatigue life of concrete can be illustrated in Fig. 2. 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 Fig. 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 $\sigma_f = a\, N^b$ were obtained – indicating a power law between the stress level and the fatigue life. The obtained values of materials parameters $a$, $b$ are shown in the Table 3. Note that in an ideal world all specimens would fail in the same cycle group and after the same number of cycles but the fatigue behaviour of a 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 as $R^2$. The fatigue strength to the first static flexural strength with 2 million repeated loading cycles is included at the last column of Table 3.

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.

Table 3. The material parameters $a$, $b$, index of dispersion $R^2$ for studied concrete and fatigue strength

| Concrete | $a$ | $b$ | $R^2$ | Fatigue strength |
|---|---|---|---|---|
| 230709 | 5.09 | -0.0397 | 0.82 | 51% |
| 210909 | 5.80 | -0.0377 | 0.99 | 58% |
| 081009 | 5.49 | -0.0205 | 0.95 | 76% |

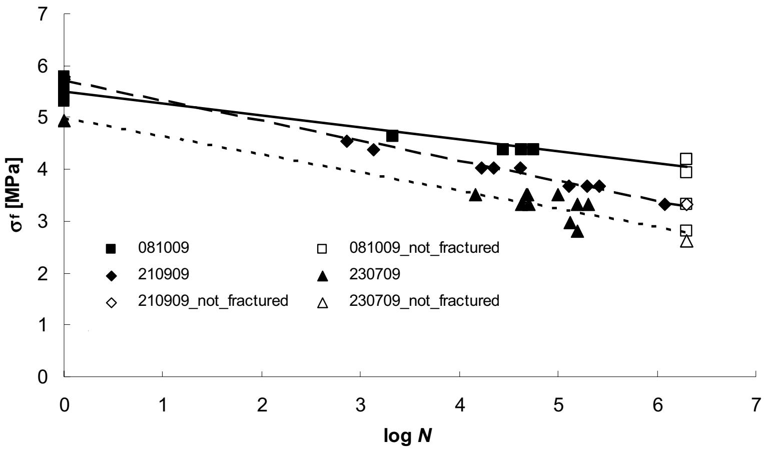


Fig. 2. $\sigma_f$–$N$ diagrams for 230709, 210909 and 081009 materials (full symbol: broken specimen; empty symbol: unbroken specimen)

## 4. Concluding discussion of results and suitability for use

Finally, we can compare the obtained results from static and fatigue experiments for the cement-based composited marked here 230709, 210909 and 081009.

It is evident that the concretes 210909 and 081009 have nearly equivalent values of mechanical properties but the first of these shows much better freezing and thawing resistance – an obvious consequence of the metakaolin application (see Table 1). Mixture 230709, on the other hand, shows lower values of mechanical properties due to a higher water to cement ratio and it is recorded as comparative, see Table 1.

The fatigue results obtained show that the material 230709 has the least appropriate fatigue characteristic values from all the materials studied. Its Wöhler curve is the lowest situated and has the greatest scatter, see Fig. 2. It can be concluded that this material is not acceptable for thin building elements from the fatigue point of view.

The fatigue results obtained for the other two new materials (210909 and 041009) can be compared with one another. Material 210909 has higher values of static characteristics but the fatigue curve has a quicker down grade (see Table 3 parameter *b* or Fig. 2) than the fatigue curve of materials 081009. The scatter of experimental results of both materials is very high and is more than acceptable in terms of practical use.

The information regarding the material behavior in static and fatigue conditions is important from a practical point of view. We can conclude that from static and fatigue tests performed using the study materials 210909 is the most suitable.

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