UHPC and FRC in Severe Environmental Conditions

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Abstract. Structure and properties of cement composite are time-varying characteristics, depending among others on environmental conditions. The key idea is a struggle for complex research of joint effect of physical, chemical and dynamic loads on the internal structure [1] of cement composite and understanding the correlation between changes in microstructure and macro-scale properties [2, 3]. During the experimental program, specimens will be exposed to combined influence of freeze-thaw cycles [4,5,6], aggressive chemical agents [7] and dynamic loading [8]. The aim is to create a theoretical basis for design of effective cement composites meant to be used in severe environmental conditions.

Introduction

The goal of the project is to evaluate the combined effect of severe environmental conditions (freeze-thaw cycles, aggressive chemical agents and dynamic loading) on the internal structure and mechanical properties of cement composites by experimental and analytical methods. The intention of this work is to establish theoretical basis for design of engineered concrete mixes whose characteristics would allow more efficient use of this material in severe environmental conditions. The areas of civil engineering that will benefit from the outcomes most heavily are transportation and industrial structures.

Experimental program

In this experimental program two groups of prismatic specimens (100x100x400 mm) were prepared – fibre reinforced concrete (FRC) samples and ultra-high performance concrete (UHPC) samples. The specimens for loading went through a special loading program. This consisted of three different types of loading:

- Freeze-thaw cycling test according to ČSN 73 13 22 [4],
- Resistance against aggressive chemical agents and deicing chemicals according to ČSN 73 1326 [7].
- Dynamic loading (four point bending test).

Specimens were subjected to physical, chemical and dynamic loads, while the rest were stored aside as reference samples.

Mix Design

Two different concrete mix designs were used in the project: fibre reinforced concrete (FRC) used in load-bearing parts of bridges in the Czech Republic (C35/45 - XC4, XD1, XF2 - Cl 0,20 could be used as a good representative based on consultations with designers) and ultra-high performance concrete (UHPC) developed in the Department of Concrete and Masonry Structures, Faculty of Civil Engineering (FCE), Czech Technical University in Prague (CTU) in recent years by the team under supervision of prof. Kohoutkova [9].
Two different mix designs, with different type of components are given in the Table 1.

- Fibre reinforced concrete (FRC), C35/45 - Mix design A.
- Ultra-high performance concrete (UHPC) - Mix design B.

| MIX DESIGN | A [kg/m³] | B [kg/m³] |
|------------|-----------|-----------|
| Concrete component | CEM I 42.5 R | 500 | 750 |
| Aggregate: | Fine 0 - 4mm | 800 | 1125 |
| Coarse 4 - 8mm | 250 | 224 |
| Coarse 8 - 16mm | 700 | 82 |
| Superplasticizer, Visco Crete 1035 | 5 | - |
| Fibers Dramix 35 | 60 | - |
| Polycarboxylate | - | 2 |
| Microsilica | - | 80 |
| Dramix OL fibers | - | 160 |
| Water | 148 | 188 |

**Test Specimens**

All tested specimens were made from steel moulds, compacted on vibratory table. Specimens were demoulded after 24 hours and then stored in water according to EN 12390-2 [10] for 28 days. The test specimens were stored in dry place until the beginning of the test. Before testing, the specimens were measured and weighed.

In this paper all the tests were carried out on prismatic specimens (100x100x400 mm).

**Dynamic load tests (Fibre reinforced concrete)**

Static load tests (four point bending test) were performed on twelve prisms. The default value of the load for the cyclic loading was determined by the static load tests. The maximum force reached (static load test) was recorded, the average was calculated as 23.9 ± 1.6 kN. This value was considered as a basis to specify the loading schedule in this series.

6 prismatic specimens were exposed to cyclic loading under the frequency of 20 Hz. Based on the experience from the preliminary series, the loading schedule was as follows:

- Peak force equal to 90 % of average resistance from preliminary series (21.5 kN), 500 000 cycles.
- Peak force equal to 95 % of average (22.7 kN), 80 000 cycles.
- Peak force equal to 100 % of average (23.9 kN), 80 000 cycles.
- Peak force continuously increased until the failure of the specimen.

The first two test specimens did not last the load Level 1 (Peak force equal to 90 % of average), and it was agreed, that the load Level 1 will be reduced to peak force equal to 85% of average. Even this load Level the specimen did not last. Loading procedure was modified as follows:

- Peak force equal to 80 % of average resistance from preliminary series (19.1 kN), 500 000 + 500 000 cycles.
- Peak force equal to 85 % of average (20.3 kN), 80 000 cycles.
- Peak force equal to 90 % of average (21.5 kN), 80 000 cycles.
- Peak force continuously increased until the failure of the specimen.
First three specimens failed in the 1st level, because of the high values of peak forces were calculated as 21.5 kN respectively 20.3 kN. The last three specimens passed three basic levels with average resistance of 25.1 ± 1.3 kN in the last level. These specimens passed more than 1 160 000 load cycles.

The test arrangement is presented in Figure 1. The MTS 500 kN, B-262 machine was used for the tests. Results are shown in Table 2.

![Fig. 1 View of the output in measuring central / experimental setup](image)

### Table 2 Test results – dynamic load test, FRC

| Spec. No. | Frequency [Hz] | Dynamic loading | Additional comment |
|-----------|----------------|-----------------|--------------------|
|           | Load level 1, specimen pass the test, YES/NO | Load level 2, specimen pass the test, YES/NO | Load level 3, specimen pass the test, YES/NO | F max [kN] |
| G1-B7     | 20             | NO              | NO                | NO | 21.50 | Specimen failure after 2 000 cycles, load Level 1 = 90% av. strength |
| G1-B8     | 20             | NO              | NO                | NO | 21.50 | Specimen failure after 49 540 cycles, load Level 1 = 90% av. strength |
| G1-B9     | 20             | NO              | NO                | NO | 20.40 | Specimen failure after 56 380 cycles, load Level 1 = 85% av. strength |
| G1-B10    | 20             | YES             | YES               | YES | 23.75 | Specimen pass > 1 160 000 cycles, crack during the test on Level 3 |
| G1-B11    | 20             | YES             | YES               | YES | 26.80 | Specimen pass > 1 160 000 cycles |
| G1-B12    | 20             | YES             | YES               | YES | 24.82 | Specimen pass > 1 160 000 cycles, crack during the test on Level 3 |

**Dynamic load tests (UHPC)**

This series was produced for the purpose of testing and familiarizing with the specimens behaviour under dynamic load. Static load tests (four point bending test) were performed on 18 prisms. The maximum force reached (static load test) was recorded, the average was calculated as 40.5 ± 5.4 kN. This value was considered as a basis to specify the loading schedule in this series.

6 prismatic specimens were exposed to cyclic loading under the frequency of 20 Hz. Based on the experience from the preliminary series, the loading schedule was modified as follows:

- Peak force equal to 80 % of average resistance from preliminary series (32.4 kN), 500 000 cycles.
- Peak force equal to 85 % of average (34.4 kN), 80 000 cycles.
- Peak force equal to 90 % of average (36.5 kN), 80 000 cycles.
- Peak force continuously increased until the failure of the specimen.

All specimens passed three basic levels with average resistance of 48.2 ± 4.2 kN in the last level. These specimens passed more than 640 000 load cycles.

Test specimens after the failure are shown in Figure 2. The MTS 500 kN, B-262 machine was used for the tests. Results are shown in Table 3.
Table 3 Test results – dynamic load test, UHPC

| Specimen No. | Frequency [Hz] | Dynamic loading | F max [kN] | Additional comment |
|--------------|---------------|-----------------|------------|-------------------|
| G1-C19       | -             | -               | -          |                   |
| G1-C20       | 20            | YES             | 50.0       | Specimen failure  |
| G1-C21       | 20            |                 | 49.6       |                   |
| G1-C22       | 20            |                 | 42.8       |                   |
| G1-C23       | 20            |                 | 42.8       |                   |
| G1-C24       | 20            |                 | 46.0       |                   |
| G1-C25       | 20            |                 | 51.2       |                   |
| G1-C26       | 20            |                 | 46.4       |                   |
| G1-C27       | 20            |                 | 43.2       |                   |
| G1-C28       | 20            |                 | 50.3       |                   |
| G1-C29       | 20            |                 | 51.1       |                   |
| G1-C30       | 20            |                 | 56.8       |                   |

Fig. 2 Specimens after the failure / experimental setup

Ultrasonic measurement (FRC)

Dynamic load characterization was completed with ultrasonic measurement. The main purpose for ultrasonic measurements was to monitor the creation of cracks. During the 3rd Level, hairline cracks were discovered in two of the specimens without affecting their load-bearing capacity. The data obtained by these measurements will be further used to calculate the elastic modulus of the material. Prior to commencement of the tests the zero measurement was performed and again always after the performance of a dynamic load cycles (levels 1-3). Device MATEST C373N with two 55 kHz probes was used for the measurement. In this system, an ultrasonic pulse velocity with a mean frequency of 55 kHz was used to measure travel time through the medium. Only the travel time of ultrasonic waves from the transmitter to the receiver is obtained. Although the travel time can be used to determine the possible position of the defect, more useful information about defects cannot be obtained. Results are shown in the table 4. Test setup and test specimens are shown in Figure 3.

Table 4 Test results – ultrasonic measurement, FRC

| Spec. No. | Ultrasonic m. prior to commencement of tests, zero measurement [μs] | Ultrasonic measurement after performance of dynamic load test level 1, round one, [μs] | Ultrasonic measurement after performance of dynamic load test level 2, round two, [μs] | Ultrasonic measurement after performance of dynamic load test level 3, [μs] | Additional comment |
|-----------|------------------------------------------------------------------|----------------------------------------------------------------------------------|----------------------------------------------------------------------------------|------------------------------------------------------------------|-------------------|
| G1-B7     | 85.3                                                             | -                                                                                | -                                                                                | -                                                                | Specimen failure after 2,000 cycles, load Level 1 < 80% ax. strength |
| G1-B8     | 85.4                                                             | -                                                                                | -                                                                                | -                                                                | Specimen failure after 49,500 cycles, load Level 1 < 80% ax. strength |
| G1-B9     | 89.2                                                             | -                                                                                | -                                                                                | -                                                                | Specimen failure after 387,000 cycles, load Level 1 > 89% ax. strength |
| G1-B10    | 87.4                                                             | 87.7                                                                             | 87.1                                                                             | 87.1                                                             | Specimen pass > 1,500,000 cycles                                  |
| G1-B11    | 87.1                                                             | 87.9                                                                             | 87.7                                                                             | 87.1                                                             | Specimen pass > 1,500,000 cycles                                  |
| G1-B12    | 87.4                                                             | 87.1                                                                             | 87.1                                                                             | 87.1                                                             | Specimen pass > 1,500,000 cycles                                  |

Tested on 20.5 – 31.4.2013
The last part of the experimental program (G1.C specimens) was focused on FRC specimens exposed to combined effects of freeze-thaw cycles and cyclic loading. Six reference specimens (G1.C1) were subjected to four-point bending tests only, the average resistance of $24.7 \pm 1.2 \text{ kN}$ was measured. This is very close to the results of G1.A and G1.B group, therefore it can be said that the properties of the material used in all the experiments were relatively stable.

A total of 12 specimens from the same batch were subjected to 100 freeze-thaw cycles in the presence of deicing chemicals. Tests of resistance to chemical antiicing salts (method A) on remains of specimens were performed. Test solution: 3% solution of NaCl. Loading cycles according to CSN 731326 - method A [8]. Freezing chamber FRIGERA was used for the test.

The surface of all the specimens was undisturbed after 100 cycles, the amount of waste was between $0 - 0.5 \text{ g/m}^2$. According to tab. 1. in CSN 731326 [8] the surface of test body is classified with level 1 – undisturbed (request for this level in Table 1 shows $50 \text{ g/m}^2$ as maximum waste, however the waste should be in the form of very fine silty particles up to 1 mm).

Six of the 12 specimens (G1.C2) were subjected to four-point bending tests, the average resistance of $23.0 \pm 0.7 \text{ kN}$ was measured.

The last six samples (G1.C3) were exposed to cyclic loading under the frequency of 20 Hz. The loading schedule was set as follows:

- Peak force equal to 85% of average resistance from G1.C2 static tests (19.6 kN), 500 000 cycles.
- Peak force equal to 90% of average (20.7 kN), 80 000 cycles.
- Peak force equal to 95% of average (21.9 kN), 80 000 cycles.
- Peak force continuously increased until the failure of the specimen.

Two specimens passed the three basic levels with the average resistance of $25.8 \pm 1.8 \text{ kN}$ in the last level. One specimen failed in the 3rd level, one more in the 2nd level, remaining two specimens did not pass the 1st level.

The difference compared to the results of pure dynamic cycling tests (G1.A and G1.B) is negligible, therefore it can be said that up to 100 cycles, there is no significant difference in the behaviour of FRC exposed to dynamic cycling whether it is exposed to freeze-thaw cycling or not. Results are shown in Table 5. Test specimens after the test, resistance to chemical antiicing salts (method A), are shown in Figure 4.
Table 5 Test results – dynamic load test and freeze-thaw cycles, FRC

| Spec. No. | Frequency [Hz] | Load level 1, specimen pass the test, YES/NO | Load level 2, specimen pass the test, YES/NO | Load level 3, specimen pass the test, YES/NO | F max [kN] | Additional comment |
|-----------|----------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|------------|------------------|
| G1-C3-1   | 20             | YES                                         | YES                                         | YES                                         | 24.00      | Specimen pass > 760 000 cycles |
| G1-C3-2   | 20             | NO                                          | NO                                          | NO                                          | 20.40      | Specimen failure after 8 175 cycles |
| G1-C3-3   | 20             | YES                                         | YES                                         | NO                                          | 21.60      | Specimen failure after 580 000 cycles |
| G1-C3-4   | 20             | YES                                         | YES                                         | YES                                         | 27.50      | Specimen pass > 640 000 cycles |
| G1-C3-5   | 20             | YES                                         | NO                                          | NO                                          | 20.40      | Specimen failure after 500 000 cycles |
| G1-C3-6   | 20             | NO                                          | NO                                          | NO                                          | 20.40      | Specimen failure after 127 290 cycles |

Tested on 20. – 22.6.2015

Fig. 4 Specimens after the test, resistance to chemical antiicing salts (method A), 100 cycles

Ultrasonic measurement (FRC), specimens exposed to combined effects of freeze-thaw cycles and cyclic loading

Dynamic load measurement was completed with ultrasonic measurement. The main purpose for ultrasonic measurements was to monitor the creation of cracks.

Prior to commencement of the tests the zero measurement was performed and again always after the performance of a dynamic load cycles (levels 1-3). Device MATEST C373N with two 55 kHz probes was used for the measurement. Obtained results are shown in the table 6.

Table 6 Test results – ultrasonic measurement, FRC

| Spec. No. | Ultrasonic m. prior the start of tests, zero measurement [µs] | Growth compared to zero measurement [%] | Ultrasonic m. after freeze-thaw cycles, zero measurement [µs] | Growth compared to zero measurement [%] | Ultrasonic m. after performance of dynamic load test level 1 | Growth compared to zero measurement [%] | Ultrasonic m. after performance of dynamic load test level 2 | Growth compared to zero measurement [%] | Ultrasonic m. after performance of dynamic load test level 3 | Growth compared to zero measurement [%] | Additional comment |
|-----------|-------------------------------------------------------------|----------------------------------------|-------------------------------------------------------------|----------------------------------------|-------------------------------------------------------------|----------------------------------------|-------------------------------------------------------------|----------------------------------------|-------------------------------------------------------------|----------------------------------------|------------------|
| G1-C3-1   | 87.2                                                        | 0.2                                    | 87.4                                                        | 0.1                                    | 87.9                                                        | 1.6                                    | 88.7                                                        | 2.5                                    | 89.9                                                        | 3.9                                    | Specimen pass > 760 000 cycles |
| G1-C3-2   | 87.6                                                        | -0.1                                   | 87.7                                                        | 0.1                                    | 87.9                                                        | 1.6                                    | 88.7                                                        | 2.5                                    | 89.9                                                        | 3.9                                    | Specimen failure after 8 175 cycles |
| G1-C3-3   | 86.5                                                        | 0.0                                    | 86.5                                                        | 0.0                                    | 87.9                                                        | 1.6                                    | 88.7                                                        | 2.5                                    | 89.9                                                        | 3.9                                    | Specimen failure after 580 000 cycles |
| G1-C3-4   | 87.5                                                        | -0.2                                   | 87.3                                                        | -0.2                                   | 87.7                                                        | -0.1                                   | 88.7                                                        | -0.1                                   | 89.1                                                        | 1.8                                    | Specimen pass > 640 000 cycles |
| G1-C3-5   | 87.1                                                        | 0.5                                    | 87.5                                                        | 0.5                                    | 87.9                                                        | -0.1                                   | 88.7                                                        | -0.1                                   | -                                                            | -                                      | Specimen used for static load test |
| G1-C3-6   | 87.9                                                        | -0.1                                   | 87.8                                                        | -0.1                                   | 87.5                                                        | 0.8                                    | 88.7                                                        | 1.4                                    | -                                                            | -                                      | Specimen failure after 500 000 cycles |
| G1-C3-7   | 86.8                                                        | 0.2                                    | 87.0                                                        | 0.2                                    | 87.5                                                        | 0.8                                    | -                                                            | -                                      | -                                                            | -                                      | Specimen failure after 127 290 cycles |

Tested on 15. – 22.6.2015
Summary

The results have proven excellent resistance of UHPC to cyclic loading compared to normal strength FRC. 92% of UHPC specimens resisted more than 640 000 loading cycles at 80 - 90 % of their static resistance, while just 42 % of FRC specimens achieved similarly good result. Average force at failure after dynamic loading was 48.2 ± 4.2 kN for UHPC specimens, more than double the value for FRC specimens, which was just 22.8 ± 2.5 kN. As the number of specimens tested was relatively small from the statistical point of view, the scatter of the results can be considered satisfactory. Better results of UHPC compared to FRC can be attributed mainly to higher amount of fibers effectively eliminating propagation of micro cracks in cement matrix. More compact structure and higher strength of cement matrix also provide better bond between the matrix and the fibers. The difference compared to the results of pure dynamic cycling tests on FRC specimens (G1.A and G1.B) and combined effects (G1.C) is negligible, therefore it can be said, that up to 100 cycles, there is no significant variance in the behaviour of FRC exposed to dynamic cycling whether it is exposed to freeze-thaw cycling or not. Dynamic load measurement was completed with ultrasonic measurement. The main purpose for ultrasonic measurements was to monitor the creation of cracks. During the 3-rd Level, hairline cracks were discovered in two of the specimens without affecting their load-bearing capacity. The data obtained by these measurements will be further used to calculate elastic modulus of the material.

It ensues from the results in Table 7 that performed experimental program does not prove negative impact of cyclic loading in the range up to 90% of the static loading strength after about 640 000 cycles.

| Mix design          | Loading type | Average failure force (kN) | Standard deviation |
|---------------------|--------------|-----------------------------|--------------------|
| FRC – dynamic loading | static       | 23.9                        | 1.6                |
|                     | dynamic      | 23.1                        | 2.2                |
| FRC – combined effects | static     | 23.0                        | 0.7                |
|                     | dynamic      | 25.8                        | 1.8                |
| UHPC – dynamic loading | static     | 40.4                        | 5.4                |
|                     | dynamic      | 48.2                        | 4.2                |

Next phase of the program (which is running now in 2016) assumes study of impact of material characteristics with combination of loading – anti-icing salts and freeze-thaw cycles. Production of the specimens and the individual tests, especially resistance against of aggressive chemical agents and freeze-thaw cycles, are very time consuming.

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