UHPC and FRC in Severe Environmental Conditions, Resistance Against Freeze-thaw Cycles, Aggressive Chemical Agents and Dynamic Loading

Author(s) & Affiliation:

Stanislav Rehacek, CTU in Prague, Klokner Institute
Ivo Simunek, CTU in Prague, Klokner Institute
Jiri Kolisko, CTU in Prague, Klokner Institute
David Citek, CTU in Prague, Klokner Institute

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 [8] and dynamic loading [7]. The aim is to create a theoretical basis for design of effective cement composites meant to be used in severe environmental conditions. Two different concrete mixes are studied throughout the project: standard strength concrete used in load-bearing parts of bridges in the Czech Republic, used as a good representative based on consultations with designers and the ultra-high performance concrete.

Keywords:

UHPC, FRC, dynamic loading, deicing agents, resistance, freeze-thaw cycles.

1. 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 mix designs whose characteristics would allow more efficient use of this material in severe environmental conditions. Those areas of civil engineering that will benefit from the outcomes most heavily are transportation and industrial structures.

2. 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 appointed 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 [8].
- Dynamic loading (four-point bending test).

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

2.1. 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) 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) during the last years by the team under supervision of prof. Kohoutkova [9].

Table 1. Mix Design of FRC (A) and UHPC (B).

MIX DESIGN		A	B
Concrete component		[kg/m^3]	[kg/m^3]
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

2.2. Test Specimens

All tested specimens were made in 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 (100 x 100 x 400 mm).

2.3. Dynamic load tests

2.3.1 Fibre reinforced concrete (FRC)

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 modified as follows:

- Peak force equal to 90 % of average resistance from preliminary series (21.5 kN), 500 000 cycles.

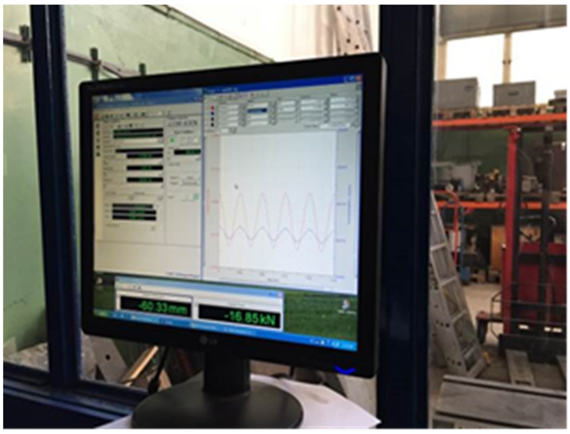
- Peak force equal to 95 % of average (22.7 kN), 80 000 cycles.
- Peak force equal to 100 % of average (23.9 kN), 80 000 cycles.
- Peak force continuously increased until the failure of the specimen.

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 modify 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 the 1st level, because 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 during the last level. These specimens passed more than 1 160 000 load cycles.

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



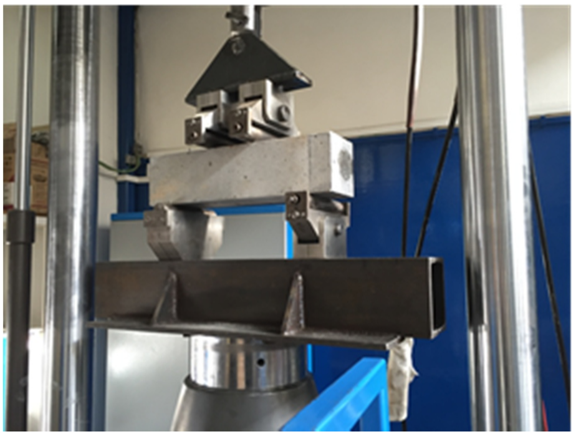


Figure 1. View of the output in measuring central / experimental setup

Table 2. Test results – dynamic load test, FRC

Specimen No.	Frequency [Hz]	Dynamic loading			F max [kN]	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		
Tested on 30.3 – 3.4.2015						
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, 2x	YES	YES	23.75	Specimen pass > 1 160 000 cycles, crack during the test on Level 3
G1-B11	20	YES, 2x	YES	YES	26.80	Specimen pass > 1 160 000 cycles
G1-B12	20	YES, 2x	YES	YES	24.82	Specimen pass > 1 160 000 cycles, crack during the test on Level 3

2.3.2 Ultra high performance concrete (UHPC)

This series was produced for the purpose of testing and familiarizing with the specimens behaviour under dynamic loading. 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 modify as follows:

- Peak force equal to 80 % of average resistance from pre. 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 during the last level. These specimens passed more than 640 000 load cycles.
Test specimens after the failure are visible in Figure 2. The MTS 500 kN, B-262 machine was used for the tests. Obtained 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
		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		
G1-C19	-	-	-	-	-	Specimen failure
G1-C20	20	YES	YES	YES	50.0	Specimen pass > 640 000 load cycles before damage
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	

Figure 2. Specimens after the failure / experimental setup

2.4. Resistance to freeze-thaw cycles

In 2015, freeze-thaw cycling tests (according to ČSN 73 1322 standard) [4] of both UHPC and FRC were finished. 400 x 100 x 100 mm prisms were used for the tests. The tests were evaluated after each 25 cycles in the range of 0 - 200 cycles, in the total 56 specimens were produced for each material (32 for freeze-thaw resistance tests, 24 reference samples). The evaluation of the influence of freeze-thaw cycles was conducted by means of four-point bending tests, the decrease of tensile strength of the material between the subsequent cycling levels was compared. The dynamic elastic modulus was also measured for the control purposes.

2.4.1 Fibre reinforced concrete (FRC)

Initial tensile strength of FRC was 7.3 MPa, compressive strength was 81 MPa, dynamic elastic modulus was 52.1 GPa. These parameters did not change until the 150th cycle (the difference was less than 0.5 %). Between the 150th and the 200th cycle, the decrease per each 25 cycles comprised approximately 1.5 % in case of tensile strength, 3 % in case of compressive strength and 1 % in case of dynamic modulus. The resulting characteristics were approximately 6.8 MPa for tensile strength, 73.5 MPa for compressive strength and 49 GPa for elastic modulus.

2.4.2 Ultra high performance concrete (UHPC)

Initial tensile strength of UHPC was 12.5 MPa, compressive strength was 145 MPa, dynamic elastic modulus was 62.5 GPa. These parameters did not change until the 125th cycle (the difference was less than 0.5 %). Between the 125th and the 200th cycle, the decrease per each 25 cycles comprised approximately 2.5 % in case of tensile strength, 4 % in case of compressive strength and 3.5 % in case of dynamic modulus. The resulting characteristics were approximately 11 MPa for tensile strength, 125 MPa for compressive strength and 58 GPa for elastic modulus.

2.4.3 Conclusions

As a result, it can be stated that UHPC is more sensitive to freeze-thaw effects at higher loading levels than the standard strength FRC. This is probably caused by the brittleness of the extremely dense structure of the material. Porous pressures created by freezing water in the microscopic cracks within the UHPC matrix are more harmful for the material than in case of FRC, where the wider cracks and higher amount of internal pores create an additional space for compensation of increased volume of ice. Nevertheless, the strengths of UHPC are still more than 60 % higher than the strengths of FRC even after 200 cycles.

2.5. Resistance to deicing chemical

Resistance to deicing chemicals was tested on the remaining FRC prisms according to ČSN 73 1326 standard, method A [8]. The surface of all the specimens was undisturbed after 150 cycles, the amount of waste was between 0-1 g/m^2. Therefore, the tests of UHPC samples were not performed, it was legitimately assumed that the waste would have been even smaller.

2.6. Resistance to combined effect (FRC), dynamic loading and freeze-thaw cycles

The last part of the experimental program (G1.C specimens) focused on FRC specimens exposed to combined effects of freeze-thaw cycles and dynamic loading. Six reference specimens (G1.C1) were subjected to four-point bending tests only, the average resistance of 24.7 ±1.2 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 remaining 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 g/m^2. According to tab. 1. in CSN 731326 - method A [8] the surface of test body is classified with level 1 – undisturbed (request for this level in Table 1. shows 50 g/m^2 as maximum waste, however the waste should be in the form of very fine silty particles up to 1 mm).

6 of the 12 specimens (G1.C2) were subjected to four-point bending tests, the average resistance of 23.0 ± 0.7 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 ± 1.8 kN during the last level. One specimen failed the 3rd level, one more 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 variance in the behaviour of FRC exposed to dynamic cycling whether it is exposed to freeze-thaw cycling or not. Obtained results are shown in Table 4.

Table 4. Test results – dynamic load test, FRC

Specimen No.	Frequency [Hz]	Dynamic loading			F max [kN]	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		
Tested on 20. – 22.6.2015						
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

2.7. 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 control the creation of cracks. The data obtained by these measurements will be further used to calculate 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. Obtained results are shown in the table 5.

Table 5. Test results – ultrasonic measurement, FRC

Specimen No.	Ultrasonic m. prior the start of tests, zero measurement [µs]	Ultrasonic m. after freeze-thaw cycles, zero measurement [µs]	Growth compared to zero measurement [%]	Dynamic loading						Additional comment
				Ultrasonic measurement after performance of dynamic load test **level 1**		Ultrasonic measurement after performance of dynamic load test **level 2**		Ultrasonic measurement after performance of dynamic load test **level 3**		
				Ultrasonic m. [µs]	Growth compared to zero measurement [%]	Ultrasonic m. [µs]	Growth compared to zero measurement [%]	Ultrasonic m. [µs]	Growth compared to zero measurement [%]	
Tested on 15. – 22.6.2015										
G1-C2-1	87.2	87.4	0.2	Specimen used for static load test						
G1-C2-2	87.6	87.7	0.1							
G1-C3-1	86.5	86.5	0.0	87.9	1.6	88.7	2.5	89.9	3.9	Specimen pass > 760 000 cycles
G1-C3-2	87.5	87.3	-0.2	-	-	-	-	-	-	Specimen failure after 8 175 cycles
G1-C2-3	87.1	87.5	0.5	Specimen used for static load test						
G1-C2-4	87.9	87.8	-0.1							
G1-C3-3	87.6	87.3	-0.3	87.5	-0.1	88.2	0.7	-	-	Specimen failure after 580 000 cycles
G1-C3-4	87.5	87.4	-0.1	87.8	0.3	88.7	1.4	89.1	1.8	Specimen pass > 640 000 cycles
G1-C2-5	87.1	87.3	0.2	Specimen used for static load test						
G1-C2-6	87.6	87.5	-0.1							
G1-C3-5	86.8	87.0	0.2	87.5	0.8	-	-	-	-	Specimen failure after 500 000 cycles
G1-C3-6	87.6	87.8	0.2	-	-	-	-	-	-	Specimen failure after 127 290 cycles

3. Conclusions

The results have proven excellent resistance of UHPC to dynamic 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 control the creation of cracks.

Resistance to deicing chemicals was tested on the remaining FRC prisms. The surface of all the specimens was undisturbed after 150 cycles, the amount of waste was between 0-1 g/m^2. Therefore, the tests of UHPC samples were not performed, it was legitimately assumed that the waste would have been even smaller.

As a result of resistance against freeze-thaw cycles, can be stated that UHPC is more sensitive to freeze-thaw effects at higher loading levels than normal strength FRC. This is probably caused by the brittleness of the extremely dense structure of the material. Porous pressures created by freezing water in the microscopic cracks within the UHPC matrix are more harmful for the material than in case of FRC, where the wider cracks and higher amount of internal pores create an additional space for compensation of increased volume of ice.

It follows from the results 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.

Next phase of the program 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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5. Acknowledgements

This contribution is the result of the research supported by the grant projects of GAČR 14-19561S.