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Physical and mechanical properties of ultra high strength fiber reinforced cementitious composites

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ABSTRACT: This paper presents the experimental research regarding the physical-mechanical properties and the durability characteristics of the ultra high performance concrete. The cementitious composite with 2 % volume of steel fibers was tested for the following characteristics: the compressive and tensile strength, the moduli of elasticity, the stress-strain characteristic curve for compression strength and flexural strength and tests after aproximately 1000 cycles of freezing and thawing. The specimens subject to 90^0C thermal treatment for 5 days displayed an increase of compressive strength up to 180 MPa at the age of 6 days. The experimental data obtained on specimens with thermal curing regime are evaluated by comparison with specimens with water curing regime.

1 INTRODUCTION

Ultra high performance fiber reinforced concrete (UHPFRC) stands for concretes with compressive strengths exceeding 150 MPa. The concrete composition includes a high cement content, mineral admixture (usually silica fume), steel fibers and a very low water/binder ratio ensured by the use of last generation superplasticizers. UHPFRC incorporates very fine sands or quartz sands with granule size up to 1 mm.

The first structural application of this concrete was the Sherbrooke footbridge built in Canada in 1997. Besides the superior physical-mechanical properties compared with ordinary concrete and even high strength concrete, UHPFRC presents very good ductility and durability properties.

2 EXPERIMENTAL PROGRAM

The experimental program comprised the study of the mechanical properties of ultra-high performance with fiber reinforcement (UHPFRC) and without fiber reinforcement (UHPC). Furthermore, the two types of concrete were tested for durability, freeze-thaw cycles respectively. Both mixtures used Portland cement type CEM I 52.5R, grey silica fume and very fine sand with granulometry of 0-0.3 mm and 0.4-1.2 mm. The coarse agregates were eliminated. The flowability of the concrete was ensured by the polymer ether-carboxylate superplasticizers. The composition of the two concretes is presented in Table 1.

Table 1. Concrete composition.

Materials	UHPC	UHPFRC
Cement CEM 52.5R	1.00	1.00
Water/cement ratio (w/c)	0.174	0.174
Water/binder ratio (w/b)	0.138	0.138
Sand (0-0.3)+(0.4-1.2 mm)	1.18	1.18
Silica fume	0.26	0.26
Superplaticizers	0.0305	0.0305
Steel fibers	0	0.174

The fibers used in the composition were 0.4 mm in diameter and 25 mm in length and were added in quantity of 2% by concrete volume.

Two curing regimes were applied for specimens used for mechanical properties determinations:

- thermal treatment for 5 days with a constant temperature of 90^0C.
- water curing for 5 days with a constant temperature of 20 ± 2^0C.

Subsenquently the specimens were kept in the laboratory enviroment (temperature 20 ± 2^0C and relative humidity 60±5%) until testing.

Three curing regimes were used to evaluate freeze-thaw resistance:

- thermal treatment for 5 days with a constant temperatures of 90^0C, then exposure to freeze-thaw cycles.
- water curing for 5 days with a constant temperature of 20 ± 2^0C, then exposure to freeze-thaw cycles.
- water curing for 334 days for the witness specimen.

The freeze-thaw procedure implied over 1000 cycles in 334 days. Each cycle consisted in 4 hours freezing at -20^0C and 4 hours thawing at $+20^0$C, while the relative humidity remained constant of 90±2%.

The strength and deformability characteristics were determined with a digital hidraulic testing machine with deformation control, type ADVANTEST 9. The displacements were measured using LVDTs. A general view of the testing machine is displayed in Figure 1.

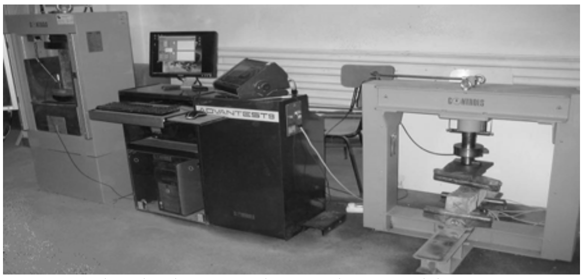

Figure 1. Mechanical properties testing machine.

The freeze-thaw procces was performed with a thermostat cabine type CONTROLS, with constant temperature and humidity control of the alternating cycles - Figure 2.

Figure 2. Thermostat cabine.

The determination of the dynamic modulus of elasticity, shear modulus and Poisson's ratio was made using the resonant frequency of longitudinal and torsion vibrations. The tests were conducted with a resonant-frequency testing apparatus type Erudite MKIV, as seen in Figure 3.

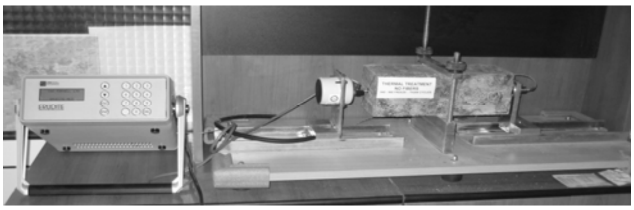

Figure 3. Resonat-frequency testing apparatus.

3 FRESH CONCRETE PROPERTIES

The flowability of the concrete was investigated with the slump flow test conducted immediately after the mixing process ended. It was observed that the steel fibers incorporation does not have a major influence on the concrete flowabilty, the slump flow measurement being about 120 mm.

The water/cement ratio was 0.174. All specimens were produced from the same batch in order to eliminate the influence of the mixing condition.

The specimens had the following geometry: 70x70x70mm and 100x100x100 mm cubes, 40x40x 160mm and 100x100x300mm prisms.

It was used a 100 liter mixer for the mixing process. When the mixing time completed, the specimens were cast in moulds while vibrated on a vibrating table. The specimens were demoulded the next day.

4 MECHANICAL PROPERTIES OF THE HARDENED CONCRETE

4.1 *Compressive and splitting tensile strength*

The compressive strength (fc) was measured on 70x70x70 mm cubes. The splitting tensile strength (fct,sp) was measured on 100x100x100mm cubes. The testing age was 6, 14 and 28 days for both (T), thermal treatment (5days, 90^{0}C) and (W), water curing regime (5 days, water, temperature 20±2^{0}C). The results are listed in Table 2 for the compressive strength and in Table 3 for the splitting tensile strength .

Table 2 . Compressive strength (fc).

Specimen geometry [mm]	Type	Curing	Mechanical properties [MPa]	Concrete Age 6 days	14	28
Cube 70x70x70	UHPC	T	f_c	160.2	160.4	167.5
Cube 70x70x70	UHPC	W	f_c	107.7	116.2	102.9
Cube 70x70x70	UHPFRC	T	f_c	181.3	185.5	181.2
Cube 70x70x70	UHPFRC	W	f_c	130.5	128.8	138.2

The compressive strength of thermal treated specimens is about 15% higher for UHPFRC compared to UHPC.

Table 3 . Splitting tensile strength (fct,sp).

Specimen geometry [mm]	Type	Curing	Mechanical properties [MPa]	Concrete Age 6 days	14	28
Cube 100x100x100	UHPC	T	$f_{ct,sp}$	7.9	9.2	9.4
Cube 100x100x100	UHPC	W	$f_{ct,sp}$	5.8	7.7	6.9
Cube 100x100x100	UHPFRC	T	$f_{ct,sp}$	17.5	20.2	20.4
Cube 100x100x100	UHPFRC	W	$f_{ct,sp}$	6.6	7.8	12.6

It can be observed an increase of about 220 % of the splitting tensile strength of UHPFRC compared with UHPC for the thermal treated specimens.

4.2 *Flexural strength*

The flexural strength was investigated by performing a 3 point bending test using 40x40x160 mm and 100x100x300 mm prismatic specimens. The specimens were thermal treated (T).

The testing procedures using ADVANTEST9 testing machine and the failure of the specimens are illustrated in Figure 4 (UHPFRC) and Figure 5 (UHPC).

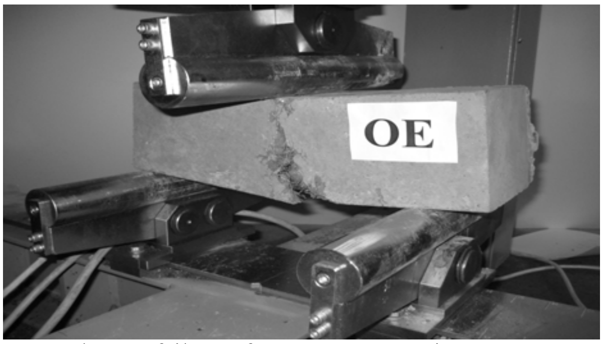

Figure 4. Flexure failure of a UHPFRC specimen.

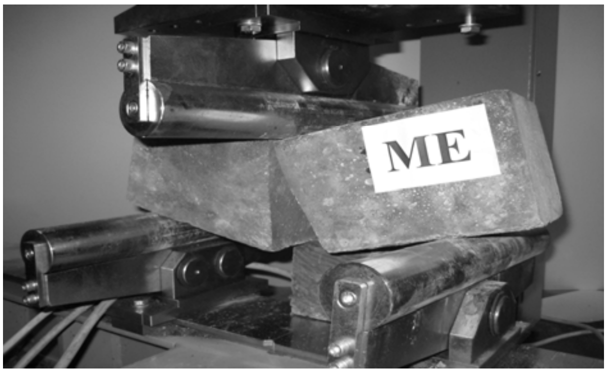

Figure 5. Flexure failure of a UHPC specimen.

Fiber reinforced concrete (UHPFRC) showed a flexural strength 150-165% higher than unreinforced concrete (UHPC). The geometry of the specimens influenced the flexural strength, smaller specimens exhibiting a higher strength, as seen in Table 4.

Table 4. Flexural strength (fct,fl).

Specimen geometry [mm]	Type	Curing	Mechanical properties [MPa]	Concrete Age 6 days	14	28
Prism 40x40x160	UHPC	T	$f_{ct,fl}$	13.4	13.8	14.8
Prism 100x100x300	UHPC	T	$f_{ct,fl}$	6.05	6.78	7.02
Prism 40x40x160	UHPFRC	T	$f_{ct,fl}$	21.8	23.1	22.30
Prism 100x100x300	UHPFRC	T	$f_{ct,fl}$	11.5	12.7	16.6

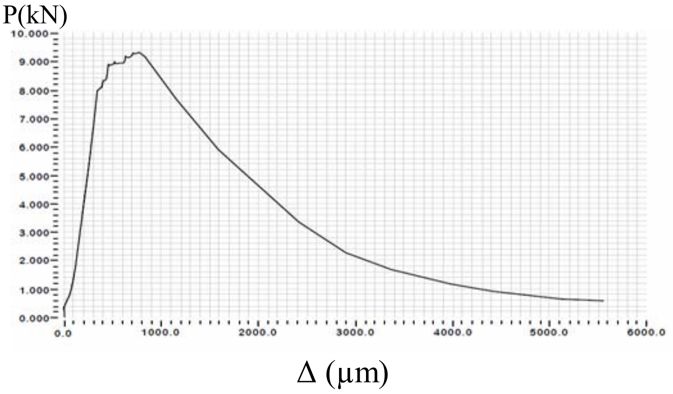

Figure 6. Load P(kN) vs. mid span deflection Δ (µm) curve (UHPFRC).

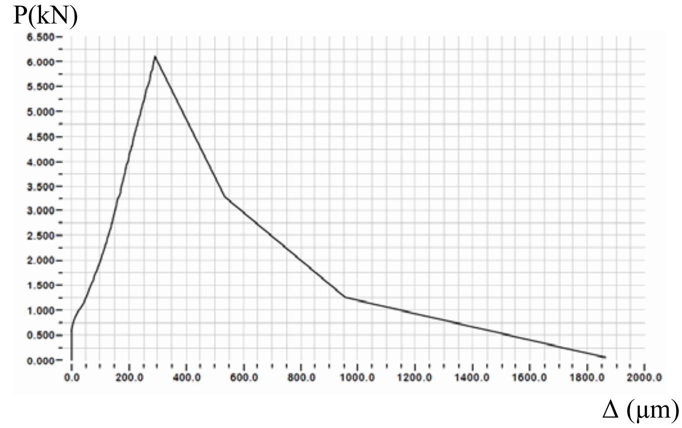

Figure 7. Load P(kN) vs. mid span deflection Δ (µm) curve (UHPC).

The flexural behavior of the two types of concrete can be observed by analyzing the load-deflection curves in Figures 6 and 7. UHPFRC displayed a ductile behavior.

The middle span deflection at maximum load, as well as the ultimate middle span deflection, is about three times higher for UHPFRC compared to UHPC (900µm compared to 300µm). The peak load of UHPFR was 1.5 times higher than the peak load of UHPC.

Table 5. Modulus of elasticity in compression.

Specimen geometry [mm]	Type	Curing	Mechanica l properties [MPa]	Concrete Age 6 days	14	28
Prism 100x100x30 0	UHPC	T	E_{static}	518 60	552 641	513 24
Prism 100x100x30 0	UHPC	W	E_{static}	499 45	550 738	550 360
Prism 100x100x30 0	UHPFRC	T	E_{static}	518 44	554 599	555 094
Prism 100x100x30 0	UHPFRC	W	E_{static}	506 60	553 778	553 997

4.3 *Modulus of elasticity in compression*

The specimens used for the determination of modulus of elasticity were 100x100x300 mm prisms with fiber reinforcement (UHPFRC) and without fibers (UHPC). The specimens were subject to thermal treatment (T) or water curing regime (W), as previously mentioned. The results are plotted in Table 5.

The results reveal a slightly increase with time of the modulus of elasticity independent of the curing regime. The UHPFRC displays a higher modulus compared with UHPC for both water curing and thermal treatment.

5 FREEZE-THAW RESISTANCE OF THE HARDENED CONCRETE

The durability of the UHPC and UHPFRC was evaluated in terms of freeze-thaw resistance. The specimens subject to freeze-thaw cycles were afterwards tested for dynamic and static modulus of elasticity. When tested, specimens exeeded 1000 freeze-thaw cycles (364 days). The results were then compared to correspondent witness specimens subject to water curing regime until testing (364days). Static and dynamic modulus of elasticity were tested using 100x100x300 prisms.

The results are plotted in Table 6 for UHPC (without fiber addition) and Table 7 for UHPFRC (fiber 2%Vol).

Table 6. Static and dynamic modulus for UHPC.

Specimen type	Curing regime	Properties [MPa]
UHPC-1	Thermal treatment 90^0C- 5 days Freeze-thaw 1000 cycles-364days	f_c=120 E_{static} = 52489 $E_{dynamic}$= 51250 $G_{dynamic}$=21362 $\mu_{dynamic}$=0.1962
UHPC-1W	Thermal treatment 90^0C- 5 days Water 20^0C- 364 days Witness specimen	f_c=94 E_{static} = 51990 $E_{dynamic}$= 50874 $G_{dynamic}$=20949 $\mu_{dynamic}$=0.2165
UHPC-2	Water curing 20^0C- 5 days Freeze-thaw 1000 cycles-364days	f_c=100 E_{static} =52200 $E_{dynamic}$= 50554 $G_{dynamic}$=21020 $\mu_{dynamic}$=0.2006
UHPC-2W	Water curing 20^0C- 5 days Water 20^0C- 364 days Witness specimen	f_c=96 E_{static} = 51460 $E_{dynamic}$= 50391 $G_{dynamic}$=21007 $\mu_{dynamic}$=0.2003

UHPC subject to freezing and thawing, had a modulus of elasticity in compression of about 52 GPa for both thermal treated and water cured specimens. UHPFRC displayed values of about 55GPa for both thermal treated and water cured specimens. Witness specimens displayed similar values, concluding that freeze-thaw cycles did not affect the modulus of elasticity.

Table 7. Static and dynamic modulus for UHPFRC.

Specimen type	Curing regime	Properties [MPa]
UHPFRC-1	Thermal treatment 90^0C- 5 days Freeze-thaw 1000 cycles-364days	f_c=163 E_{static} = 55075 $E_{dynamic}$= 53572 $G_{dynamic}$=22401 $\mu_{dynamic}$=0.1965
UHPFRC-1W	Thermal treatment 90^0C- 5 days Water 20^0C- 364 days Witness specimen	f_c=155 E_{static} = 53710 $E_{dynamic}$= 53460 $G_{dynamic}$=21963 $\mu_{dynamic}$=0.2182
UHPHFRC-2	Water curing 20^0C- 5 days Freeze-thaw 1000 cycles-364days	f_c=150 E_{static} =55858 $E_{dynamic}$= 53467 $G_{dynamic}$=22251 $\mu_{dynamic}$=0.2032
UHPFRC-2W	Water curing 20^0C- 5 days Water 20^0C- 364 days Witness specimen	f_c=115 E_{static} = 54550 $E_{dynamic}$= 53109 $G_{dynamic}$=21860 $\mu_{dynamic}$=0.2159

6 CONCLUSIONS

The paper presents the mechanical properties of ultra high performance concrete. The influence of steel fibre reinforcement, age, geometry of the specimens and enviromental conditions were evaluated.

Fiber reinforcement influence was analyzed towards compressive strength, splitting tensile strength, flexural strength and load-deflection curves.

Smaller specimens exihibited higher flexural strength.

Splitting tensile strength of UHPFRC is about 2.2 times higher than that of UHPC.

It was observed a ductile post peak behaviour for UHPFRC with 2%steel fibers by concrete volume.

For about 85-95% of the peak load UHPC and UHPFRC displayed a quasi-linear behaviour.

UHPC and UHPFRC specimens were not affected by the freeze-thaw cycles in terms of modulus of elasticity.

This reaserch will further be completed with experimental results regarding simple and complex state of stress and strains in UHPC and UHPFRC members.

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