DURABILITY, LOW AND HIGH TEMPERATURE BEHAVIOUR OF ULTRA HIGH-PERFORMANCE FIBRE REINFORCED CONCRETE

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Abstract

The objective of the research presented in this paper is to define the flexural behaviour of thin plates made of UHPC tested under 4-point bending and subjected to different temperature fields. Temperatures imposed during loading are between - 40°C and 100°C and applied to two types of Ductal® (FM and FO). The tests show a negative influence of high temperatures on the Ductal® FO and a positive influence of negative temperatures on the behaviour of both FM and FO Ductal®. In addition, some specimens of Ductal® FM and FO have undergone accelerated aging involving temperature, humidity, UV. This article shows the effects of aging on the behaviour of Ductal®. These exploratory tests demonstrate the interest to predict the behaviour of UHPC for use in extreme conditions which are vis-à-vis high or low temperatures, but also aging conditions.

Résumé

L'objectif de ces travaux de recherche présentés dans cet article est de définir le comportement en flexion de plaques minces réalisées en BFUP sollicitées en flexion 4 points et soumises à des champs de températures différents. Les températures imposées durant le chargement sont comprises entre - 40°C et 100°C et appliquées à deux types de Ductal® (FM et FO). Les essais montrent une influence négative des températures élevées sur le Ductal® FO et une influence positive des températures négatives sur le comportement des deux Ductal® FO et FM. De plus certains spécimens de Ductal® FM et FO ont subi un vieillissement accéléré regroupant température, humidité, UV. Le présent article montre les effets de ce vieillissement sur le comportement des Ductal®. Ces essais exploratoires montrent l'intérêt de prédire le comportement des BFUP pour leur utilisation dans des conditions extrêmes, que ce soit vis-à-vis des températures élevées ou faibles mais aussi des conditions de vieillissement.

1. INTRODUCTION

Several initiated projects by Lafarge UHPFRC team in remote cold areas such as Mongolia, Antarctica or Northern Canada regions have questioned UHPFRC performances in different temperature conditions, especially low, in the case of combined effects of stress and temperature. This study identifies the different influences of temperature on the overall behaviour of two types of Ductal®, namely Ductal® FM and Ductal® FO. Several authors have already worked on durability of UHPC. Main conclusions are that these results mainly depend on the mix design of the UHP matrix and the high volume fraction of the reinforcement; that produces a diffuse micro-cracking pattern and a hardening behaviour. It seems that the very fine crack widths created, allowed a fast self-healing of micro-cracks, limiting the influence of the external environment consequently [1-3]. Aim of the present research is to combine effects of temperature and moisture on UHPC.

2. EXPERIMENTAL TESTING

2.1 Test characteristics

Specimens tested were overall dimensions of 450 mm long, 140 mm wide and 20 mm high. Two types of UHPC were tested: Ductal® FM and FO. Ductal® FM is reinforced by steel fibres dosed with a volume rate of 2.1 %. Ductal® FO is reinforced by organic fibres dosed with a rate of 4.3 %. Ductal® FM plates were heat treated. Ductal® FO plates were stored for 28 days at 20 ° C and 100 % humidity. Total in the study, 36 specimens (half of each type) were tested.

2.2 Aging test characteristics

Three specimens of each type underwent a cycle of accelerated aging. The artificial aging test is performed in accordance with standard NF T 30-049 on the theme Paints and varnishes / cladding paints / accelerated aging test. The theoretical cycle of artificial aging is carried out in four phases (Fig. 1):

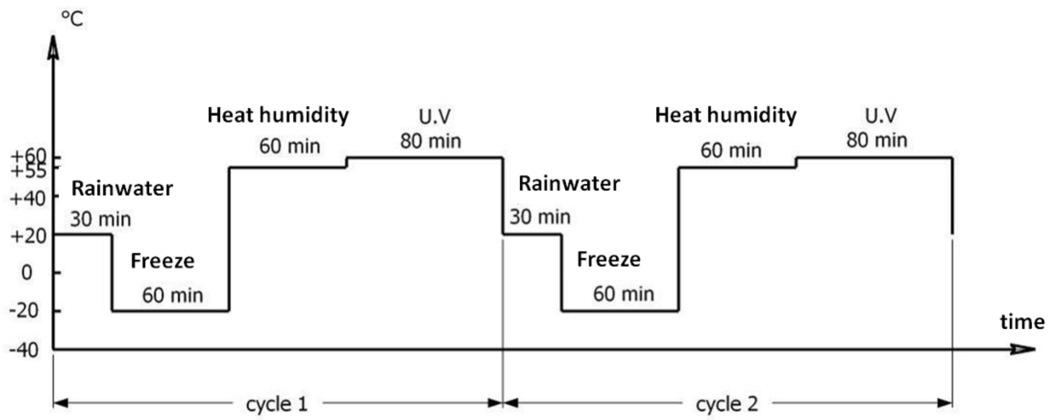


Figure 1: Aging test used

- A period of rain: A phase of artificial rain (water) is conducted for a period of 30 minutes. Watering is carried out by a device for the formation of fine droplets falling on the test specimens according to an incidence of 30 to 45 °. The chamber temperature was maintained at 20 ° C ± 1 ° C.
- A phase of cold: This phase allows maintaining the samples at a temperature of -20°C ± 1°C for a period of 60 minutes.
- A phase of moist heat: This phase keeps the specimens at a temperature of 55 °C ± 1 °C and a relative humidity of 95 % ± 1 % for a period of 60 minutes.

- And a phase of ultraviolet: This phase allows maintaining the samples at a temperature of 60 °C ± 1 °C, a relative humidity of 20 % ± 1 % and a UV radiation for a period of 80 minutes.

Control the temperature and humidity is provided by a climatic chamber type Vötsch (Fig. 2). The total number of cycles applied to the specimens represents 500 hours or 125 cycles.

Figure 2: a – climatic chamber, b – UV, c - rainwater

2.3 Bending test characteristics

Figure 3 depicts the test setup used in this research. Test specimens were subjected to four point bending. The distance between supports is 420 mm. The distance between support and applied load is equal to 140 mm. Load was applied at a rate of 1 mm/min. Load and displacement data was measured with the help of load cell and LVDT transducer and recorded by a data logger at 0.5 s intervals.

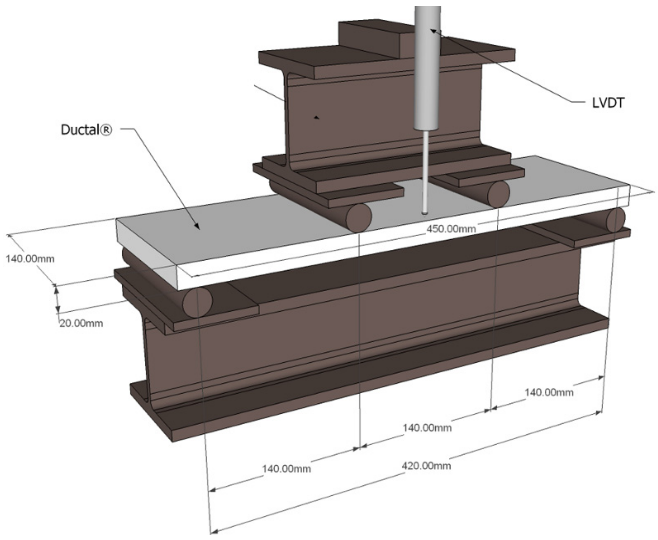


Figure 3: Four point bending test

3. RESULTS ANS ANALYSIS

3.1 Introduction

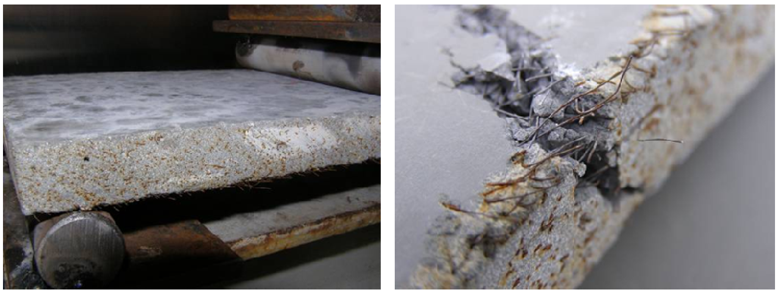
The maximum force Fmax has been measured by the force sensor. The term Pmax corresponds to the value of the force applied to each support frame of the 4-point bending bench. My is the bending moment due to the load Pmax. Normal stress σmax is the corresponding maximum stress. Normal stress σe is the stress value at the crack opening. Displacement δe corresponds to the displacement value read for the elastic load. Term K corresponds at initial stiffness. Elastic modulus value is estimated from the equation of beam loaded by four point flexure load test. This module corresponds to the linear behavior when the specimen is not considered cracked.

$$\delta = \frac{P \cdot a}{24EI}\left(3L^2 - 4a^2\right) \quad \longrightarrow \quad E = \frac{P \cdot a}{24\delta \cdot I}\left(3L^2 - 4a^2\right) \tag{1}$$

a: distance between support and applied load, I: beam inertia, P: load,
L: beam span, δ : deflection at mid-span

3.2 Aging effects

After the aging cycle applied to specimens, two visual observations can be made. For plates made of Ductal® FM, corrosion of metal fibres located on the lateral faces of the test specimens is recorded. This corrosion remains on the surface as the fibres embedded in the matrix are not impacted. For Ductal® FO, aging resulted in surface staining of UV exposed surfaces (Fig. 4). Table 1 shows the raw results of bending tests.



a – fiber steel corrosion Ductal ® FM

b – surface coloring Ductal ® FO

Figure 4: Aging effects

For reference specimens (Ductal® FM), the average maximum stress is equal to 48 MPa with a standard deviation of 2.8 MPa. Three specimens (Ductal ® FM) having undergone the aging cycle have a lower resistance (- 9 %) than control samples, the mean stress is 44 MPa with a standard deviation of 3.5 MPa. The same general remarks apply to the values of the normal stress at the crack opening. The tests show that aging has an impact on the overall behaviour of Ductal® FM specimens. Reference specimens have a slightly higher stiffness (22 %). Note that the standard deviation of the values is quite similar. For the elastic modulus, the trends displayed on the stiffness are similar with a lower modulus of elasticity due to aging (- 25 %). For reference specimens (Ductal® FO), the average maximum stress is 20 MPa with a standard deviation of 1.9 MPa. The three specimens having undergone the aging cycle have a resistance slightly higher (+ 4 %) than the control test specimens, the mean stress is 21 MPa with a standard deviation of 0.8 MPa. The tests show that aging has an effect on the overall behaviour of Ductal® FO specimens. In all cases the reference specimens have a slightly higher stiffness (20 %). For the elastic modulus, the trends displayed on the stiffness are similar with a lower modulus of elasticity due to aging (- 20 %).

Table 1: Aging test results

	Ductal ® FM						Ductal ® FO					
Test conditions	reference			Aged			reference			Aged		
Temperature [°C]	20						20					
Fmax [N]	5423	4811	5260	4246	4843	4995	2193	2246	2354	2193	1917	2315
Pmax [N]	2711	2405	2630	2123	2422	2497	1097	1123	1177	1097	959	1157
My [kN.mm]	380	337	368	297	339	350	153	157	165	154	134	162
σmax [MPa]	50.6	45.2	49.0	39.9	44.8	46.6	20.3	20.8	21.8	20.5	18.1	21.9
σmax,moy [MPa]	48.3			43.8			20.2			21.0		
Δσmax [MPa]	2.77			3.47			1.90			0.76		
Aging effect	- 9 %						+ 4 %					
σe [MPa]	23.8	23.3	21.2	19.7	19.7	20.1	18.8	20.7	21.7	17.3	16.5	19.5
σe,moy [MPa]	22.8			19.9			20.4			17.8		
Δσe [MPa]	1.38			0.20			1.48			1.54		
Aging effect	- 13 %						- 13 %					
δe [mm]	0.98	0.88	0.77	0.99	0.97	0.99	0.77	0.85	0.91	1.01	0.81	0.90
K [N/mm]	2819	2788	2866	2136	2292	2189	2637	2633	2578	1836	2157	2290
Κ moy [N/mm]	2824			2205			2616			2094		
ΔK	39.4			79.5			33			233		
Aging effect	- 22 %						- 20 %					
E [MPa]	53,677			40,122			48,741			39,148		
ΔE	2,832			2,379			1,661			7,987		
Aging effect	- 25 %						- 20 %					

3.3 Temperature effects

Analyses conducted on the effects of temperature are similar to those conducted on the effect of aging. For each type of concrete, 5 temperatures were applied to the specimens, - 40°C, - 20°C, 20°C, 60°C, 100°C for Ductal ® FM and - 40°C, - 20°C, 20°C, 40°C, 60°C for Ductal® FO. Table 2 shows the raw results of bending tests performed on specimens Ductal® FM and Table 3 shows the results for Ductal® FO.

Table 2: Ductal® FM temperature effects

	Ductal ® FM				
Temperature [°C]	- 40°C	- 20°C	20°C	60°C	100°C
Fmax [N]	6,482	6,111	5,260	5,300	5,525
Pmax [N]	3,241	3,056	2,630	2,650	2,763
My [kN.mm]	454	428	368	371	387
σmax [MPa]	60.0	56.6	48.3	49.1	51.2
Temperature effect	+ 24 %	+ 18 %	reference	+ 2 %	+ 6 %
σe [MPa]	25.4	29.5	22.8	21.2	20.5
Temperature effect	+ 11 %	+ 29 %	reference	- 8 %	- 10 %
δe [mm]	1.16	1.18	0.88	0.85	0.81
K [N/mm]	2412	2662	2824	2676	2623
Temperature effect	- 15 %	- 6 %	reference	- 5 %	- 7 %
E [MPa]	42,987 ± 2,787	47,295 ± 2,695	53,677 ± 2,832	51,721 ± 2,937	50,697 ± 3,030
Temperature effect	- 20 %	- 12 %	reference	- 4 %	- 6 %

Table 3: Ductal® FO temperature effects

	Ductal ® FO				
Temperature [°C]	- 40°C	- 20°C	20°C	40°C	60°C
Fmax [N]	3,560	3,240	2,250	1,950	1,675
Pmax [N]	1780	1620	1125	975	838
My [kN.mm]	249	227	158	137	117
σmax [MPa]	32.5	30.7	20.2	18.1	15.5
Temperature effect	+ 61 %	+ 52 %	reference	- 11 %	- 24 %
σe [MPa]	23.9	24.8	20.4	14.9	11.8
Temperature effect	+ 17 %	+ 22 %	reference	- 27 %	- 42 %
δe [mm]	1.16	1.14	0.91	0.51	0.64
K [N/mm]	2380	2409	2457	2500	2461
Temperature effect	- 3 %	- 2 %	reference	+ 2 %	+ 0 %
E [MPa]	40,413 ± 2,812	40,739 ± 2,061	48,741 ± 1,661	48,311 ± 4,070	47,556 ± 4,801
Temperature effect	- 17 %	- 16 %	reference	- 1 %	- 2 %

Temperature does not have the same effects on all characteristics of the Ductal® FM. Low temperatures increase the resistances of up to 18 % at - 20°C and 24 % to - 40°C. In contrast, high temperatures do not change the maximum stress at 60°C (+ 2 %) and 100°C (+ 6%). Low temperatures also increase the cracking stress (+ 11 % at - 40°C and + 29 % at - 20°C). Conversely high temperatures tend to decrease the strength of - 8 % at 60°C and - 10 % at 100°C. Finally, low temperatures decrease the elastic modulus of Ductal® FM down to - 20 % for a temperature of - 40°C, - 12 % for a temperature of -20°C. High temperatures do not much influence the value of the elastic modulus, - 4 % at 60°C and - 6 % at 100°C.

Temperature does not have the same effect on all characteristics of the Ductal ® FO. Low temperatures increase the resistances of up to 52 % at - 20°C and 61 % at - 40°C. In contrast, high temperatures greatly reduce the maximum stress at 40°C (- 11 %) and at 60°C (- 24 %). Low temperatures also increase the cracking stress of Ductal® FO (+ 17 % at - 40°C and + 22 % at - 20°C). Conversely, high temperatures tend to decrease the strength of - 27 % at 40°C and - 42 % at 60°C. During the test and due to the temperature some drying of cement paste can develop some internal self stresses due to differential humidity / drying between the top and the bottom of the sample that may explain some variations. Finally, low temperatures tend to lower the elastic modulus of Ductal® FO down to - 17 % for a temperature of - 40°C, - 16 % for a temperature of - 20°C. High temperatures do not much influence the value of the elastic modulus: - 1 % at 40°C and - 2 % at 60°C.

Curves of Figures 5 and 6 correspond to the average stress-deflection behaviour obtained in bending (Fig. 7) for each type of Ductal® under the different temperature conditions.

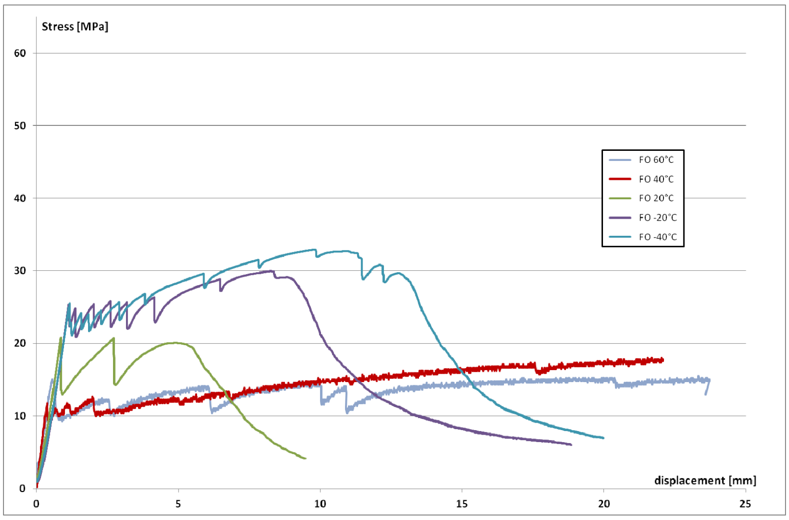


Figure 5: Ductal ® FO behaviour

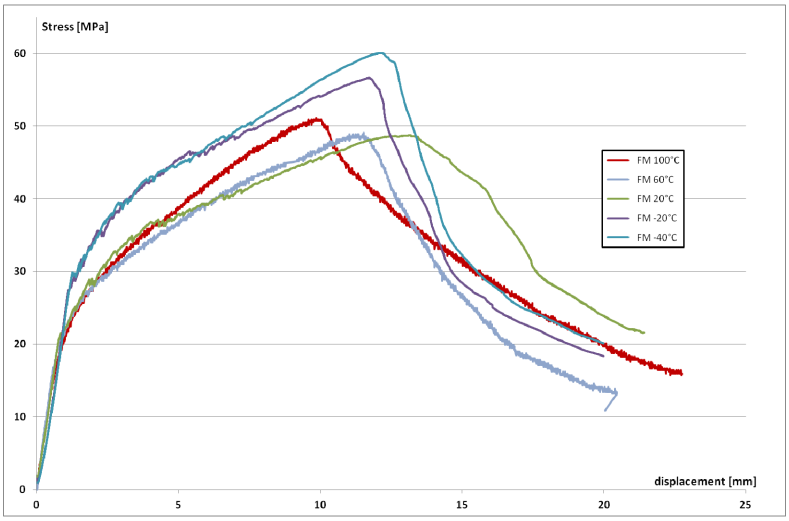


Figure 6: Ductal® FM behaviour

20°C -20°C

Figure 7: Temperature effect evaluated in bending tests on Ductal® specimens

4. CONCLUSIONS

In conclusion, Ductal® FM and Ductal® FO do not react the same way as a function of temperature and climate action. The Ductal® FO is more sensitive to external actions. In general, low temperatures allow increased resistance for both types of Ductal®, while the elastic modulus is decreased. High temperatures have little effect on the behaviour of Ductal® FM but decrease the resistance of Ductal® FO to - 24 %. The effects of aging are similar on both types of Ductal® formula since the results are reduced by about 20 % for Young's modulus, 15 % for the elastic stresses. During aging and due to the aging process with important variation of temperature and a high number of cycles, there can be some internal self stresses due to the differential humidity / drying (although temperature has stabilized) that may explain some variations (especially for Ductal® FO).

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