
LONG TERM BENDING BEHAVIOR OF ULTRA-HIGH PERFORMANCE CONCRETE (UHPC) BEAMS

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ABSTRACT

Unlike normal concrete (NC) the behavior of ultra-high performance concrete (UHPC) is different under long-term efforts, if we refer to creep, shrinkage or long-term deflections. It is well known that UHPC has special properties, like compressive strength higher than 150 MPa and tensile strength higher than 20 MPa - in case of UHPC reinforced with steel-fibers [1]. Nevertheless, UHPC is not so elucidated regarding creep straining or serviceability behavior in case of structural elements. Some studies made on UHPC samples [2] [3] shown that the creep is significantly reduced if the concrete is subjected to heat treatment and if it contains steel-fiber reinforcement. Relating thereto, it is important to know how does structural elements made of this type of concrete works in service life under long-term loadings. The results obtained on UHPC samples, regarding creep straining from tension or compression efforts may not be generalized in case of structural elements (e.g. beams, slabs, columns) subjected to bending [4]. Making this study it was proposed to understand the influence of the heat treatment and steel-fiber addition on the rheological phenomena of UHPC bended beams.

Keywords: ultra-high performance concrete; bending; creep; deflection

1. INTRODUCTION

Ultra-High Performance Concrete (UHPC) has an increased content of binder (cement + silica powder) and, because of the presence of quartz aggregate – which is very fine – and of a low water/cement ratio, the consistency of this concrete is similar to mortars [5].

With high compressive strength (greater than 150 MPa [6]), and also with high tensile strength (greater than 7 MPa, in case of concrete without steel-fiber addition [7]), the matrix of this type of concrete is very compact and homogeneous, having a very dense

REZUMAT

Spre deosebire de betonul obișnuit (BO), modul de comportare al betonului de ultra-înaltă performanță (BUIP) este diferit sub acțiunea eforturilor de lungă durată, în ceea ce privește curgerea lentă, contracția sau săgețile dezvoltate în timp. Este cunoscut faptul că BUIP are proprietăți speciale, cum ar fi rezistența la compresiune mai mare de 150 MPa și rezistența la întindere mai mare de 20 MPa – odată cu adăugarea fibrelor de oțel [1]. Cu toate acestea, BUIP necesită studii suplimentare privind modul de comportare în exploatare. Studiile făcute pe probe din BUIP [2] [3], au arătat ca fenomenul de curgere lentă este diminuat prin aplicarea tratamentului termic și adăugarea fibrelor de oțel. Astfel, este importantă cunoașterea modului de comportare a acestui tip de beton sub acțiunea încărcărilor de lungă durată și în cazul elementelor structurale. Rezultatele obținute pe probe din BUIP în ceea ce privește curgerea lentă nu pot fi generalizate și în cazul elementelor structurale (ex: grinzi, plăci, stâlpi) solicitate la încovoiere [4]. Realizând acest studiu, s-a urmărit înțelegerea efectului adus de tratamentul termic și de fibrele de oțel asupra grinzilor din BUIP solicitate la încovoiere de lungă durată.

Cuvinte cheie: beton de ultra-înaltă performanță; încovoiere; curgere lentă; săgeată

structure. This is why it has an explosive behavior under compressive efforts at the failure moment (Fig. 1) [8]. In contrast with normal concrete (NC), UHPC develops micro-cracks at a higher level of loadings, due to its high amount of binder, and because the micro-cracks are formed through the concrete matrix and aggregates, not at their interference [9].

The compressive strength obtained on samples subjected to special vibrating and compacting technologies, can reach up to 800 MPa in case of UHPC reinforced with steel-fibers. Due to the use of silica powder as a binder and of quartz powder (very fine

aggregates), these concretes were named “reactive powder concretes” [10].



Fig. 1. Compressive failure of an UHPC cylindrical sample [8]

Shah and Weiss [11], define UHPC as follows: “Ultra-High Performance Concrete (UHPC) is defined as a special material with high durability and a minimum compressive strength of 150 MPa (22 ksi)”.

Regarding the creep phenomenon, this is defined as that complex phenomenon where the concrete suffers deformations due to the transformation of the jelly phase of the cement stone and due to the water migration in the concrete structure, under the effect of long-term and short-term loadings [12]. The creep phenomenon could be divided in two components, namely: basic creep and drying creep [13]. In case of UHPC, due to its lower water/cement ratio, the viscous nature of the cement matrix is consolidated in time, while the water migrates into the concrete structure. Also, the creep in case of UHPC decreases significantly with heat treatment [14]. For beams tested on long term-bending, the creep of the compressed zone is evaluated as the ratio between the initial strains and the strains developed in time, after loading ($\phi = \epsilon_{td} / \epsilon_i$) [15]. Kamen et al. [16] studied, among others, the tensile and compressive creep on UHPC, with or without steel-fibers reinforcement. As a main result of his research, he observed that

the tensile creep coefficient was equal to the compressive one, obtained on cylindrical and prismatic samples loaded at 50% of their strength. Another factor besides steel-fibers addition, which reduces creep effect, is thermal treatment. Garas et al. [17] observed that creep is significantly reduced (about 40%) in case of UHPC samples exposed to thermal treatment and, after that, subjected to long-term compression or tensile stresses, unlike those which were not exposed to thermal treatment. It is well known that some of the main factors that influence concrete creep are the loading step, the concrete age at the loading moment and the value of the long-term loading. If we refer to normal strength concrete, this develops a creep coefficient proportional with the value of the long-term loading. For example, if we double or triple the loading, the creep coefficient will increase with the same range [18]. In case of UHPC, Flietstra [2] observed that, by increasing the load, the creep is not that much influenced. He noticed that on the cylindrical samples subjected to long-term compression effort, the creep coefficient doubled even if the applied load was tripled. This behavior can be seen in Figure 2 [2].

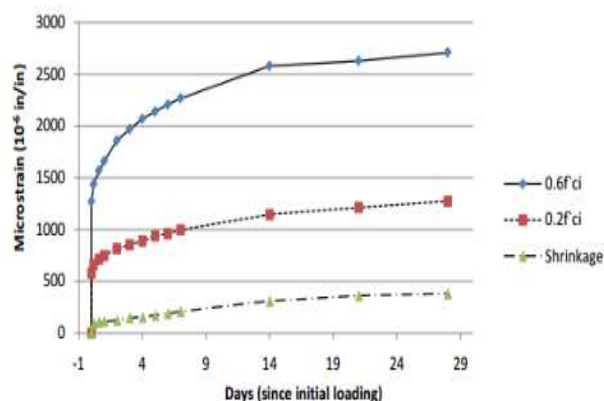


Fig. 2. Creep strains influenced by the loading step [2]

Nevertheless, the creep of UHPC is still unsolved, and it depends and can be influenced by many factors. In addition, it is necessary to find out clues about how it can influence the design of structural elements, and to see how much the time-depending strains (creep, shrinkage) and displacements of these

elements can be modified over the time. Knowing the behavior in terms of long-term strains of UHPC members in service life, we can well-predict the displacements and the cracking state, thus making slender and more economical structures.

In accordance with the prescriptions given by Donna and Raafat [19], the long-term deflection in case of large-span beams or girders can represent around 50% of the initial deflection. Currently, at global level it was attempted to define and model the behavior of UHPC beams subjected to bending; however, concerning the long-term bending of UHPC beams, the mechanism is not well defined and no design code does address this fact for UHPC members. Ashour et al. [20] studied the long-term deflection on high-strength concrete (HSC) beams subjected to a loading level of 50% of their bearing capacity. He evaluated the creep of the entire elements using the increase of the mid-span deflection in time. Using the same way to evaluate the creep of the UHPC beams presented in this paper, it was possible to define the evolution of strains and deflections for four beams reinforced with various percentages of steel-fibers (0.00; 0.50; 1.50 and 2.55% - vol.-%).

2. RESEARCH OBJECTIVE

The main objective of the research is the behavior of long-term bent beams made of UHPC, having a compressive strength of at least 150 MPa. The studies published worldwide are still limited in terms of long-term actions on structural elements made of UHPC with or without steel-fibers. In the experimental program, it was chosen to test beams with I section, subjected to long-term bending representing 45% of their bearing capacity.

Four I-section beams with cross-sectional dimensions of 120 × 240 mm and total length of 3200 mm, were subjected to long-term bending. Among the four beams, one was without steel-fibers addition, while the others contained 0.50%, 1.50% and 2.55% (vol.-%), respectively, hybrid steel-fibers addition. Hybrid fibers represent the combination

between short and long steel-fibers. Half from each quantity were short-fibers, and half – long-fibers. The identification codes of the beams and their percentage of steel-fibers addition is presented in Table 1.

Table 1. Beams name and their steel-fiber percentage volume

Element No.	Beam ID	Steel-fiber percentage (vol. - %)
1	1 HB 0.00	0
2	1 HB 0.50	0.50
3	1 HB 1.50	1.50
4	1 HB 2.55	2.55

The behavior of the four beams was analyzed in terms of time-increasing strains and deflections. In addition, it was observed the influence of different quantities of steel-fibers, added to the concrete mass, and it was analyzed the effect they had on the creep of the compressed zone of the beam and on long-term deflections. Based on these, it could be determined the optimal steel-fiber percentage, in order to achieve an economical design; also, this could help create new slender structures with minimum maintenance costs.

3. MATERIALS

3.1. Concrete

The experimental beams were made of ultra-high performance concrete, with a medium compressive strength higher than 150 MPa. The concrete composition was determined according to steel-fibers percentage from the concrete mass. Even if the water/binder ration (w/b) was 0.2, the concrete has a good workability, due to addition of superplasticizer Glenium ACE440.

In case of beams without steel-fibers addition, the concrete composition consisted of 51% binder and 49% other materials, from the total concrete mass. For beams with steel-fibers addition the materials proportions were about 48% binder, 46% other materials and the rest of 6% represented the steel-fibers, as percentages from the concrete mass. To obtain

a homogeneous mix, and to avoid the cracking due to the shrinkage process, a special attention was given to the mixing times of component materials. The order of introduction of materials in the mixer was: the aggregate; the binder, the water + additive and, in the final phase, the steel-fibers.

After the casting (24 hours later), the beams and the samples taken for the determination of physical and mechanical properties of the concrete were exposed to thermal treatment at a temperature of 90°C and a relative humidity (RH) of 90% for 120 hours (5 days). The thermal treatment was applied using a special oven (Fig. 3), which was built for that purpose.



Fig. 3. The oven used for applying the thermal treatment

By thermal treatment, the concrete strength increases due to the influence of high temperature and humidity. Using high temperature in the treatment process, the internal humidity of the concrete decreases; this also helps binder hydration and, by applying steam at that temperature, provides a relative humidity of 90%, which helps the hydration of non-hydrated binder at the concrete surface. Also, one of the main attributes of the high temperature and humidity is to maintain an optimum temperature of the concrete from the inside out, avoiding the premature cracking of the elements [21].

The samples molded at the same time with the beams, which were used to determine the physical and mechanical properties, were kept in the climate chamber at a temperature of $(20 \pm 2)^{\circ}\text{C}$ and a relative humidity (RH) of

$(60 \pm 5) \%$. The beams were kept in the same climate conditions until the date they were tested. Figure 4 presents an image of the UHPC samples kept in the climate chamber.



Fig. 4. UHPC samples kept in the climate chamber

After applying the thermal treatment, at the age of 6 days, it was considered that the concrete has reached the maximum strength. On the samples taken from each beam, the compressive and the tensile strength were determined, as well as the elasticity modulus.

The machine used to determine the compressive strength was a hydraulic press with a capacity of 3000 kN, with a loading speed of 2 MPa/s. For each test, the main criterion in concrete quality evaluation was to have a minimum strength of 150 MPa. Only beams with that minimum compressive strength were used in the experimental program. The compressive strength of the concrete after thermal treatment is presented in Table 2.

Table 2. Concrete compressive strength after thermal treatment

Beam name	Steel-fiber percentage (vol. - %)	Medium compressive strength (f_{cm}) (MPa)
1 HB 0.00	0.00	172.60
1 HB 0.50	0.50	175.40
1 HB 1.50	1.50	180.90
1 HB 2.55	2.55	190.30

The tensile strength was determined using the three-point bending method, being similar for long-term bending of tested beams. As samples, prisms with dimensions of

40 x 40 x 160 mm, without notch at middle span, were used.

The tensile strength (f_{ct}) of the plain and steel-fiber reinforced concrete, determined by using the three-point bending method after the samples were subjected to thermal treatment is presented in Table 3.

Table 3. Concrete tensile strength after thermal treatment

Beam name	Steel-fiber percentage (vol. - %)	Tensile strength (f_{ct}) (MPa)
1 HB 0.00	0.00	13.56
1 HB 0.50	0.50	20.25
1 HB 1.50	1.50	27.92
1 HB 2.55	2.55	34.52

The results showed that the thermal treatment had a beneficial effect on concrete strengths and, due to addition of steel-fibers, the most significantly influenced property was the tensile strength, which increased by 160% as compared with the plain concrete. Also, the compressive strength of the concrete was influenced by the steel-fibers, but only in proportion of 10%.

3.2. Reinforcement

The reinforcing bars were made of S500 steel, with a yielding strength of 500 MPa. In the tension zone, the beams were reinforced with 3 ϕ 14 bars and, at the top of the cross-section two ϕ 6 constructive bars were positioned. In case of the beam without steel-fiber addition, the shear reinforcement was represented by ϕ 6 stirrups, made of S500 steel, at a distance of 100 mm and, for the other beams, the stirrups were positioned only in the supports area and in the zone where the forces were applied.

The hybrid reinforcement with steel-fibers was represented by two types of fibers. Half of each quantity were long fibers (type WMS-25/04/H-20BP) and the other half were short fibers (type MSF 6/0175/S). The long fibers had a diameter of 0.4 mm and a length of 25 mm, while the short fibers had a diameter of 0.16 mm and a length of 6 mm. Figure 5

shows an image of the steel-fiber types used as hybrid reinforcement.



Fig. 5. Long (left) and short (right) steel-fiber reinforcement

Regarding the reinforcement percentage of the beams, given by reinforcing bars (ρ_s), for all four beams it was used an optimal percentage of 2.0%. In the compressed zone of the cross section, the influence of reinforcing bars, which had a reinforcing percentage of 0.25%, was of interest. The steel-fiber percentage was determined using the ratio between steel and concrete volumes.

4. ELEMENTS CONFIGURATION AND TESTING

In the experimental program, four beams of UHPC reinforced with different percentages of hybrid steel-fibers were constructed, these being subjected to long-term bending. The dimensions of the beam cross-sections were 120 x 240 mm and the total length was 3200 mm. The long-term bending was applied as two concentrated forces ($2 \times P_{ld}$) in the middle third of the beam. The beam configurations with dimensions are shown in Figure 6.

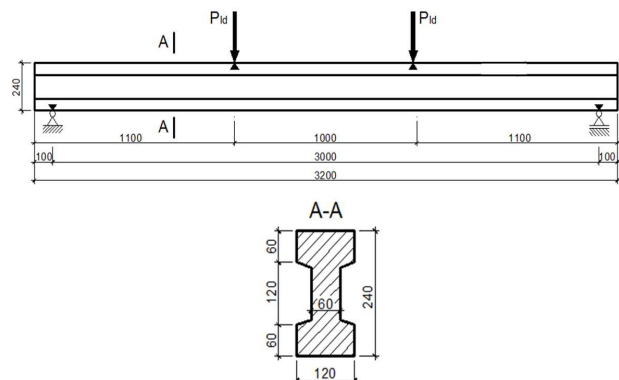


Fig. 6. Beams configuration and static sketch

The long-term loading represented 45% of the bearing capacity of each beam. To record the ultimate bending moment, similar beams were tested to failure at short-term bending. The values are presented in Table 4.

Table 4. Long-term loading values

Beam name	Bearig capacity M_u (kNm)	Log-term loading $M_{ld}=0.45M_u$ (kNm)
1 HB 0.00	45.10	20.20
1 HB 0.50	50.05	22.50
1 HB 1.50	54.44	24.50
1 HB 2.55	60.00	27.00

The bending effort was applied using weights on a ripen system. Using this type of system the two concentrated forces resulted by amplifying the weights by ten times. Figure 7 presents an image of tested beams subjected to long-term bending.



Fig. 7. UHPC beams subjected to long-term bending

The beams were monitored for 360 days. The interest area was the middle zone of the beam, where the strains and the deflections were measured for all types of beams. The measured values were recorded using devices with a precision of 0.01 mm.

5. RESULTS AND DISCUSSIONS

After 360 days of monitoring, the total specific strains of the compressed zone decreased with the increasing of the steel-fiber

percentage, having the values presented in Table 5.

Table 5. Specific strains of the compressed zone

Beam name	Steel-fiber percentage (vol. - %)	Specific strains (‰)
1 HB 0.00	0.00	0.610
1 HB 0.50	0.50	0.580
1 HB 1.50	1.50	0.550
1 HB 2.55	2.55	0.527

In addition, the initial strains of the compressed zone were smaller for the beam with 2.55% (vol.-%) steel-fiber addition, as compared with the beam without fibers. This was possible because the steel-fibers increased the stiffness of the cross-section. The strain stabilization time was significantly reduced by the steel-fibers, as show in Table 6.

Table 6. Stabilization time of the strains in the compressed zone

Beam name	Steel-fiber percentage (vol. - %)	Stabilization time (days)
1 HB 0.00	0.00	120
1 HB 0.50	0.50	90
1 HB 1.50	1.50	90
1 HB 2.55	2.55	56

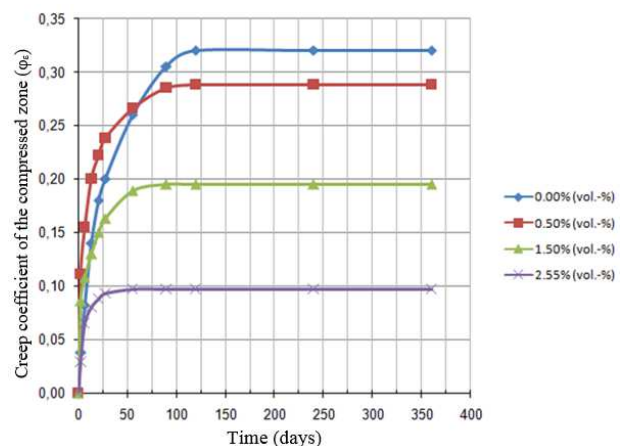


Fig. 8. Creep coefficient of the compressed zone of the beams

The variation of strain with time was observed using the creep coefficient (ϕ_ϵ). The variation of creep for each type of beam is shown in Figure 8.

The beam deflections also decreased due to the addition of steel-fibers. In Table 7, the values of the long-term deflections and of their stabilization time for each type of beam are presented.

Table 7. Long-term deflection of the beams

Steel-fiber percentage (vol. - %)	Long-term deflection Δ_{ld} (mm)	Stabilization time (days)
0.00	1.16	120
0.50	0.91	90
1.50	0.76	90
2.55	0.65	56

By increasing the steel-fiber addition from 0.50% (vol.-%) to 2.55% (vol.-%), the moment of inertia of the cross section also increased. This influenced directly the instant and long-term deflections, due to the increase of stiffness. Figure 9 shows the influence of steel-fibers on the long-term deflection of each type of beam, and its evolution in time, using the creep coefficient reported on long-term deflection.

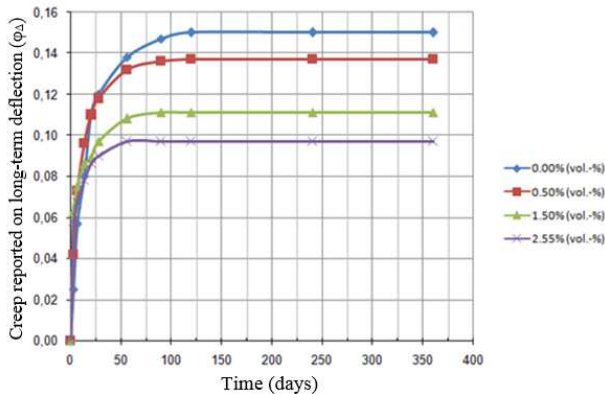


Fig. 9. Creep reported on long-term deflection

For all the elements subjected to long-term bending, regardless of the steel-fiber percentage, the maximum crack width does not increase more than 1 mm. This value, obtained at the moment of applying the long-term loading, remained constant for all 360 days of monitoring. The only quantity that

varied was the number of cracks that have developed over the time. Thus, it was observed that the number of cracks decreased by increasing the volume of steel-fibers in the concrete mass. The number of cracks was reduced by half for the beam with 2.55% (vol.-%) steel-fibers, unlike the beam without steel-fibers addition.

6. CONCLUSIONS

The maximum value of the creep coefficient in the compressed zone, after 360 days, for the beam without steel-fibers addition was 0.320, while in case of the beam with 2.55% (vol.-%) steel-fiber addition it was 0.097, which means a decrease of 70%. The differences between percentages of 0.50%, 1.50% and 2.55% (vol.-%) steel-fibers, were about 30%.

The decrease of the long-term deflection was strongly influenced by the increase of the steel-fibers percentage. The beam with 2.55% (vol.-%) steel-fiber addition showed a smaller long-term deflection, which means a decrease of up to 78% as compared to the beam without steel-fibers. The differences between steel-fibers percentages were around 35%.

During the monitoring period, the crack width did not vary, but new cracks appeared with a medium width of 0.02 mm and a height of 60 mm. In case of the beams with steel-fiber addition, while the steel-fiber percentage was increased, the cracks were developed only in the areas where the two loading forces were applied, forming groups of cracks.

Regarding the analysis of the results on the behavior of UHPC beams reinforced with different percentage of steel-fibers, it was observed that every type of UHPC beam showed a good behavior in time, in terms of strains, deflections and cracks. For a structural application, the author suggests that a volume percentage of 0.50% steel-fibers would be sufficient to ensure a good behavior in time.

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