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. Nevertheless, UHPC behavior is not completely elucidated in what concerns creep straining or serviceability behavior in case of structural elements. Some studies made on UHPC samples shown that 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. By performing this study, it was aimed to understand the influence of heat treatment and steel-fiber addition on the rheological phenomena of UHPC bended beams.

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

REZUMAT

Spre deosebire de betonul obişnuit (BO), modul de comportare al betonului de ultra-înaltă performanţă (BUIP) este diferit sub acțiunea eforturilor de lungă durată, în ceea ce priveşte 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. Cu toate acestea, BUIP necesită studii suplimentare privind modul de comportare în exploatare. Studiile făcute pe probe din BUIP, au arătat ca fenomenul de curgere lentă este diminuat prin aplicarea tratamentului termic și adăugarea fibrelor de oțel. Astfel, este importantă cunoaşterea 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 priveşte curgerea lentă nu pot fi generalizate și în cazul elementelor structurale (ex: grinzi, plăci, stâlpi) solicitate la încovoiere. 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 performanţă; încovoiere; curgere lentă, săgeată.

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 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 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 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 the 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 the heat treatment [14]. In case of 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 ($\varphi=\varepsilon_{ld}/\varepsilon_i$) [15]. Kamen et al. [16] studied, among others, the tensile and compression creep on UHPC, with or without steel-fiber 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% from their strength. Another factor besides steel-fiber addition, which reduces creep effect, is the thermal treatment. Garas et al. [17] observed that creep is significantly reduced (about 40%) in the case of UHPC samples exposed to thermal treatment and after that subjected to long-term compression or tensile efforts, unlike those that were not exposed at the thermal treatment. It is well known that one of the main factors that influence the concrete creep is 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 factor [18]. In the 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].

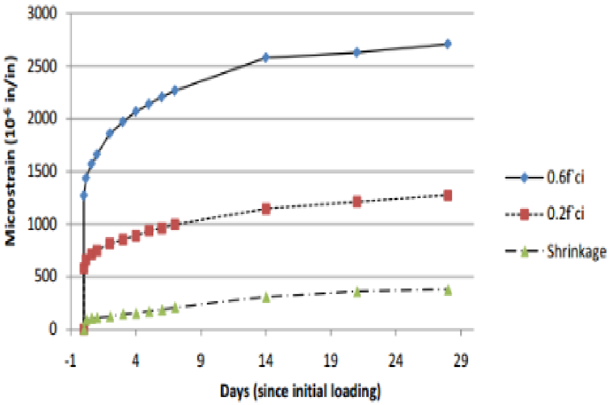

Fig. 2. Creep strains influenced by the loading step [2]

Nevertheless, the creep of UHPC it is still unsolved, and it depends and can be influenced by many factors. Also, 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, the displacements and the cracking state can be correctly predicted, leading to the design of slenderer and more economic 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% from the initial deflection. Currently, at the global level it was tried to define and modeling the behavior of UHPC beams subjected to bending, but in this domain of long-term bending of UHPC beams is not well defined the mechanism and any design code does not approach this fact at the level of UHPC members. Ashour et al. [20] studied the long-term deflection on high-strength concrete (HSC) beams subjected to a loading level of 50% from 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 developing mode of the strains and deflections of four beams reinforced with different percentage 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 bended beams made of UHPC, having a compressive strength of at least 150 MPa. The researches 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 was chosen to realize beams with I section subjected to long-term bending, representing 45% of their bearing capacity.

There was four I-section beams, subjected to long-term bending, with their cross-section dimensions of 120x240 mm, and total length of 3200 mm. Among the four beams, one was without steel-fiber addition, and the others contained 0.50%, 1.50% respectively 2.55% (vol.-%) hybrid steel-fiber addition. Hybrid fibers represent the combination between short and long steel fibers. Half from each quantity were short-fibers and half long-fibers. The notation of the beams and their percentage of steel-fiber addition are presented in the Table 1.

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

Element no.	Beam name	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 of strains and deflections. In addition, the influence of different quantities of steel-fibers added to the concrete mass was monitored, and their effect on the creep of the compressed zone of the beam and on long-term deflection was analyzed. Based on these, it could be concluded what percentage of steel-fibers is optimal, in order to achieve an economical design; this could also help in the design of 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 the steel-fiber percentage of the concrete mass. Even if the water/binder ratio (*w/b*) was 0.2, the concrete has a good workability, due to addition of superplasticizer Glenium ACE440.

In the case of beams without steel-fiber addition, the concrete composition was 51% of the concrete mass binder and 49% other materials. In the case of beams with steel-fiber addition the proportions of materials in the concrete mass were about 48% binder, 46% other materials and the rest of 6% represented the steel-fiber percentage. To obtain a homogeneous mixing and to avoid the cracking due to the shrinkage process, a special attention was given to the mixing times of the component materials. The order of introduction of materials in the mixer was as follows: the aggregate; the binder, the water + the additive and, in the final phase, the steel fibers.

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


Fig. 3. The oven for applying the thermal treatment

By the applying of thermal treatment, the concrete strength is increasing due to the influence of high temperature and humidity. Using high temperature in the treatment process, the internal humidity of the concrete is decreasingș this helps as well the binder hydration and, by applying steam at that temperature, provides a relative humidity of 90%, which helps in hydrating the non-hydrated binder at the concrete surface. In addition, one of the main roles 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, used to determine the physical and mechanical properties, were kept in the climate chamber at a temperature of (20 ± 2) °C and at a relative humidity (RH) of (60 ± 5) %. The beams were kept in the same climate conditions until the date they were tested. Figure 4 presents a picture 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 is considered that the concrete has reached the maximum strength. On the samples taken from each beam the compressive and tensile strength and also the modulus were determined.

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 the 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 three-point bending method, being similar for long-term bending of tested beams. As samples, prisms with dimensions of 40x40x160 mm, without notch at middle span were used.

The tensile strength (f_{ct}) of the plain and steel-fiber reinforced concrete, determined 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 that the most significantly influenced property due to addition of steel fibers was the tensile strength, which increased by 160% compared with the plain concrete. In addition, 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 steel S500, with yielding strength of 500 MPa. In the tension zone, the beams were reinforced with 3Ø14 bars and, at the top of the cross section 2Ø6 constructive bars were positioned. In the case of the beam without steel-fiber addition, the shear reinforcement was represented by 100 mm-spaced Ø6 stirrups, made of steel S500. In the case of 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 made with 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, and the short fibers, a diameter of 0.16 mm and a length of 6 mm. Figure 5 presents an image of the steel-fiber types used as hybrid reinforcement.

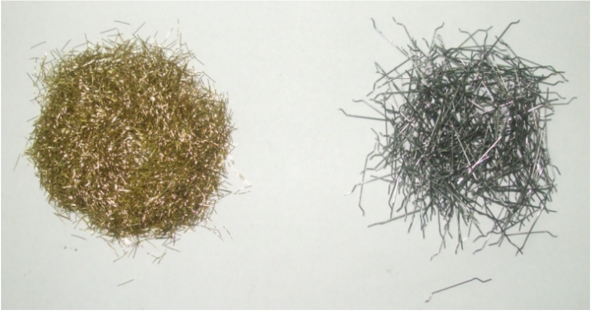

Fig. 5. Long (left) and shirt (right) steel-fiber reinforcement

Regarding the beam reinforcement percentage, given by reinforcing bars (ρ_s), in the case of all four beams an optimum percentage of 2.0% was used. In the compressed zone of the cross section, the influence of reinforcing bars was of interest; these had a reinforcing percentage of 0.25%. 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 percentage of hybrid steel fibers, subjected to long-term bending, were used. The dimensions of the cross sections of the beams were 120x240 mm and the total length was 3200 mm. The long-term bending was applied as two concentrated forces (2xP_{ld}) in the middle third of the beam. The beams configuration with dimensions is presented in Figure 6.

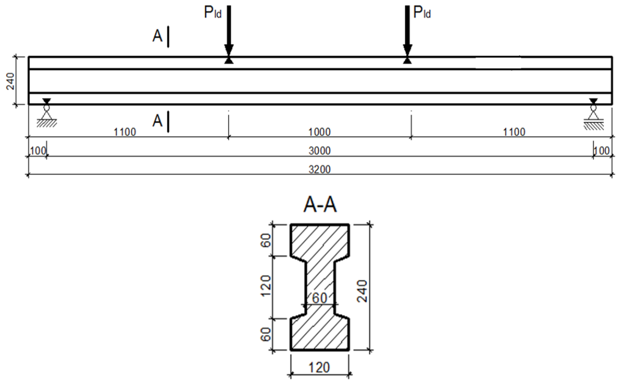

Fig. 6. Beams configuration and static sketch

The long-term loading represented 45% of the bearing capacity of each beam. For register 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 by 360 days. The interest area was the middle zone of the beam where was measured the strains and the deflections on every type of beam. The measured values were registered using devices with precision of 0.01 mm.

5. RESULTS AND DISCUSSIONS

After 360 days of monitoring, the total specific strains of the compressed zone decreased by increasing the steel-fiber percentage and they had 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

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

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

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

The variation of strains with time was monitored using the creep coefficient (φ_ε). In Figure 8 presents the variation of creep for each beam type.

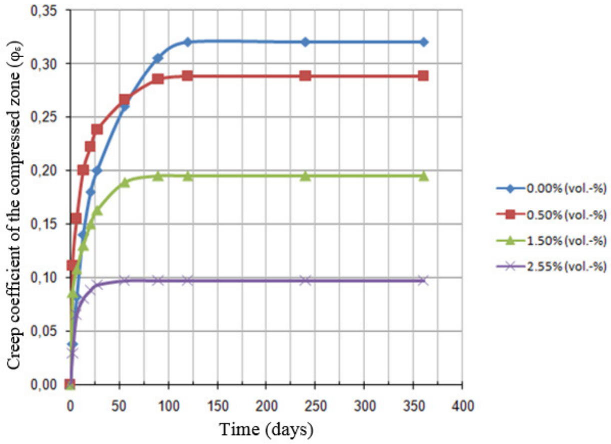

Fig. 8. Creep coefficient of the compressed zone of the beams

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

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 amount from 0.50% (vol.-%) to 2.55% (vol.-%), the modulus of elasticity of the cross section also increased. This influenced directly the instant and long-term deflection, because of the stiffness increase. Figure 9 shows the influence of steel fibers on the long-term deflection of each type of beam and its variation with time, based on ratio between the creep coefficient and the long-term deflection.

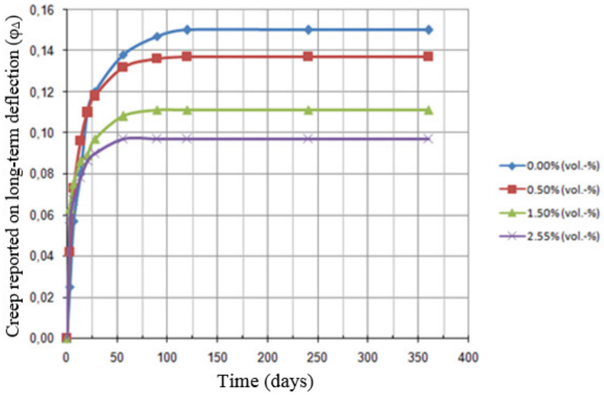

Fig. 9. Creep reported on long-term deflection

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 when applying the long-term loading, remained the same during all the 360 days of monitoring. The only parameter that varied was the number of cracks that developed over the time. Thus, it was observed that the number of the cracks decreased by increasing the volume of steel fibers in the concrete mass. The number of cracks was reduced by half in case of the beam with 2.55% (vol.-%) steel fibers, unlike the beam without steel-fiber addition.

6. CONCLUSIONS

The maximum value of the creep coefficient from the compressed zone, at 360 days, was 0.320 for the beam without steel-fiber addition, 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 beams with 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-fiber percentage. For the beam with 2.55% (vol.-%) steel-fiber addition a smaller long-term deflection was recorded, which means a decreasing up to 78% as compared to the one of the beam without steel fibers. The differences between the 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 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 percentages of steel fibers, it could be observed that every type of UHPC beam had a good behavior in time in terms of strains, deflections and cracks. For a structural application, a volume percentage of 0.50% steel fibers will be enough to ensure a good behavior in time.

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