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Long-term Behavior of Ultra – High Performance Concrete (UHPC) Bended 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 (Magureanu, 2010). Nevertheless, UHPC is not so elucidated regarding creep straining or serviceability behavior in case of structural elements. Some studies made on UHPC samples (Flietstra, 2011) (Burkart, 2009) 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 (Spasojevic, 2008). 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.
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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 a low water/cement ratio, the consistency of this concrete is similar to mortars [5].

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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 [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]. Due to the use of silica powder as a binder and quartz powder (very fine aggregates), these concretes were named “reactive powder concretes” [10]. Shah S. and Weiss W. [11], defines 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 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 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 A. et al. [16] studied, among others, the tensile and compression 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% from their strength. Another factor besides steel-fibers addition which reduce creep effect, is the thermal treatment. Garas V. et al. [17] observed that the 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 efforts, unlike those which were not exposed at the thermal treatment. It is well known that one of the main factors which influences 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, it 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 J. [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 1 [2].

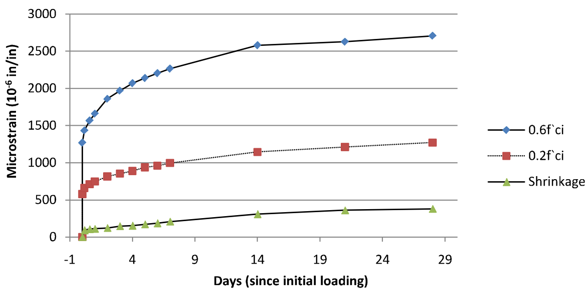

Fig. 1. Creep strains influenced by the loading step [2]

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, we can well predicted the displacements and the cracking state, making slender and more economical structures.

In accordance with the prescriptions given by Donna S. and Raafat E. [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 modelling 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 S. 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% from 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-fibers addition, and the others contained 0.50%, 1.50% respectively 2.55% (vol.-%) hybrid steel-fibers addition. Hybrid fibers represents the combination between short and long steel-fibers. Half from each quantity were short-fibers and half long-fibers. Notation mode of the beams and their percentage of steel-fibers addition is 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	0.00
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. Also, it was watched the influence of different quantities of steel-fibers, added to the concrete mass, and it was analyzed the effect they had on creep of compressed zone of the beam and on long-term deflection. Based on these, we could say what percentage of steel-fibers is optimum, in order to achieve an economical design, and also it can help us to create new slender structures with minimum costs of maintenance.

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 was composed of 51% binder and 49% other materials, from the concrete mass. In case of beams with steel-fibers addition the materials proportions were about 48% binder, 46% other materials and the rest of 6% represented the steel-fibers percentage from the concrete mass. For obtaining a homogeneous mixing, and to avoid the cracking from the shrinkage process, a special attention was given to the mixing times of the component materials. The introduction order of materials in the mixer was: the aggregate; the binder, the water + additive and, in the final phase the steel-fibers.

After casting (24 hours later) the beams and the samples taken for determination the 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). 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 decreasing and also it helps 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. Also, one of the main attribute 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 relative humidity (RH) of (60 ± 5) %. The beams were kept in the same climate conditions until the date they were tested. 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 was determined the compressive and tensile strength and also the 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. 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

Tensile strength was determined using three-point bending method, on prisms with dimensions of 40x40x160 mm, without notch at middle span. 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 shown that the thermal treatment had a beneficial effect on concrete strengths and due to addition of steel-fibers the most influenced property was the tensile strength which increased by 160% 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 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 case of the beam without steel-fiber addition, the shear reinforcement was represented by Ø6 stirrups, made of steel S500, at distance of 100 mm and, in 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 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, and the short fibers, a diameter of 0.16 mm and length of 6 mm.

Regarding reinforcement percentage of the beams, given by reinforcing bars (ρ_s), in case of all four beams, it was used an optimum percentage of 2.0%. In the compressed zone of the cross section, it was of interest the influence of reinforcing bars, which 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 were made four beams of UHPC reinforced with different percentage of hybrid steel-fibers, subjected to long-term bending. The dimensions of the cross section of the beam 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 are presented in Figure 2.

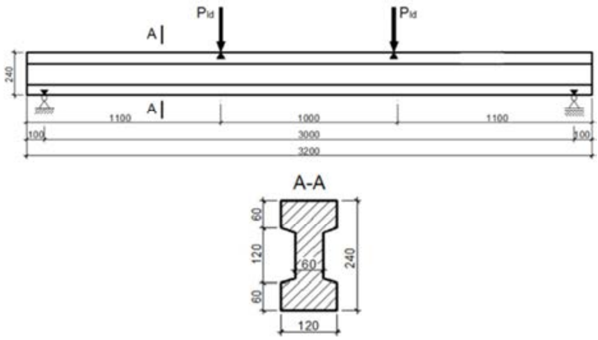

Fig. 2. Beams configuration and static sketch

The long-term loading represented 45% from bearing capacity of each beam. For register the ultimate bending moment, similar beams were tested to failure at short-term bending. 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 3 presents an image of tested beams subjected to long-term bending.

Fig. 3. 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 4.

Table 4. 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 5.

Table 5. 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 mode of the strains in time, was observed using the creep coefficient (φ_ε). In Figure 4 can be seen the variation mode of the creep of each beam type.

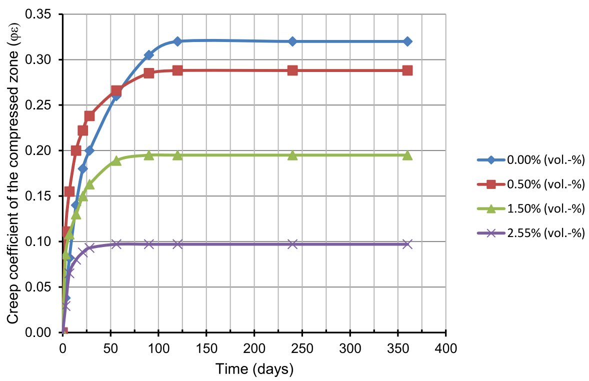

Fig. 4. Creep coefficient of the compressed zone of the beams

The beams deflections had also decrease due to the addition of steel-fibers. In Table 6 are presented the values of the long-term deflections and their stabilization time for each type of beam.

Table 6. 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 fact influenced directly the instant and long-term deflection, because of the stiffness increasing. Figure 5 shows the influence of steel-fibers on the long-term deflection of each type of beam, and how it was developed in time, using the creep coefficient reported on long-term deflection.

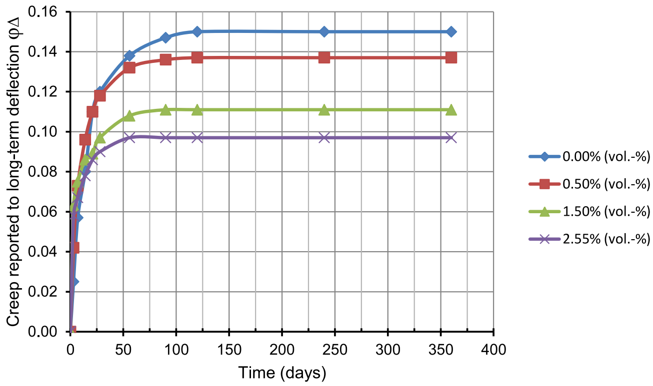

Fig. 5. Creep reported on long-term deflection

For all the elements subjected to long-term bending, regardless the steel-fiber percentage, the maximum crack width does not increase more than 1 mm. This value, obtained in the moment of applying the long-term loading, was kept for all 360 days of monitoring. The only parameter that varied was the number of cracks which have 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-fibers addition.

6. Conclusions

The maximum value of the creep coefficient from the compressed zone, after 360 days, in case of 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 decreasing of the long-term deflection was strongly influenced by the increasing of the steel-fibers percentage. The beam with 2.55% (vol.-%) steel-fiber addition registered a smaller long-term deflection, which means a decreasing up to 78% than the one of 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 can be seen that every type of UHPC beam had a good behavior in time in terms of strains, deflections and cracks. For a structural application I suggest that a volume percentage of 0.50% steel-fibers it is enough to ensure a good behavior in time.

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