Modeling of viscoelastic properties of Ultra High Performance Fiber Reinforced Concrete (UHPFRC) under low to high tensile stresses

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Abstract

The purpose of this paper is to explore the UHPFRC time-dependent behavior under sustained tensile loading at very early age (3 days) and to highlight its sensitivity to the level of loading by laboratory testing and numerical analysis. Uniaxial creep and relaxation tests were performed at 3 days age at various stress levels by means of a Temperature-Stress Testing set-up (TSTM). Under low tensile stresses, the material exhibits a linear viscoelastic behavior. Under high tensile stresses the creep response becomes non-linear. A numerical algorithm was used to convert the creep results into relaxations and compare them with measured relaxations. A generalized Maxwell chain model was applied to predict the UHPFRC tensile relaxations at a low load level.

Keywords: UHPFRC, tensile creep, relaxation, Maxwell model, strain hardening, viscoelasticity, stress level, TSTM, early age

1. Introduction

Ultra High Performance Fiber Reinforced Concretes (UHPFRC) with an extremely dense microstructure and outstanding mechanical properties (compressive strength >150 MPa, tensile strength > 8 MPa, tensile strain hardening), are most adapted for the improvement of the load carrying and protective functions of existing or new structures. The water/binder ratio of UHPFRC is in the range of 0.13 to 0.18, with a dominant autogenous shrinkage. The long term value of the autogenous shrinkage in UHPFRC is not larger than that of usual concretes or SCC. However, in cast-in-situ applications for rehabilitation, as thin layers, under high restraint, it leads to high tensile eigenstresses. These stresses are mitigated by the viscous properties of UHPFRC and can be balanced by their tensile strain hardening response leading eventually to a distributed microcracking at service state. It is thus important to determine the effect of high tensile stresses on the viscous response of UHPFRC, before or within the strain hardening domain. Since many researches have been carried out on the creep properties of cementitious materials in compression, their creep potential in tension is still an open field.

The objectives of this paper are to characterize the basic creep and relaxation of UHPFRC at early age under tension, at various stress levels, and to determine generalized Maxwell model parameters for the viscous response at low stress levels,. Relaxation test series are being performed in order to: (1) estimate the viscoelastic potential activated by two ways of testing: creep and relaxation at similar stress level and (2) get insights on the underlying phenomena of the obtained responses.

2. State of the art

Altoubat et al. [1] showed that the tensile basic creep of plain and steel fiber reinforced concrete is very sensitive to the age at loading during the first two days after casting and stabilizes after a few days. Similar tendency was observed by Ostergaard et al. [2] in a study on the basic creep of normal and high-strength concrete. For specimens loaded at very early age of 1 day, the creep response was not proportional to applied stress, which confirms the more pronounced nonlinearity in viscoelastic response for decreasing age of specimen’s loading. Bissonnette et al. [3] investigated the tensile creep of plain and steel fiber concrete at 7 days age, for over 60 days. They found that until 50% of the tensile strength, creep deformations were proportional to the applied stress. For High Performance Concrete, Atrushi [4] showed a threshold of non-linearity for a 60% tensile creep stress level with a loading at 1 day age. At the contrary, Reviron et al. [5] observed no significant deviation from a linear viscoelastic response on 6 concrete specimens of 90 days age, tested during 3 days under tensile creep in both sealed and drying conditions, with 50%, 70% and 90% stress levels. Basic creep was surprisingly more than two times smaller than compressive one for a similar concrete, but drying creep was comparable. According to

Bissonnette et al. [6], creep response in compression and in tension for low levels of loading is similar. Similarly, Gutsch et al. [7] found no significant deviation from a linear viscoelastic response of concretes loaded at an age varying from 1 to 28 days under tensile creep or relaxation, at various stress levels, up to 70% of the tensile strength.

The viscoelastic behavior was barely investigated for UHPFRC material under high tensile stress levels. Kamen [8],[9] investigated UHPFRC creep properties for low and medium stress levels under compression and tension. As expected, specimens loaded at an early age of 3 days showed more basic creep deformation than similar ones loaded at 7 days. At 3 and 7 days, the stress/strength ratio threshold between linear and non-linear viscoelastic response in compression was around 35%. Kamen et al. [9] showed, on the basis of isothermal tensile tests in a TSTM set-up, that UHPFRC viscous response at early age (3 days) significantly deviates from a linear response when the tensile stress level changes from 32 to 63 %. Further, at very early age (36 to 43 hours) UHPFRC specimens are very sensitive to the age of loading. A modeling of viscoelastic properties of UHPFRC in tension was performed for a linear domain with Kelvin model based on creep result, and Maxwell chain model based on creep converted to relaxation curves [8], [9].

3. Experimental study

3.1. Experimental procedures

The UHPFRC mix used belongs to the CEMTEC$_{\text{multiscale}}$ family developed by Rossi at LCPC [10]. A Temperature Stress Testing Machine (TSTM) set-up with one free and one restrained dogbone shaped specimen of 1 m length, 750 mm measurement basis, and 50 x 100 mm cross section [8] was used for tests. All specimens were produced by following the same casting procedures and mixing sequence to insure systematic reproducibility. A constant temperature of 20°C was imposed to the bath controlling the cooling circuit surrounding the specimen during the entire experiments. The ultimate tensile strength at 3 days was obtained in an uniaxial tensile test, $f_{U,t}$=9MPa. The imposed stress levels for tensile creep tests were then estimated in function of this value, and are given in Tab. 1. Just after the mixing, the material was cast into the two TSTM molds, and kept free from eigenstresses until the age of loading of 72 hours. The specimens were then tested until 8 days age. The excellent reproducibility of the material properties was demonstrated for each test series by a careful quality control plan based on measurements of the fresh UHPFRC mix properties (slump flow with mini-cone on UHPC matrix), air content, and setting time (by means of Ultrasound velocity measurements with Freshcon testing set-up and temperature measurements in the fresh paste).

Table 1: Tensile stress levels in a creep test

Stress level	**Stress/strength**	**Stress level [MPa]**
1. Low	30%	2.7
2. Medium	60%	5.4
3. High	90%	8.1

3.2. Creep and relaxation results

Fig. 1a) presents the results of basic creep tests of specimens loaded at 72h. Each specific creep curve corresponds to one creep specimen under the imposed stress level. They were obtained by subtracting the monitored free shrinkage from the creep deformation. The instantaneous deformation, until Point A, for three stress levels remains proportional to the applied load, and is of 24 μm/m/MPa which corresponds to an elastic modulus of E=41.6 GPa. From Point A on the delayed deformation begins and we can observe a higher value of specific creep for 5.4 and 8.1 stress level, which shows a non-linear creep response. For the low stress level of 2.7 MPa the specific creep value tends to decrease after some time. For the 8.1 MPa stress level, the delayed deformation is higher and reaches 47 μm/m/MPa after 190 h, which shows non-linearity in the creep response. From the obtained results we cannot observe the clear threshold for a non-linear tensile creep, since deviation from linearity of creep curves is present between all gradually increasing stress levels.

The relaxation test was performed in the TSTM set-up with an imposed deformation corresponding to a 30% stress level. A closed-loop deformation control was used to compensate for the ongoing free shrinkage in real time. The result is presented on Fig. 1b) in the form of relative relaxation.

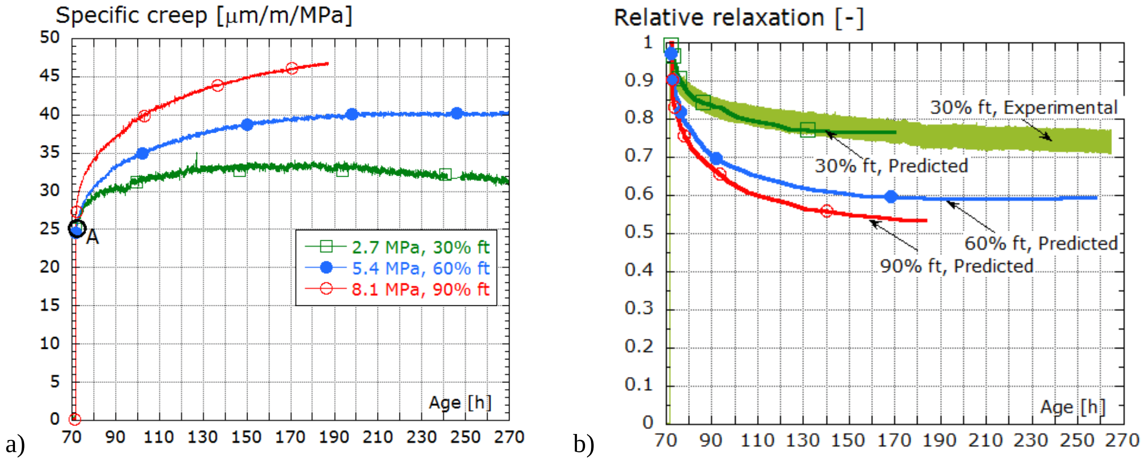

Figure 1: a): Experimental tensile specific creep results, b): Relative relaxations: predicted from experimental creep curves for 2.7, 5.4 and 8.1 MPa (30, 60, 90% of f_t), and experimentally obtained for 2.7 MPa (30% of f_t) stress level.

4. Numerical study

4.1. Relaxation predicted from creep

The step-by-step numerical algorithm of Bazant [11] was used to predict the relaxation response from experimentally obtained creep results for all stress levels, assuming that for high stress levels in the non linear viscoelastic domain, this principle also applies. This assumption allows us to make a preliminary prediction of relaxation response, which will be compared in a further study with results of the experimental relaxations at higher stress levels (ongoing tests). The predicted relaxation curves for three stress levels are shown on Fig. 1b). Results are presented in form of relative relaxation by dividing the relaxation deformation by its initial value. Based on these predictions, we can observe that the viscoelastic potential of UHPFRC allows the relaxation of around 20 to 40% of elastic stresses after 100h. The results of the predicted relaxation at low stress level (30 %) perfectly match those measured experimentally. Similarly, Clément [12] performed creep and relaxation tests in compression on 2 years old regular concrete, and observed that until 60% load level, relaxations obtained numerically from creep tests data corresponded to those obtained experimentally.

4.2. Maxwell chain model

A non-ageing generalized Maxwell chain model with four chains was sufficient to fit the relaxation curves obtained for a low stress level by both direct experimental measurements and transformation of creep results by means of the Bazant-algorithm [10]. The formula for the corresponding Prony series is shown on Fig.2a, where ε_0: imposed deformation, τ_κ: retardation time, t: time, t_0: time of loading. The parameters obtained for the Maxwell model are shown in Table 2. The value of the total elastic modulus E_{tot} is 41.6 GPa.

a)

$$\sigma(t,t_0)=\varepsilon_0\, E_{tot}(t_0)\sum_{k=1}^{n}\frac{E_k(t_0)}{E_{tot}(t_0)}\cdot e^{-\frac{t}{\tau_k}}$$

where: $E_{tot}(t_0)=\sum_{k=1}^{n}E_k(t_0)$

b)

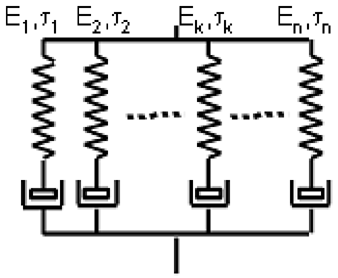

Figure 2: a) function of Prony series b) generalized Maxwell model

Table 2: Maxwell chain model parameters

$\tau_k[h]$	1	10	100	1000	10000
$\frac{E_k(t_0)}{E_{tot}(t_0)}$	0.04	0.16	0.05	0	0.75

5. Discussion and conclusions

(1) Tensile creep tests of UHPFRC under three stress levels (2.7, 5.4, 8.1 MPa - corresponding to 30 %, 60 %, 90 % of f_t) and relaxation for low solicitation level were successfully performed at 3 days to accurately determine the viscoelastic behavior of UHPFRC at early age, under moderate to high stress levels.

(2) Creep results were converted to relaxations using Bazant algorithm [11], and compared with the experimentally obtained relaxation for low solicitation level. For a low stress level of 30% of f_t, the creep and relaxation show perfectly the same viscoelastic response.

(3) Maxwell chain model parameters were determined to fit relaxation results in the linear domain for a low load level. For the entire period of test of 8 days a non-ageing model was sufficient to correctly represent the obtained results.

On-going relaxation tests for higher load levels will allow getting more insights on the underlying phenomena of the obtained viscoelastic responses.

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