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Basic creep of concrete under compression, tension and bending

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HIGHLIGHTS

- ▶ Experimental setups developed to achieve direct tensile and bending creeps are presented.
- ▶ Precautions taken to obtain relevant data are described.
- ▶ Results are available for specimens subjected to 50% of the strength in tension.
- ▶ Final discussion compares the basic creep under tension, bending and compression.
- ▶ The analysis of results highlights considerable coupling between shrinkage and tensile creep.

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ABSTRACT

Investigations on concrete creep are often limited to the compression behavior due to the difficulty of performing tensile tests on cement-based materials. This paper describes the experimental setup developed to achieve direct tensile and bending concrete creep. The precautions taken to obtain relevant data are described. For comparison, tensile, flexural and compressive basic creep test were conducted in parallel. Although the approach is still controversial, the basic creep strain was determined by subtracting the shrinkage strain and instantaneous strain from the total strain. Results available for specimens subjected to 50% of the strength in tension or in compression are presented. The final discussion compares the basic creep under the different types of loading.

1. Introduction

Because of its poor strain capacity and low tensile strength, concrete is brittle and highly sensitive to cracking. In most cases, cracks can significantly reduce the lifetime of a structure by allowing the ingress of aggressive agents. Cracks have various origins, which are all associated with the existence of extensions: effect of external loading, physicochemical pathologies leading to the formation of new expansive products (Alkali-Aggregate Reaction – AAR, Delayed Ettringite Formation – DEF, Corrosion). A non-uniform state of deformation associated with thermal or hydric gradients or restrained strain in bonded cement-based overlays induce built-in tensile stresses which can also initiate cracking. The heterogeneity of concrete also plays an important role in the mechanism of crack formation. Even if a specimen is tested in compression, the first damage that occurs at the paste-aggregate interface is the consequence of tensile stresses resulting from the differences between the two phase moduli (for paste and aggregate) and from the interfacial transition zone (ITZ) [1], which has limited mechanical performance. According to Liners [2], the application of a compressive preload on a specimen can generate damage in tension, resulting in a significant drop in the tensile strength of up to 50% depending on the level and the duration of loading application. Therefore, in order to predict the risk of cracking in concrete elements, it is important to focus on the mechanical properties of concrete in tension, and particularly on its delayed behavior, the effects of which (cracking or stress relaxation) are not yet well understood. Since Freyssinet highlighted the creep of concrete in France in 1912, regardless of Hatt's findings in the United States in 1907 [3], the phenomenon has been extensively studied, as shown by the numerous publications on this topic (see [4–10] for example). However, due to the difficulties of performing a tensile test on cement-based materials [11], particularly for fixing of the samples to the loading device [12] and measuring the values of the strains, which are too small for most extensometers to cope with, the majority of experimental studies on concrete creep have dealt with compressive creep. When experiments involve tensile creep of cement-based materials, the tests are usually limited to early age behavior [11,13–23]. However, as the tests are performed a short time after casting, the coupling between creep and the effects of hydration (strength gain, shrinkage, etc.) remains

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very noteworthy. Contributions related to the tensile creep of cement-based materials beyond 28 days after casting, corresponding to stabilized hydration reactions, are relatively rare. Such studies deal, on the one hand, with the influence of various parameters (related to the material properties and/or to the test conditions) on tensile creep [24–28] and, on the other hand, with the comparison between tension and compression behavior [27,29–32].

This paper focuses on achieving direct tensile and bending creep devices so that tensile and compressive concrete creep can be compared in the corresponding direct tests and in bending tests. The experimental setups developed are presented first. All the precautions necessary to obtain relevant measurements are described. These points are important because tensile creep strain is low and some artifacts, due to temperature change, for example, can prevent any analysis of the results. The specimens tested were protected from drying by watertight adhesive aluminum foil that maintained the conditions required for basic creep [33]. Then, experimental results concerning shrinkage and total strains are presented and analyzed. Although the approach is still controversial, the basic creep is determined by subtracting the instantaneous strain due to the loading of the specimen and the strain due to the autogenous shrinkage from the total strain. Basic creep under tension and bending is finally compared to compressive creep. The analysis of results highlights considerable coupling, more than that observed in compression, between shrinkage and tensile creep.

2. Experimental program

2.1. Material

Tests were carried out on a high performance concrete. As previously explained, the knowledge of the viscoelastic properties in compression but, above all, in tension is essential for the design of concrete-based structures if cracking risks are to be reduced to a minimum. The formulation of the concrete, given in Table 1, was developed by Andra (French Agency for Nuclear Waste Management) for nuclear waste repository structures in deep geologic formations. This concrete mix has already been studied extensively through investigations concerning instantaneous and delayed mechanical behavior in compression [34–36].

The average density of the fresh concrete was 2410 kg/m^3 and the required fluidity, characterized by a slump value of 21 cm, was obtained by adding a superplasticizer based on modified polycarboxylic ether. Depending on the type of tests to be performed and on the number of samples required, several specimens were cast for:

- Compressive creep, carried out on cylindrical specimens (110 mm in diameter and 220 mm in height) with a space reserved in the center to house displacement transducers.
- Tensile creep, measured on 70 × 70 × 280 mm prisms.
- Bending creep, measured on 100 × 100 × 500 mm prisms.

The average compressive strength and Young's modulus of this HPC, measured from quasi-static tests on six different batches, were respectively 69.7 MPa and 41,925 MPa with a dispersion of less than 5% for the six batches. The mean direct tensile strength, measured at 28 days on 10 specimens, was 3.0 MPa with a coefficient of variation of 15%. In order to reduce uncertainty, the specimens used to determine the basic mechanical properties and the ones used for creep tests were from the same batch. Direct tensile strength measurements showed larger dispersions than those of compressive strength. This can be explained by the effect of the usual heterogeneity of concrete, which has more influence on tensile properties than on compressive ones. Whereas a compressive stress tends to consolidate concrete (by closing the pre-existing microcracks and reducing the initial porosity), tensile stress tends to induce local damage of the material microstructure by propagating initial defects (shrinkage induced cracking, air bubbles, etc.). Therefore, the response in tension becomes more sensitive to initial defects, the concentration of which is closely related to the concrete heterogeneity. During creep tests, the loading rate (which is the ratio between the applied stress and the concrete strength) is an important parameter for creep strain analysis and interpretation. So, accurate knowledge of the concrete strength prior to the creep loading is an important issue. Unfortunately, such a goal is not easy to achieve in the absence of non-destructive tests to determine the concrete strength. Because of the scatter on the tensile strengths, a loading rate based on the average strength of the concrete leads to creep test results that are somewhat biased, especially in cases of high stress level [28].

Table 1
Concrete mixture proportions.

Composition of concrete in kg/m^3	
Cement CEM I 52.5R PM-ES (Val d'Azergues), Lafarge	400
Limestone sand 0/4 mm, Boulonnais	858
Limestone aggregate 4/12.5 mm, Boulonnais	945
Superplasticizer Glénium 27, MBT	2.2
Total water	178

After demolding, the specimens used for creep tests were first stored in water for 15 days to limit capillary depression effects by saturating the porosity. In order to dissociate creep from the drying effects (shrinkage, cracking, etc.), tests were performed in autogenous conditions (without moisture exchanges with the environment) after the first curing in water. For this purpose, the specimens were first dried and then sealed with triple layers of self-adhesive aluminum foil [33]. The first drying was performed during about 12 h in order to avoid the phenomenon of capillary rise which could prevent the good bonding of the aluminum foil and of the strain gauges and thus to maintain constant conditions during the test period. The weight loss during this superficial drying was about 0.05% of the specimen weight. They were then equipped with extensometers for strain measurement and were stored in the test room where temperature and humidity were controlled (20 °C ± 1 °C, 50% RH ± 5%) until the creep tests at 28 days. This curing procedure provided an additional advantage for the present study in that the development of hydration could be considered as relatively stable before the start of the creep tests.

2.2. Experimental devices

2.2.1. Compressive creep test apparatus

The compressive creep devices were equipped with hydraulic jacks. The device allowed simultaneous loading of two aligned specimens (Fig. 1a).

Longitudinal deformations were recorded by means of inductive transducers located within a reservation created during casting by placing a removable metallic insert on the mold axis (Fig. 1b). The sensor (stroke ± 0.5 mm) measured the relative displacement of two sections separated by 115 mm and located outside the hooped area. The measurement was made thanks to a LVDT sensor for which the extended base of measure is arranged along the central axis of the specimen at the time of casting the concrete: the central steel rod was, in this case, fixed to the lower part of the specimen by a steel nut embedded in the concrete during casting. The LVDT sensor was fixed to the upper part of the specimen. Thus, the displacement of the magnetic core of the steel rod corresponds to the displacement between the nut and the LVDT sensor. The deformation of the specimen core is thus obtained by dividing the displacement by the measurement basis (115 mm). Previous studies had shown that the strain measurement uncertainty was equal to 9 μm/m and that the difference from an external measurement (on three generatrices on the surface of the specimen) was negligible (less than 5%) [37]. The loading and strain measurements were performed in accordance with the RILEM recommendations [38].

2.2.2. Tensile creep test apparatus

For the purposes of the study, an oedometric device used in soil mechanics was transformed to measure tensile creep (Fig. 2). The tensile creep test apparatus was a rigid frame with a hinged lever arm (① in Fig. 2). The 5/1 ratio of the lever arm allowed high loading levels to be reached while manipulating masses of reasonable weight. A 70 × 70 × 280 mm prismatic specimen (② in Fig. 2) was loaded using calibrated weights placed on a plate (③ in Fig. 2) fixed to the lever arm. The force was then transmitted to the specimen through a cable, one end of which was welded to a steel cap glued onto one side of the specimen while the other end was hinged to the frame (④ in Fig. 2). A screw system located at the bottom of the bench (⑤ in Fig. 2) allowed the horizontality of the lever arm to be controlled and thus the 5/1 ratio to be kept during the loading. A stop placed below the lever arm (⑥ in Fig. 2) prevented any sudden fall of the weights in case of rupture of the loaded specimen, thus reducing the risk of accident.

Creep strains generally develop very slowly. In the case of tensile creep, given the Young's modulus and the loading rate calculated with respect to the tensile strength, the strains were very small. In such conditions, a thermal length change can prohibit any useful analysis of the results. For this reason, all the experiments were performed in a test room where temperature and RH were controlled. Additional precautions were taken during the test: two specimens, one loaded to measure tensile creep and the other unloaded to measure shrinkage strain, were positioned side by side in a thermally insulated box (Fig. 3) and were thus maintained in the same thermo-hygrometric conditions.

One of the major difficulties when performing a tensile test on cement-based materials concerns the fixing of the specimen to the loading device. Devices commonly used on other materials, such as steel grips or clamps, are inappropriate for a brittle material like concrete. During tensile tests, concrete specimens have commonly been attached by [39]: anchoring a metallic insert in the concrete