



Creep testing of concrete since setting time by means of permanent and repeated minute-long loadings



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ABSTRACT

Monitoring the evolution of early age properties of concrete is necessary to provide input data to the models of prediction of the behavior of concrete structures since setting time. The experimental challenge lies in the fact that this monitoring must be fully automatic since the earliest age because the hardening process of the concrete takes place continuously over a period counted in hours and even in days after the casting time. This research paper presents a new methodology developed at ULB and IFSTTAR to monitor the creep and relaxation of an ordinary concrete chosen as reference concrete since setting time. Compressive creep rigs and two test devices were used: at ULB, a Temperature Stress Testing Machine (TSTM) specifically designed for testing concrete since setting time under free and restraint conditions and at IFSTTAR, a test set up called BTJASPE developed to monitor, in compression, the modulus of elasticity, the creep and the relaxation of a concrete since very early age. For the sake of the study, the same concrete has been used in the two laboratories. In addition, this study is performed at a constant temperature to exclude this parameter, at this step of the study. The methodology is based on experimental measurements with two kinds of test. A classical creep test with permanent loading during one week and a repeated minute-long loading test for which every 30 min, a loading is applied and kept constant during 5 min and finally totally removed. The classical test is used to characterize the non-aging creep function and the repeated minute-long loading test is used to quantify the aging creep functions.

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1. Introduction

Nowadays, the construction phases of modern concrete structures (high-rise buildings, piers of a bridge...) become more and more challenging. Consequently, for the design of concrete structures it is important to have knowledge in depth of the early age behavior of concrete, which influences the whole service life. Even though the mechanical behavior of hardened concrete can usually be correctly predicted; it is not always the case for the early age behavior of concrete, when the mechanical properties change rapidly in function of the advancement of the hydration reaction. Among all the usual parameters (strengths, E-modulus...) needed for the design of the concrete structures, creep and relaxation must also be taken into account. Stress induced by the restriction of the thermal and autogenous strain can be significantly reduced thanks

to relaxation. For example, in the design of a concrete dam, Slowik, et al. [1] showed that at early age, the relaxation phenomenon is responsible for a decrease of 70% of the thermally induced stresses in the structure.

For field applications or research purposes, measuring early age deformations as input data for modelling is of a great interest and should be included in numerical codes [2,3]. For ordinary concrete (composed by Portland cement), existing models allow obtaining satisfied results for material properties like compressive strength and Young's modulus but not for early age creep [4]. For concrete with high substitution of cement by mineral additions like slag, fly ash, limestone filler, the early age properties of concrete are not necessarily well predicted by models coming from standards [5]. In fact, just after setting, deformations in concrete evolve very fast. According to the superposition principle, in sealed and isothermal conditions, the total strain ($\varepsilon(t)$) is the sum of three terms: the autogenous strain ($\varepsilon_{au}(t)$), the elastic strain ($\varepsilon_{el}(t)$) and the basic creep strain ($\varepsilon_{bc}(t)$) (Equation (1)).

$$\varepsilon(t) = \varepsilon_{au}(t) + \varepsilon_{el}(t) + \varepsilon_{bc}(t) \quad (1)$$

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For the monitoring of the autogenous strain, many tests rigs have already been developed in the past [6,7]. The elastic strain depends on the evolution of the Young's modulus. Several existing testing devices for the measurements of the Young's modulus are presented in Refs. [8–10]. The basic creep strain depends on the evolution of the creep function. Even if experimental tests consisting in applying a permanent loading at different ages were previously reported in Refs. [11–19], no specific testing methodology aimed at monitoring early age creep has already been developed for concrete.

2. Research significance

Creep and relaxation of concrete have not been thoroughly investigated at early age. Some studies related to the compressive creep have been carried out and are reported in Refs. [11–19] for concrete with an age at loading of 1 day and more. For practical reasons, it is difficult to access creep before an age of 1 day (minimal concrete age required before mould release, grinding the sample, fixing the extensometer, very low magnitude of load applied and consequently very low displacement measured). These studies [11–19] have shown that creep is strongly influenced by the age of concrete at loading inducing changes in terms of amplitude and kinetic. Among many previous studies like those reported in Refs. [11–19], several theories were developed to clarify mechanisms related to this behavior. However each theory alone does not allow explaining all experimental observations. Globally each theory can be linked to two mechanisms: direct mechanisms linked to the cement paste and responsible of the highest part of the creep amplitude and indirect mechanisms linked to the heterogeneity of the concrete [20,21]. Direct mechanisms are related to the water mobility and can be separated in short and long terms phenomena [22–24]. The short term phenomenon is reversible with a small characteristic time of about 10 days and linked to a stress-induced water movement towards the largest diameter pores and also occurs under increasing volume for uniaxial compression. The long term phenomenon is irreversible with a high characteristic time and related to viscous flow in the hydrates and occurs under almost constant volume. The creep rate of this long term phenomenon evolves as a power function t^n [20,25,26] with an exponent n between -1 and -0.9 according to [27], between -0.72 and -0.69 according to results of [28] on concrete and an exponent n between -0.86 and -0.6 on cement paste according to results of [18]. Nanoindentation tests were carried out on C–S–H by Vandamme et al. [29]. It was shown that C–S–H exhibits a logarithmic creep which is in agreement with results obtained on concrete. Vandamme [30] compared also this logarithmic behavior with other heterogeneous and porous materials with porosity including several orders of magnitude (soils and wood). For these non-aging materials, a logarithmic long-term creep was also observed. It can then be assumed that this long term creep is not linked to a hydration process or any chemical specificity of the C–S–H.

The indirect mechanisms are due to micro-cracks which occur progressively in the cement paste and at the interface between cement paste and inclusions. Their presence can cause a redistribution of stress in the material. Rossi et al. [31–33] proposed an approach of the creep mechanisms by means of a micro-cracking process which occurs during loading. Over the time, an increase of the density of micro-cracks occurs. These micro-cracks are distributed through the volume of the specimen and allow water transfers which induce some additional self-desiccation shrinkage.

It is even more uncommon to find experimental results in the literature for the relaxation phenomenon of concrete at early age. The experimental testing of the relaxation is very complicated for technological reasons. The relaxation testing needs to take into

account in real time the difference between the total deformation and the shrinkage added to the thermal deformation. This difference must be performed all along the test, so that the jack of the testing frame can be controlled by this value. All these reasons explain why the study of the creep and the relaxation in compression at very early age is not very developed. Only one kind of experimental methodology is used till now to monitor the evolution of the creep of concrete: static loading on a series of samples [11–19]. This experimental procedure requires the completion of a large number of tests which is time consuming and the earliest obtained results often correspond to an age of concrete of one day. The period situated between the setting and an age of one day is then often missing. However, in several structural cases, concrete elements are in compression during the first 24 h as a result of the restrained thermal strain. An underestimation of the compressive creep and relaxation phenomenon during the heating period leads to an underestimation of the evolution of the tensile stresses which occur during the cooling period of the concrete [34,35]. Following these observations, the aim of this collaborative work between the BATir-ULB and IFSTTAR laboratories is to develop a new experimental testing methodology of creep and relaxation of concrete since setting by means of the lowest possible number of tests [36–38]. The present paper reports on the experimental results obtained from a comprehensive test program on creep and relaxation of an ordinary concrete. Creep and relaxation tests have been investigated since the end of setting in isothermal conditions at 20 °C and in sealed conditions.

3. Experimental program

3.1. Materials and mixtures

The tests presented here were performed on an ordinary concrete for which mix proportions are given in Table 1. All materials come from the same batch of production. An ordinary Portland cement of type CEMI 52.5 N was used. Its chemical composition is given in Table 2. Siliceous sand and gravel coming from Sandrancourt (France) were used. Sand and gravel were dried. The effective water-to-cement ratio is 0.45. The mixing procedure is the same for both laboratory. Different mechanical properties have already been characterized by IFSTTAR and ULB. The evolution of the tensile and compressive strengths, the heat release and the Young's modulus are presented in Ref. [8]. The initial and final setting times are defined by the criteria developed by Carrette et al. in Refs. [39,40] and based on the monitoring of the ultrasound p and s waves transmission through concrete.

Table 1
Mixture proportions and materials properties of the concrete.

Components	
CEMI 52.5 N – SR 3 CE PM-CP2 NF (kg/m ³)	340
Sand (Sandrancourt 0/4) (kg/m ³)	739
Gravel (Sandrancourt 6.3/20) (kg/m ³)	1072
Added water (kg/m ³)	184
W_{added}/C	0.54
W_{eff}/C	0.45
Slump	S1
Paste volume (L/m ³)	260
$f_{c,1d}$ (MPa)	12
$f_{c,2d}$ (MPa)	22
$f_{c,28d}$ (MPa)	40
Initial setting time (h)	5.7
Final setting time (h)	6.7

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