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Comparison of tensile and compressive creep of fly ash concretes in the hardening phase

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ABSTRACT

Tensile and compressive creep tests of fly ash concretes in the hardening phase have been performed in the Temperature-Stress Testing Machine (TSTM) at NTNU. All tests were performed under nominally identical conditions, e.g. dimensions, curing conditions, measurement set-up and load-regime. Two concretes with 17% and 33% fly ash (as % by weight of cement and fly ash content) were investigated. Contradictorily to most of the compressive versus tensile creep comparisons found in the literature, both the investigated concretes showed similar creep behaviour in compression and tension throughout the hardening phase. It was also seen that for the investigated time-span, the specific creep development over time was found to increase (i.e. soften) with increasing amount of fly ash.

1. Introduction

The time-dependent stress response of concrete is a complex and much studied phenomenon which is usually described by creep or relaxation. Creep and relaxation are closely connected physically, and in concrete structures they often occur simultaneously. As often found in engineering practice, the term creep is in the following used to denote both creep and relaxation of stresses.

Early age concrete is subjected to volume changes caused by autogenous deformation (AD) and thermal dilation (TD). If these volume changes are restrained, stresses will start to develop in the concrete. Together with AD and TD, creep is one of the key factors when it comes to restrained stress development and the corresponding early age crack assessment of concrete structures. AD- and TD-induced stresses at early ages can be significantly influenced by creep. Studies have found a reduction of restrained stresses by 30–50% due to the beneficial creep behaviour of concrete [1–5]. On the other hand, temperature-induced compressive creep at very early ages can contribute to an increase in the succeeding tensile stress development [6,7]. In addition to its importance in early age crack assessment, creep is also of considerable significance when it comes to deformation and crack width calculations.

Concrete creep has been found to be dependent on a number of factors, e.g. load level, temperature, loading age, size of specimen and type of stress (compressive versus tensile) [8]. Concrete creep is also dependent on concrete mix-design, such as constituents and w/b ratio. The importance of tensile creep of concrete when cracking is to be considered has been long recognized. However, only a few studies on early age tensile creep are available in the literature, and in addition, the research results are rarely consistent [9,10]. For instance, while several studies conclude that (long time) tensile creep is larger than compressive creep [3,11–13], other studies presents contradictorily results [14, 15]. Observations of similar compressive and tensile creep compliances have also been reported [16]. Experimental challenges connected to tensile creep tests is probably one of the reasons for the limited amount of reported tensile creep results.

A comprehensive experimental test program on fly ash (FA) concretes has been performed at NTNU over the last years. The aim has been to determine decisive parameters for early age crack assessment [5]. The present paper presents a set of results from this test program: tensile and compressive creep tests performed under nominally identical conditions in the Temperature-Stress Testing Machine (TSTM) at NTNU. The investigated concretes contain the mineral additives silica fume (SF) and fly ash (FA). The tests have been performed at different loading ages and subjected to 20 °C isothermal and sealed conditions.

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2. Creep model

In the current study, the time-dependent stress response of concrete has been modelled based on the theory of linear viscoelasticity for ageing materials. This theory, which is a simplification of the real material performance, implies that creep strains under a constant stress are linearly related to the stress level. This linearity has currently been described by the compliance function $J(t,t')$ modelled by the Double Power Law, Eq. (1), see [17].

$$J(t,t') = \frac{1}{E_c(t_{eq}')}\left[1+\varphi_0 \cdot t_{eq}'^{-d} \cdot (t-t')^p\right] \tag{1}$$

In the above equation, t [days] is the concrete age, t' is the concrete age at which the actual stress was applied, $E_c(t_{eq}')$ is the E-modulus at t_{eq}', t_{eq}' is the equivalent age at t', and φ_0, d and p are creep model parameters. The above described creep model is not unique; several alternative approaches are found in the literature [15,18–20]. The currently used model was chosen based on previous experience at NTNU, as it has been found to be suitable and sufficiently accurate when evaluating creep test results.

The E-modulus is very important when modelling creep, see Eq. (1). The age dependent development of the E-modulus has been modelled by Eq. (2), which is a modified version of CEB-FIP MC 1990 [21], see [22,23]:

$$E_c(t_{eq}) = E_{c28} \cdot \left\{ exp\left[s \cdot \left(1 - \sqrt{\frac{28-t_0^*}{t_{eq}-t_0}}\right)\right]\right\}^{n_E} \tag{2}$$

In Eq. (2), $E_c(t_{eq})$ represents the E-modulus as a function of equivalent age t_{eq}. E_{c28} is the E-modulus at 28 days, s and n_E are curve-fitting parameters, and $t_0 = t_0^*$ is the start time for stress development [equivalent time]. The parameter t_0 was included in Eq. (2) by [22], while t_0^* was introduced later in the program CrackTeSt COIN [24,25].

3. Experimental set-up

All creep tests, both compressive and tensile, were performed in the Temperature-Stress Testing Machine (TSTM) System at NTNU. The TSTM System consists of a Dilation Rig, Fig. 1, and a Temperature-Stress Testing Machine (TSTM), Fig. 2. Both rigs are connected to a Temperature-control System (Julabo FP45), providing an accurate control of the concrete temperature during testing. The TSTM System is located in a conditioned room which holds a constant temperature of 21 °C ± 0.5 °C. The TSTM System was built in 1995 and is well established and documented, e.g. [26,27]. During the years 2009–2013 the TSTM System was reconstructed with new software for managing and logging as well as a new and improved measurement set-up to achieve the necessary accuracy and robustness of the system [5].

The Dilation Rig and the TSTM are always run in parallel. The Dilation Rig measures free deformation, i.e. the sum of thermal dilation and autogenous deformation, of a sealed concrete specimen, while the TSTM measures the stress generation of a sealed concrete specimen through the hardening phase at a chosen degree of restraint. After the reconstruction the TSTM now is both load-controlled and deformation-controlled, providing a unique possibility to test tensile and compressive creep at the same stress level under the exact same test conditions [5]. When performing a creep test in the TSTM System, a load is applied the concrete specimen in the TSTM and then kept constant while simultaneously measuring the length change. The resulting creep data can then be found by subtracting the stress-independent strain measured in the parallel Dilation Rig from the length change measured in the TSTM. All creep tests were carried out in the following way:

1. Mixing and casting in the TSTM and the Dilation Rig (dummy)
2. After casting, the TSTM specimen was allowed to move freely, while the load was kept at 0.0 ± 0.02 MPa
3. At the chosen loading time, a load corresponding to 1.0 MPa compressive or tensile stress was applied to the TSTM specimen. Immediately after applying the load, the software was programmed to let the TSTM specimen move freely while maintaining the stress at 1.0 ± 0.02 MPa

During all creep tests, the following data were measured: free deformation in the Dilation Rig, deformation in the TSTM, stress in the TSTM as well as temperatures in the Dilation Rig, the TSTM and the room. The creep strain was found by subtracting (for creep in compression) or adding (for creep in tension) the free deformation measured in the Dilation Rig from the deformation measured in the TSTM.

The TSTM can also be used to directly determine the E-modulus. At the time of loading in the TSTM, deformation and load data are stored 10 times a second. This feature provides a stress-strain relation during the load application. The concrete E-modulus can then be determined based on the recorded data, providing an E-modulus representing the specific load application. The E-modulus obtained from the given TSTM equipment has been shown to give good agreement with the corresponding E-modulus determined from independent mechanical testing [5]. Similar correspondence between E-moduli obtained from TSTM tests and parallel methods has also been seen in other studies, e.g. [28].

4. Experimental program

Two concretes were included in the creep test series: *ANL FA* (17% FA) and *ANL FA + 16FA* (33% FA), where the total fly ash content is given in parenthesis as % by weight of cement and fly ash content. The

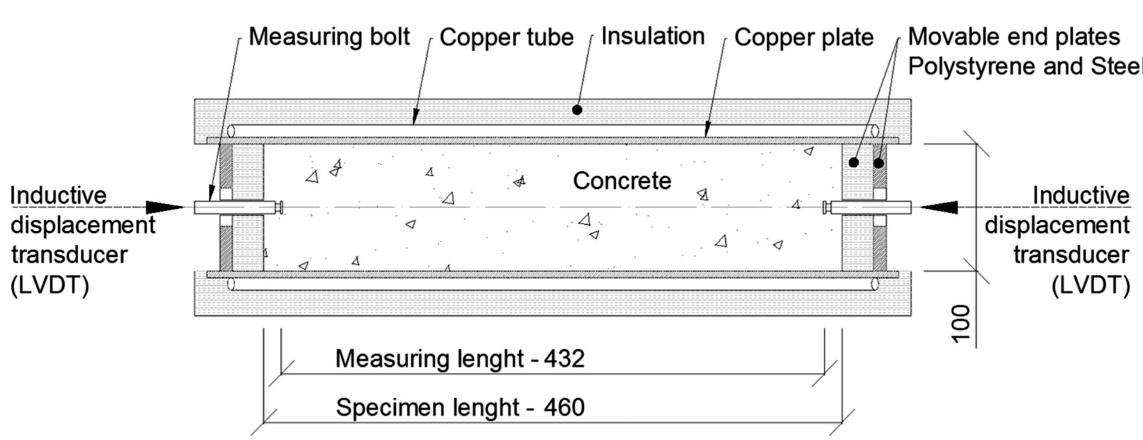

Fig. 1. The Dilation Rig [mm].