ARTICLE IN PRESS

Cement and Concrete Research xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: www.elsevier.com/locate/cemconres

Microstructural effects in the simulation of creep of concrete

Alain B. Giorla[a,*], Cyrille F. Dunant[b]

[a] Oak Ridge National Laboratory, One Bethel Valley Road, Oak Ridge, TN 37831-6148, USA
[b] Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, UK

ARTICLE INFO

Keywords:
Concrete
Creep
Finite element
Microstructures

ABSTRACT

The influence of the microstructure on the visco-elastic properties of concrete is investigated using finite element simulations at the meso-scale. We first derive a constitutive law for the creep of the cement paste which accounts for both recoverable and permanent deformations, as well as the influence of temperature and internal relative humidity. The model is calibrated on a set of experiments at the cement paste scale, and then validated after upscaling to the concrete scale. The model is then applied to study the influence of the microstructure on the macroscopic creep of concrete. We show that materials with finer particles exhibit less creep, and that the anisotropy of creep can be explained with the shape and orientation of the aggregates. Furthermore, the acceleration of the stress relaxation in the presence of damage is explained by the micro-mechanical interaction between the aggregates, the cement paste, and the micro-cracks.

1. Introduction

Concrete is the most used material in the world, and therefore a good understanding of its long-term behaviour is required for sustainability. Long-term behaviour of concrete depends both on durability aspects, e.g. alkali-silica reaction (ASR), freeze-thaw cycles, carbonation, and on its viscous properties. Both these aspects are critical in structures such as nuclear or hydraulic power plants which have long planned lives and are further subject to particular safety concerns. Models predictive over the long term require understanding the phenomena affecting the structures of interest at a fundamental level. In particular, behaviours should be derived from the complex processes that occur at the microstructure level.

Increasingly, concrete degradation phenomena are approached with numerical methods in which concrete is modelled as a two- or three-phase composite containing aggregates, cement paste and perhaps a transition zone between them. Examples include prediction of the material strength [1–9], visco-elastic properties [10–12], drying shrinkage [13,14], or damage due to ASR [15–17], high temperature [18], leaching [19], or irradiation [20,21]. These multi-scale models are based on our best understanding of the physical processes concrete undergoes, therefore, they are suitable for long-term extrapolation as well as interpretation of experimental results.

The accuracy and predictive ability of such meso-scale models is strongly tied to the choice of constitutive behaviour which represent the various physical processes in the material. A primary purpose of these models is to provide insights on the phenomena occurring at the micro-scale, as well as characterizing the interactions between the aggregates and the cement paste. Therefore, the absence of certain aspects in the constitutive behaviour might have a strong influence on the simulated results and on the conclusions one might draw from them. Notably, most models at this scale neglect the visco-elasticity of the cement paste, or model it as fully decoupled, considering that the driving mechanisms of interest have a much higher (or slower) rates than creep. However, this is not necessarily the case as the influence of creep can be seen from very short to very long time scales. At short time scale, the visco-elastic nature of the material leads to a strong dependency between the failure behaviour and the loading rate [3,22,23], and is also known to mitigate early-age shrinkage cracking risks [24–26]. At very long term, the recent study of the authors on the role of creep in ASR and irradiation showed that the stress relaxation of the cement paste also delays in the long run the propagation of the damage in the microstructure [16,27].

While several models for creep exist in the literature, either at the macro-scale [28,32-34] or at the scale of the calcium-silicate hydrate (C-S-H) phase in which the creep phenomenon occurs [35–39], the underlying physical mechanism remains poorly understood and subject to debate and on-going research [28-30,40-42]. The separation into two main processes is commonly accepted:

- a reversible process involving the sliding of C-S-H structures one on another, in some models this is complemented with water movements in the gel pores,
- an irreversible process caused by changes in the C-S-H micro-structural arrangement.

---

[*] Corresponding author.
E-mail addresses: giorlaab@ornl.gov (A.B. Giorla), cfd30@cam.ac.uk (C.F. Dunant).

https://doi.org/10.1016/j.cemconres.2017.12.001
Received 8 May 2017; Received in revised form 3 October 2017; Accepted 22 December 2017
0008-8846/ Published by Elsevier Ltd.

Please cite this article as: Giorla, A.B., Cement and Concrete Research (2018), https://doi.org/10.1016/j.cemconres.2017.12.001

The first mechanism controls the short-term creep, and is typically represented at the C-S-H scale with a linear dash-pot. It is assumed to derive from the viscous sliding of C-S-H structures on each other. These may be the C-S-H sheets but also the C-S-H needles forming the bulk of the microstructure. In a previous work, Shahidi et al. [43] showed that the viscous behaviour of penny-shaped interfaces translates into an equivalent Kelvin-Voigt model at the upper scale using an analytic micro-mechanical homogenization scheme. The spring added in parallel at the cement paste level corresponds to the restraint caused by the elastic phases. The B3 model [28] and its various derivatives assume that this deformation spans a wide range of characteristic times following a progressive solidification theory. In a subsequent model, Hilaire et al. [34] used a single characteristic time, which seems more appropriate considering that Bazzoni [44] found that the C-S-H particles forms as needles of a single size characteristic of the binder, and Müller [45] showed that the gel intrinsic porosity also has a single characteristic size. Irfan-ul Hassan et al. [46] use an automated setup to identify the creep properties of cement paste during hydration. Their creep tests last 3 min, and they report no irreversibility in the creep.

The second mechanism controls the long-term creep and is assumed to be a logarithmic function of time. This behaviour has been identified at both the macro-scale [47] and the micro-scale with nano-indentation on mature C-S-H [29]. Different mechanisms have been proposed, which are all based upon modifications of the C-S-H microstructure.

In the micro-prestress theory proposed by Bažant et al. [28], it is assumed that the material is subject to very high localized stresses, which are progressively relaxed over time and redistributed throughout the microstructure even in absence of external loads. However, Gawin et al. [32] showed that this assumption is not sufficient to simulate the drying creep of concrete, and found better agreement by assuming that relative humidity plays a driving role in the creep deformation: they use a concept of effective stress used in poro-mechanics ($\mathbf{sigma}_e^s = \boldsymbol{\sigma} + \alpha p^s \mathbf{I}$, α Biot's coefficient, $\boldsymbol{\sigma}$ total stress, and p^s solid pressure) to calculate the creep deformation. Jirásek and Havlásek [33] considered a similar assumption by using a differential equation between the apparent viscosity of the material and the temperature and relative humidity variations.

In the nano-granular theory proposed by Vandamme and Ulm [29], derived from an analogy with the mechanical behaviour of soils, creep originates from the dislocation of C-S-H particles and their displacement into an adjacent empty pore of sufficient size. This causes a time-dependent deformation of the C-S-H micro-structure. As the deformation increases, the space available diminishes which leads to a progressive deceleration of the creep.

Rossi et al. [30] proposed a combination of micro-cracking and water diffusion into the newly-opened cracks to explain creep. The displacement of water from one crack to another reduces the cohesive force at the crack tip, allowing it to further propagate and leading to a load-induced drying shrinkage. This is consistent with the occurrence of acoustic emissions observed during a creep experiment as well as the non-linearity of creep for high level of load, but the authors did not provide a mathematical model to support their theory.

Finally, Pignatelli and colleagues [31] proposed a model in which C-S-H crystals, locally under load through the contact of other crystals dissolve and precipitate where there is no contact. Creep occurs as C-S-H needles interpenetrate through this mechanism. As this causes the microstructure to compact, the long-term creep differs from the short-term creep.

In all models, the long-term creep seems to be related to progressive slipping in the C-S-H microstructure, followed by its compaction. Table 1 identifies for each of the theory described above the mechanism corresponding to the slipping and compaction phases of the creep process. In the modelling, this can be represented as a time-dependent dashpot [28]. The separation of the behaviour in two processes is convenient from the point of view of modelling, but homogenization of creeping composites suggests that since a single phase is responsible for the time-delayed behaviour, and does not exhibit measurable changes in its intrinsic behaviour over time, a single characteristic time should describe creep in the long and short term. The transition between apparent short-term and long-term behaviour is then linked to the irreversibility of the behaviour.

While the need to account both for long-term and short-term behaviour is accepted now in the concrete community, few mesoscale models for concrete use it to describe the visco-elastic behaviour of the cement paste. In fact, the rare meso-scale models which actually account for creep at that scale approximate the cement paste behaviour with non-ageing Maxwell chains, either in the upscaling of visco-elasticity itself [10,11] or in the analysis of discrete crack propagation in visco-elastic materials [3,48]. This linear representation of the material shows no irrecoverable deformation, and is therefore unable to capture some of the non-linear effects observed in concrete creep such as non-superposition or non-linearity at high levels of load (see for example [49]). These aspects are critical for long-term modelling of the material.

The constitutive equation for the visco-elastic behaviour of mature cement paste we propose relies on four parameters that can be easily read on a creep curve, provided it includes at least one unloading step. Importantly, the proposed model has a single characteristic time, but yields both long and short term behaviour compatible with the phenomenological observations reported in the literature. The behaviour proposed in this work is properly classified as an ageing linear visco-elastic material. Extensions are proposed to account for the influence of temperature and relative humidity. These effects are calibrated on independent experiments from the literature. Several examples of multi-scale analysis of concrete creep experiments are shown to validate the behaviour. The discussion emphasizes micro-structural effects on the apparent concrete behaviour, notably the influence of the shape and orientation of the inclusions. The model is integrated within the space-time finite element method presented by the authors in [50], as implemented in the C++ finite element framework AMIE [15,51]. We validate our model based on the experiments by Le Roy [52], and use it to interpret the results by Denarié and co-workers [3] who studied the coupling between damage and creep. A key finding of this paper is the identification of the role of the particle size distribution of the inclusions in creep properties.

2. Constitutive behaviour of the cement paste

We assume that creep originates from two separate and simultaneous mechanisms:

Table 1
Slipping-compaction mechanisms in different creep theories.

Theory	Decohesion	Hardening
Micro-prestress [28]	Breaking of high-stress atomic bonds	Redistribution of the stress over the microstructure
Nano-granular [29]	Displacement of C-S-H grains into empty spaces	Self-compacting of the microstructure
Micro-crack [30]	Displacement of water out of existing cracks and pores	Displacement of water into the newly-formed cracks
Dissolution-precipitation [31]	Dissolution-precipitation of crystals under pressure	Increase in the affected interfaces