Cement and Concrete Research 71 (2015) 14–28

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: http://ees.elsevier.com/CEMCON/default.asp

Investigation of the effect of aggregates' morphology on concrete creep properties by numerical simulations

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ARTICLE INFO

Article history:
Received 1 September 2014
Accepted 5 January 2015
Available online 28 January 2015

Keywords:
Modeling (E)
Creep (C)
Particle size distribution (B)
Microstructure (B)
Interfacial transition zone (B)

ABSTRACT

Prestress losses due to creep of concrete is a matter of interest for long-term operations of nuclear power plants containment buildings. Experimental studies by Granger (1995) have shown that concretes with similar formulations have different creep behaviors. The aim of this paper is to numerically investigate the effect of size distribution and shape of elastic inclusions on the long-term creep of concrete. Several microstructures with prescribed size distribution and spherical or polyhedral shape of inclusions are generated. By using the 3D numerical homogenization procedure for viscoelastic microstructures proposed by Šmilauer and Bažant (2010), it is shown that the size distribution and shape of inclusions have no measurable influence on the overall creep behavior. Moreover, a mean-field estimate provides close predictions. An Interfacial Transition Zone was introduced according to the model of Nadeau (2003). It is shown that this feature of concrete's microstructure can explain differences between creep behaviors.

1. Introduction

Concrete structures evolves due to time-dependent phenomena such as shrinkage and creep. Predicting basic creep is necessary to estimate the time-dependent prestress losses in thick structures such as nuclear containment buildings. For this purpose, experimental investigations were conducted by Granger [1] in order to assess the basic creep of six concretes with various formulations.

According to this study, concretes with apparently similar formulation may exhibit different long-term behaviors. For instance, the concrete from Flamanville and the one from Paluel have very similar formulation regarding cement composition, water to cement ratio and grain size distribution as shown in Table 1. Fillers were added to the concrete from Paluel so that the total amount of fine aggregates (smaller than 100 μm) was almost equal in these two concretes. However, the major difference between the two concretes is the nature of the aggregates: crushed granite (granodiorite) for Flamanville and semi-crushed sand–lime river gravel for Paluel. Actually, the time-dependent strains of these two concretes are very different as shown in Fig. 1: The average strain measured on concrete samples from Flamanville after three years of the same compressive loading was twice as much as the one measured on samples from Paluel. Since tests revealed comparable mechanical properties for aggregates, Granger [1] also measured the basic creep strains of the cementitious matrices without finding noticeable deviation. He concluded that the differences of overall creep properties were due to the aggregates (shape, mineralogy or interface with the cement paste).

Because experimental results are difficult to obtain, a natural way to perform parametric studies is to rely on models. The purpose of this paper is to numerically investigate the effect of size distribution and shape of inclusions on the long-term creep of a matrix-inclusion material where the viscoelastic phase is the matrix. The matrix has the same behavior as a cement paste, the inclusions are perfectly bonded to the matrix and they have the elastic properties of aggregates.

One could use X-ray tomography images as inputs of 3D FFT-based computations [2]. This procedure has two drawbacks: the image must be segmented in order to differentiate the phases, and boundary effects may occur since the sample is not the unit cell of a periodic material. Filtering strategies have recently been defined to mitigate the effect of such boundary effects and get a macroscopically consistent estimate of the overall behavior [3]. This study is focused on numerically generated periodic microstructures so as to tightly control the volume fraction of inclusions, their sizes and their shapes. The generation of several microstructures with prescribed grain size distribution and spherical or polyhedral shape of inclusions is made by dense sphere packing or Random Sequential Adsorption algorithm. The 3D numerical homogenization procedure for viscoelastic microstructures proposed by Šmilauer and Bažant [4] is used to compute the time-dependent response to a constant applied load. The Interface Transition Zone is described, the model of Nadeau [5] is recalled and the assumption to extend it to viscoelasticity is exposed. Then, the obtained results are compared to the predictions of mean-field homogenization.

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http://dx.doi.org/10.1016/j.cemconres.2015.01.003
0008-8846/

Table 1
Formulation of two concretes of Granger [1].

	Flamanville	Paluel
(12.5/25 mm)	700 kg	700 kg
(5/12.5 mm)	340 kg	348 kg
(0/0.8 mm)	170 kg	
(0.1/0.5 mm)	485 kg	
(0/5 mm)	140 kg	722 kg
Filler Piketty		50 kg
Cement (St Vigor) (CPA HP PM)	375 kg	375 kg
Water	180 kg	180 kg
BV40 plasticizer	1.5 kg	1.56 kg
Young Modulus of aggregates	51–65 GPa	65 GPa
Young Modulus of concrete at 28 days	31.9 GPa	38.4 GPa
Compressive strength f_c at 28 days	50 MPa–53.4 MPa	43.0 MPa–52 MPa

In the first part of the paper, the microstructure generator is described, the 3D numerical homogenization method is introduced, some numerical tests are performed to validate and assess the performances of the simulations, the case of an Interfacial Transition Zone is exposed and its effect on the creep strain is numerically estimated. In the second part, the micromechanics methods are recalled and their predictions are compared to the numerical results. The paper ends with a discussion and a conclusion.

2. Simulation of viscoelastic matrix-inclusion microstructures

2.1. Generation of matrix-inclusion microstructures

In this section, the microstructure generator and the 3D numerical method for computing the overall viscoelastic response are presented. A matrix-inclusion microstructure is generated according to given volume fraction, sieve curve and shape of inclusions.

2.1.1. Scope statement

Some features are to be enforced in order to obtain a valuable matrix-inclusion microstructure generator:

- Inclusions are placed in a cubic cell and they should not overlap.
- The microstructure should be periodic.
- A tight control of the volume fraction, the size distribution and the shape of inclusions are required.
- High volume fractions of inclusions (>50%) are needed to represent realistic microstructures of concrete.
- The simulated material should be isotropic.
- The generator should run as fast as possible.

At least two methods may fulfill these requirements. The Random Sequential Adsorption (RSA) algorithm [6] is the simplest method to design and implement. Its ability to handle convex polyhedra makes it useful to assess the effect of shape of inclusions. A high volume fraction of inclusions (up to 68%) may be reached for wide sieve curves. On the other hand, this method fails to simulate monodisperse grain size distribution for volume fraction greater than 30%.

The other algorithm is the one of Lubashevky and Stillinger [7] which is dedicated to pack efficiently sets of ellipsoidal inclusions. In the case of monodisperse spheres, volume fraction up to 63% can be reached. To the authors' knowledge, there is no extension of this method to polyhedral inclusions.

2.1.2. Determination of the number of inclusions and their volumes

Given the sieve curve (volume fraction vs particle diameter), the volume fraction of inclusions f_g and the dimension l of the cubic cell, the starting point, common to both methods, is the generation of the random number of the inclusions in the cubic cell and their volumes.

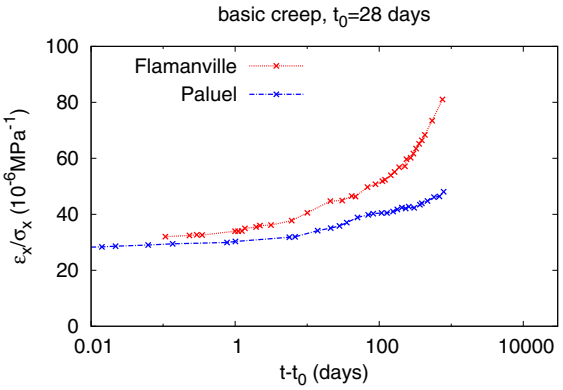

Fig. 1. Results of uniaxial compressive creep tests reported by L. Granger [1]. Although the formulations of concretes from Flamanville and Paluel were comparable, the basic creep strain (10^{-6} MPa^{-1} vs days) proved different. The compressive stress was 12 MPa and the concrete was loaded at $t_0 = 28$ days.

The sieve curve is first approximated by a piecewise linear function of the equivalent diameters on twenty classes, each class representing 5% of the total volume of inclusions. The equivalent diameter of an inclusion, d, is given by $d = \sqrt[3]{\frac{6}{\pi}v}$, where v is the volume of the inclusion. Each class must provide a volume $V_{5\%} = 0.05 \times l^3 \times f_g$ of inclusions. On each class $i \in \{0, 1, \ldots, 19\}$, the distribution of diameters is such that the approximated sieve curve $s(d)$ is an affine function of d on the interval $[d_{i+1}, d_i]$ with $D_{\max} = d_0 > d_1 > \ldots > d_{20} = d_{\min}$ [Fig. 2]. The classes are filled one after another, starting from the class 0 of largest inclusions $[d_1, d_0]$ to the class 19 of the smallest inclusions $[d_{20}, d_{19}]$. While the volume of the generated inclusions in class i is less than $V_{5\%}$, a new inclusion of diameter d_{picked} is repeatedly generated in this class as explained hereafter.

Let $F_i(d)$ be the probability to pick in the class i an inclusion of diameter lower than d. Since the sieve function is piecewise linear, $F_i'(d)\frac{\pi}{6}d^3$ must be uniform. Taking into account $F_i(d_{i+1}) = 0$ and $F_i(d_i) = 1$, we find that F_i is given by

$$F_i(d) = \frac{d^{-2} - d_{i+1}^{-2}}{d_i^{-2} - d_{i+1}^{-2}}.$$

Hence, d_{picked} is generated by:

$$d_{picked} = F_i^{-1}(R()) = \left(d_{i+1}^{-2} + \left(d_i^{-2} - d_{i+1}^{-2}\right)R()\right)^{-\frac{1}{2}}$$

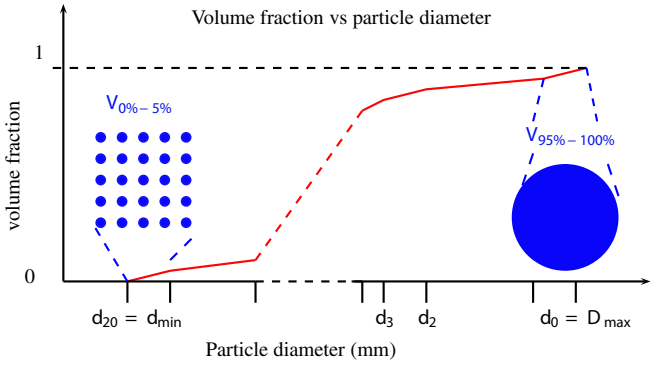

Fig. 2. The sieve curve:volume fraction vs particle diameter. This curve is approximated by a piecewise linear function on twenty classes, each class representing 5% of the total volume of inclusions.