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Analytical and 3D numerical analysis of the thermoviscoelastic behavior of concrete-like materials including interfaces

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ABSTRACT

We investigate in this paper analytically and numerically by means of 3D simulations the viscoelastic behavior of concrete and mortar subjected to creep loading and moderate temperatures at mesoscale. These heterogeneous materials are assumed to be composed of thermoelastic aggregates distributed in a linear thermoviscoelastic matrix; moreover, the Interfacial Transition Zones (ITZ) between aggregates and matrix, whose behavior is also considered as linear thermoviscoelastic, are explicitly introduced. The numerical specimens consist in unstructured periodic meshes containing polyhedral aggregates with various size and shapes randomly distributed in a box. Zero-thickness interface finite elements are introduced between aggregates and matrix to model the ITZ. Macroscopic response and averaged stresses and strains in the matrix and aggregate phases are compared to analytical estimations obtained with classical mean-field approximation schemes applied in the Laplace–Carson space, in which the ITZ are introduced via imperfect interfaces modeled with the Linear Spring Model (LSM). The effects of ITZ thickness, aggregate shape and uniform temperature increase are then studied to evaluate their respective influence on the local and macroscopic creep behavior of mortar and concrete. Globally, it is found that the model response is in relatively good agreement with numerical simulations results, and that as expected while the ITZ do not affect significantly the concrete behavior, they have a non-negligible impact on the mortar one.

1. Introduction

When considering concrete structures in the nuclear context (i.e. containment building, waste storage structures…), two main functions have generally to be guaranteed: containment and protection against radionuclide migration. The constitutive material must then meet high requirements in terms of performance and durability. In particular, loss of containment abilities due to long-term creep and induced development of cracks shall be prohibited. It is well known that concrete is a heterogeneous material made up at the mesoscale of linear elastic aggregates distributed in a mortar matrix whose behavior is time-dependent. Besides, the presence of an ITZ (Interfacial Transition Zone) constituted by a thin interface between the aggregates and the matrix is known to also influence the overall behavior, due to its lesser mechanical (and higher transport) properties, see e.g. [1–4]. It is then of particular importance to correctly characterize the respective role and impact of both phases and ITZ regarding the creep strains, since the initiation and propagation of cracks are strongly related to the local stresses and strains states as well as their history.

In the literature, while a number of numerical studies address the problem of the effects of ITZ influence in cementitious materials in elasticity (e.g. [5,6]), less are developed in a viscoelastic framework, at least partly due to the resulting more complex formulation. From the theoretical viewpoint, numerous approaches for estimating mechanical as well as transport properties of cementitious materials including ITZ are based on an explicit representation of the interface and the use of analytical homogenization techniques such as the self-consistent scheme to upscale the physical properties, see e.g. [1,7–10]. However, if such developments are relatively well adapted to the case where the interface thickness is moderately low (i.e. mortars), they appear by contrast less satisfactory for concretes since the ratio of respective size between the interfaces and aggregates ranges from 2 to 3 orders of magnitude. Models devoted to thin interfaces, i.e. accounting specially for the small size of the interface with respect to the inclusion one, are comparatively more suited to the case of ITZ surrounding aggregates and coarse sand particles. In particular, the resulting imperfect interfaces whose material properties are lower than the

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inclusion ones may be properly approached by the Linear Spring Model (LSM) developed by e.g. [11–13]. This model describes the displacement jump across the interface as a function of the normal stress (assuming the stress jump is zero) via rigidity coefficients estimated with simple expressions involving the interface mechanical properties and its thickness h. Such model has been successfully applied to the simulation of imperfect interfacial debonding [14] and thin and compliant interfaces (e.g. [13,15]).

Numerically, the study of interface effects in diverse situations has also generated interest among the research community (see e.g. [6,16]). The advantages of numerical simulations are that they allow considering in the material samples various and more complex configurations regarding aggregate shapes and sizes, including possible different ITZ thicknesses and mechanical properties, which cannot be reached in general analytically. Also, local analyses of physical fields (strain, stress, temperature, etc.) can be performed so as to quantify statistical information as dispersion in aggregates, ITZ and matrix subvolumes, contrary to analytical upscaling schemes which are mostly limited to per-phase averaged quantities. Diverse methods have been applied to solve the problem of heterogeneous materials including interfaces: among others, one can cite the classical finite element method (FEM) [17,18], lattice models [19–21], XFEM/level set methods [22,23], and FFT-based methods [3]. We note that in some of these references, interfaces are explicitly introduced without the recourse of special elements or procedures, meaning that the results directly depend on the spatial resolution/discretization of the material. Some other methods make use of homogenized zones encompassing ITZ to avoid their explicit introduction. Interestingly, a number of studies have emphasized the interest of specific interface elements for describing fracture processes in addition to ITZ effects in cementitious materials via cohesive-zone models, see e.g. [24–26].

In this paper we investigate analytically and numerically the thermoviscoelastic behavior of concrete and mortar at mesoscale, with a particular focus on the effects of ITZ. One purpose of the study is to test the capacities of simplified analytical models based on classical estimation methods against computation results performed on numerical samples expectedly (much) more representative of such concrete and mortar materials. Specifically, the simulations are carried out by applying the FEM on 3D specimens consisting in polyhedral aggregates of various sizes and shapes randomly distributed in a box. We make use of previous developments and procedures to generate mesoscale numerical samples and to perform computational analyses [27–30]. The matrix and ITZ phases are considered as linear thermoviscoelastic materials ruled by different generalized Maxwell models. Specific interface elements are introduced between the aggregates and the matrix to simulate the ITZ, whose behavior is characterized by the LSM extended to the thermoviscoelastic case. These interface elements are considered to be very well suited for this purpose, and are one good reason to carry out FEM simulations, though it should be noticed that alternative methods may be more efficient than FEM for general numerical simulations (i.e. without interfaces) of representative element volumes (REV), see e.g. [31]. Note that the aggregates in the placement procedure are not allowed to intersect each other by construction, so that possible ITZ percolation effects are not reproduced; this is also the case for the analytical model since the microstructure representation takes only into account separate inclusions.

A particular attention will be put on the analysis of the overall and intra-phase response of the numerical specimens when subjected to classical creep and heating loadings. In particular, the evolution of averaged stresses and strains in the matrix and aggregate phases will be reported and compared to the analytical estimations obtained with different mean-field approximation schemes applied in the Laplace–Carson (LC) space. The influence of the ITZ thickness on the overall and local response of the specimens will also be studied. We expect recover the quantitative results highlighting the much more importance of ITZ in mortar behavior than in concrete one. Further, the impact of the aggregate shape on both local and macroscopic response will be analyzed through different mesostructures with flat and elongated particles. Finally, a local analysis regarding the evolution of the mean stresses and strains in each aggregate and in matrix subvolumes will be performed so as to quantify their dispersion.

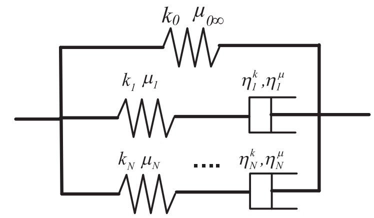

Fig. 1. Representation of a Generalized Maxwell model with $N+1$ elements.

2. Linear viscoelastic modeling

As mentioned in the introduction, we are concerned in this paper with the analysis of the thermoviscoelastic behavior of concrete with a special focus on the effects of the ITZ. In this section the models used for the viscoelastic formulation are recalled, while the extension to the thermoviscoelastic case is detailed in Section 5.

2.1. Matrix behavior

The behavior of the matrix material is assumed to be linear viscoelastic, with bulk $k^m(t)$ and shear $\mu^m(t)$ moduli ruled separately by a generalized Maxwell model with $N+1$ elements (see Fig. 1 for the representation of a Maxwell model with the element labeled as 0 composed only of a spring) as:

$$k^m(t) = k_0^m + \sum_{i=1}^{N} k_i^m e^{-t/\tau_i^m}, \quad \mu^m(t) = \mu_0^m + \sum_{i=1}^{N} \mu_i^m e^{-t/\tau_i^m} \tag{1}$$

in which k_i^m and μ_i^m with $i \in \{0, N\}$ are the elastic moduli of the Maxwell elements, τ_j^m are their relaxation times, N is the number of viscoelastic elements. It is assumed to simplify that τ_j^m and N are the same for both moduli, but it is not strictly mandatory. Accordingly the behavior law takes the form:

$$\boldsymbol{\sigma}_m(t) = 3\int_{0^-}^{t} k^m(t-\tau)\frac{d\epsilon_m}{d\tau}d\tau\,\mathbf{1} + 2\int_{0^-}^{t} \mu^m(t-\tau)\frac{d\boldsymbol{e}_m}{d\tau}d\tau \tag{2}$$

with $\boldsymbol{\sigma}_m(t)$, $\varepsilon_m = 1/3\mathrm{tr}(\boldsymbol{\varepsilon}_m)$ and $\boldsymbol{e}_m$ the macroscopic stress tensor, bulk and deviatoric part of the strain tensor $\boldsymbol{\varepsilon}_m$ of the matrix, respectively; $\mathbf{1}$ is the second-order identity tensor.

It is well-known that in the case of linear viscoelasticity the time-dependent problem may be equivalently reformulated as a linear elastic problem in the Laplace–Carson (LC) space, allowing to applying classical upscaling techniques (see e.g. [32–35]). We recall that the LC transform $\tilde{f}(s)$ of a function $f(t)$ takes the following form:

$$\tilde{f}(s) = s\int_{0}^{\infty} e^{-st} f(t)dt \tag{3}$$

with s the variable in the LC space. One advantage of this transformation is to replace the time integral formulation (2) by an equivalent elastic-like formulation in the LC space as:

$$\tilde{\boldsymbol{\sigma}}_m(s) = 3\tilde{k}^m(s)\tilde{\varepsilon}_m 1 + 2\tilde{\mu}^m(s)\tilde{\boldsymbol{e}}_m \tag{4}$$