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A two-yield surfaces, viscoplastic constitutive model for ceramics and geomaterials

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ABSTRACT

This work describes an innovative multi-axial, elasto-visco-plastic constitutive model based on the assumption that plastic deformations are induced by two mechanisms: a short term, instantaneous mechanism, and a long term, viscous mechanism. The need for this approximation has been recently deduced from experimental compaction of fine grained powders (consisting of clays). This constitutive approach implies the need to consider the existence of two yield surfaces: the first one is a conventional, rate-independent, elasto-plastic yield surface, whereas the second one is a Perzyna-type, visco-plastic yield surface. The method for combining the hardening laws of the two, very different yield surfaces within a consistent framework is discussed in detail and the numerical algorithms for the implicit, backward Euler integration of the proposed model are fully explained. In the final part of the work, model simulations are compared with experimental results, showing that model simulations are reliable for both ceramics and geomaterials.

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1. Introduction

Creep deformations of ceramic materials are important in many high temperature, engineering applications, ranging from high performance gas turbines [2], hot isostatic pressing [22], porous ceramic nuclear fuels [17], and refractory materials in the steel industry. Although viscous phenomena in ceramics are mostly evident at high temperature, delayed phenomena might assume a non-negligible role also in some applications at room temperature, for instance involving the mechanical response of the ceramic powders.

In all of the mentioned engineering applications, reliable constitutive models are typically needed to obtain realistic descriptions of the mechanical behaviour of the ceramic pieces under working conditions. Unfortunately few constitutive models are available for describing the mechanical response of ceramics materials in the plastic range [23].

Two general constitutive approaches have been proposed for modeling visco-plastic behaviour of ceramics at high temperatures. The first approach takes account of the cited ductility at high temperature and is based on the use of Gurson's model [8] for defining the flow potential of a hardening porous solid, and Duva & Hutchinson's model [10] for defining the strain rate potential of a voided material. This approach has been followed for instance by [5,16,17].

In contrast, the second constitutive approach is based on the application of general elasto-visco-plastic formulations to ceramics, with a proper selection of yield and creep functions and plastic potentials. This method has been implemented, among others, by [11,4,23]. Within this kind of approach, one of the simplest viscoplastic models was proposed by Perzyna [19,20], who proposed the use of nested visco-plastic yield surfaces. An alternative formulation was proposed by [6], as an improvement of Perzyna's approach for non-smooth yield surfaces. Further, a slightly different proposal based on non-stationary flow surface theory was made by [18].

The constitutive model proposed in this work belongs to the second category and capitalizes the experimental evidences recently presented by [14] on the behaviour of wet, fine grained powders consisting of clay. The experimental results were obtained at room temperature and showed that two deformation mechanisms can be recognized for both elastic and plastic strains, namely a short-term (immediate) mechanism, and a long-term, viscous one. Even in ceramics at high temperature, [17], proposed the existence of two creep mechanisms: the scattering-creep and the dislocation-creep. Thus the existence of two (or more) deformation mechanisms in ceramics and geomaterials is physically well motivated and can be reasonably expected. In addition, the existence of a short term, instantaneous mechanism of deformation is appealing because it improves the model response in the case of

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very high strain rates applied to a purely viscoplastic response. In any case the identification of the possible micro-scale mechanisms that might be responsible for the different macro-scale, deformation mechanisms (that are expected to change with temperature) has not been attempted, due to the lack of experimental data.

In this work, the experimentally motivated, existence of two deformation mechanisms is incorporated in a theoretically consistent constitutive framework. For the sake of simplicity, both the elastic strain and the short-term plastic mechanism are assumed here to be perfectly instantaneous (i.e. rate-independent), thus the rate dependency is limited to a fraction of the plastic strain. The framework described above implies the existence of two nested yield surfaces, namely the inner one which is treated as a Perzyna-type, viscous yield surface, whereas the external one which is a conventional, rate independent yield surface. A similar constitutive approach has never been proposed so far, to the best of our knowledge, and constitutes the major contribution of this work. A further novelty of the work is the definition of an innovative, non-linear viscosity function, that resulted particularly advantageous for the simulation of the observed logarithmic strain–time response and for the numerical implementation of the model, compared to similar functions proposed in the literature [15].

Although the proposed visco-plastic framework implying two yield mechanisms, is completely general and can be applied in principle to any rate-independent, smooth yield function, the description provided in this work makes reference to a simple Cam Clay yield function [21]. The visco-plastic model is formulated for isothermal conditions, and the future developments will concern the incorporation of temperature effects, to describe non-isothermal conditions. The resulting model provides realistic simulations of ceramics and geomaterials.

The paper is organized as follows: Section 2 describes the theoretical formulation of the proposed model, with emphasis on the method used for combining together the different hardening laws of the two yield surfaces, within a consistent theoretical framework. The numerical algorithm for the implicit, backward Euler integration of the model is explained in detail in Section 3, with some considerations about model calibration and choice of initial conditions. Typical model responses and comparisons of model simulations with experimental results are shown in Sections 4 and 5, respectively, whereas the conclusions are finally drawn in Section 6.

Notation:

The following tensorial product will be used:

$$(\boldsymbol{A} \otimes \mathbf{B})[\boldsymbol{C}] = (\mathbf{B} \cdot \boldsymbol{C})\boldsymbol{A} \quad \text{and} \quad \left(\boldsymbol{A} \underline{\otimes} \mathbf{B}\right)[\boldsymbol{C}] = \frac{1}{2}\left(\boldsymbol{A}\boldsymbol{C}\mathbf{B}^T + \boldsymbol{A}\boldsymbol{C}^T\mathbf{B}^T\right),$$

for every second-order tensor $\boldsymbol{A}$, $\mathbf{B}$ and $\boldsymbol{C}$. The symbol $\boldsymbol{\sigma}$ denotes the stress tensor, and ϵ indicates the strain tensor. $\mathbf{I}$ represents the second order, identity tensor. The increment of a given quantity (e.g. the strain ϵ) will be denoted with the symbol δ (namely $\delta\epsilon$), whereas the corresponding rate of variation will be denoted with a superposed dot (namely $\dot{\boldsymbol{\epsilon}} = \delta\boldsymbol{\epsilon}/\delta t$, where t is the time).

2. Formulation of the constitutive model

The constitutive model is developed in a general multi-axial stress space, within the small strain theory. The viscoplastic approach that will be described below has a general applicability and can be implemented in any rate-independent framework, in order to obtain a rate-dependent formulation. In this work, however, for the sake of illustrating the proposed approach, the Modified Cam-Clay elastoplastic model has been selected as rate-independent model [21].

Starting from laboratory tests performed on different clays, Madaschi and Gajo [13,14] have recently shown the need for splitting the deformation increment into an elastic and a plastic fraction, both of which should in turn be split into an instantaneous and a delayed, viscous component. In this work, however, for the sake of simplicity, the elastic strain increment will be assumed completely instantaneous.

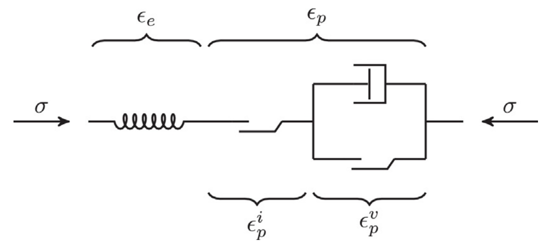

Fig. 1. Proposed rheological model.

The basic assumptions of the model, deduced from the experimental observations, are summarized below:

- E1 two deformation mechanisms are assumed for the plastic strain: an instantaneous and a viscous one;
- E2 the elastic strain increment is assumed entirely instantaneous;
- E3 the plastic strain rate does not affect the strength at the critical state, i.e. the final strength that is reached at large shear strains, when the volumetric strain remains constant [25];
- E4 according to isotache concept [24,3], in a one-dimensional creep test, the viscous plastic deformations has a linear behaviour with respect to the logarithm of time.

From assumptions E1 and E2, the strain decomposition is given by Eq. (1)

$$\boldsymbol{\delta\epsilon} = \boldsymbol{\delta\epsilon}_e + \underbrace{\boldsymbol{\delta\epsilon}_p^i + \boldsymbol{\delta\epsilon}_p^v}_{\boldsymbol{\delta\epsilon}_p} \tag{1}$$

where the strain increment tensor is additively decomposed into three components: the instantaneous elastic ($\delta\epsilon_e$), the instantaneous plastic ($\delta\boldsymbol{\epsilon}_p^i$) and the viscoplastic ($\delta\boldsymbol{\epsilon}_p^v$) component. The corresponding rheological model is shown in Fig. 1.

Assumption E3 has been deduced from experimental results obtained on fine grained porous media (with grain size ranging from clays to sands) thus, this assumption is meaningful mainly for a completely uncemented condition, such as that one inside a shear band, where cementation effects are completely lost due to the large shear strains. Since assumption E3 implies that the rate effects are negligible at very large shear deformations when the volumetric strain rate is null and the shear strength remains constant (i.e. at the critical state), we will assume below that the viscous response depends on the volumetric strain rate, thus when the stress state approaches the final (critical) state, the volumetric strain rate goes to zero so also the viscous effects do.

Assumption E4 has been deduced from experiments performed on fine grained materials (with a grain size ranging between clays and silts) and could be easily modified to take account of the experimental response of different ceramic and rock-like materials. In any case, assumption E4 was observed to simulate well the few (short duration) experimental results on ceramic materials that are available in the literature.

2.1. The yield surfaces and the hardening parameters

The assumption E1 implies the existence of two yield mechanisms (namely two yield surfaces) related to two different plastic

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