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A thermomechanical constitutive model for cemented granular materials with quantifiable internal variables. Part I—Theory

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A B S T R A C T

This is the first of two papers introducing a novel thermomechanical continuum constitutive model for cemented granular materials. Here, we establish the theoretical foundations of the model, and highlight its novelties. At the limit of no cement, the model is fully consistent with the original Breakage Mechanics model. An essential ingredient of the model is the use of measurable and micro-mechanics based internal variables, describing the evolution of the dominant inelastic processes. This imposes a link between the macroscopic mechanical behavior and the statistically averaged evolution of the microstructure. As a consequence this model requires only a few physically identifiable parameters, including those of the original breakage model and new ones describing the cement: its volume fraction, its critical damage energy and bulk stiffness, and the cohesion.

1. Introduction

A number of naturally occurring and artificial materials are classified as cemented granular materials (CGMs) (Fig. 1). The well-known naturally occurring examples include calcite, quartz and clay cemented sands (Dvorkin and Yale, 1997) and sedimentary rocks like sandstones, conglomerates and breccias (Topin et al., 2007). Artificially cemented materials widely used in engineering include asphalts, mortars, concrete, bio-, mortar-, and polymer-grouted soils (Anagnostopoulos, 2005). Other CGMs are solid propellants, high explosives and wheat endosperm (Topin et al., 2007).

All the CGMs described above share a common texture of grains being bridged by cement matrix that partially or completely fills the voids; for this reason, CGMs often share microscopic processes that control their macroscopic behavior. This paper focuses on lightly to medium cemented granular materials. The mechanical behavior of such materials is controlled by the grain properties and their (re-)organization, as for uncemented granular materials, plus the effect of the cement, which, even in small amounts, can significantly alter the stress distribution within the grains and therefore the mechanical response of the aggregate (e.g. Wong and Wu, 1995; Alvarado et al., 2012). The inelastic behavior of this class of materials is thus governed by three main processes (Menendez et al., 1996): grain crushing, cement damage and fragment reorganization.

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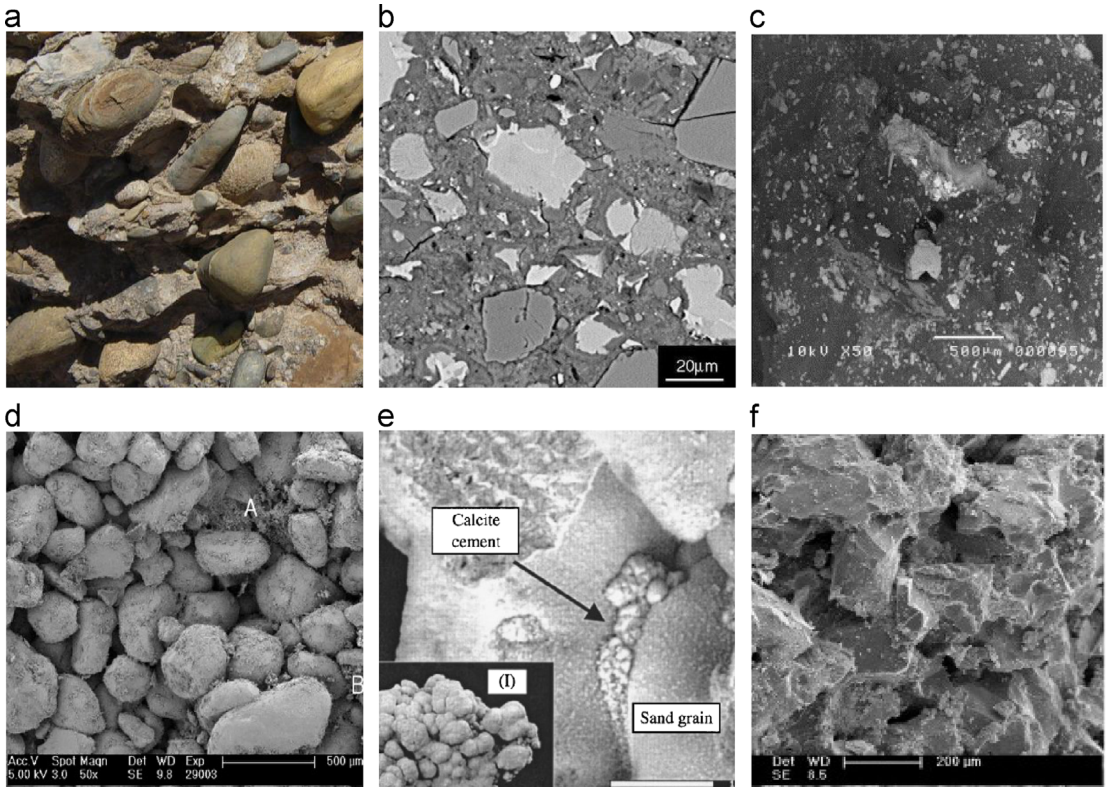

Fig. 1. Examples of cemented granular materials: (a)–(c) heavily cemented granular materials (Commons, 2006; Winter, 2012; Wong et al., 2007), and (d)–(f) lightly cemented granular materials (Alvarado et al., 2012; Ismail et al., 2002; Rong et al., 2012). (a) Conglomerate, (b) Concrete, (c) Asphaplt, (d) Saltwash Sandstone, (e) Calcite cemented sand and (f) Biocemented Sand.

In this paper, we propose a continuum constitutive model for CGMs, starting from the micro-mechanical observation of grain and cement failures. Each of these phenomena will be captured by a separate internal variable with meaningful statistical interpretations. The injection of physical understanding of the micro-mechanics underlying the macroscopic response minimizes the number of required parameters, which will here have a clear physical meaning and are all measurable. The formulation follows the thermo-mechanical framework, and thus the proposed model obeys the laws of thermodynamics.

The choice of the internal variables is justified in Section 3, followed by the study of the elastic stored energy in Section 4. The thermo-mechanical framework is revised in Section 5 and a possible model within the proposed framework is introduced in Section 6. Finally, the range of phenomena that the proposed model is able to reproduce is explored through a sensitivity analysis in Section 7.

2. Previous work on CGM characterization and modelling

In 1993, Gens and Nova noticed that there was a general lack of *conceptual frameworks and mathematical models able to integrate the behavior of CGMs in a consistent and unified manner* (Gens and Nova, 1993). Although several experiments and computational methods have been designed to study CGMs, the observation of Gens and Nova is likely still relevant today.

2.1. Experimental observations

Some experimental works have focused on the influence of microscopic features on the macroscopic response, in particular the effect of cement content and type and the composition and fabric of the granular phase (Schnaid et al., 2001; Coop and Atkinson, 1993; Airey, 1993; Ismail et al., 2002). Other authors focused instead on the study of the micro-mechanisms involved (Menendez et al., 1996; David et al., 2001; Wong and Baud, 2012). The addition of cement to granular materials is known to increase the size of the yield strengths, and enhance the shear and bulk elastic moduli (e.g. Coop and Atkinson, 1993; Airey, 1993; Clough and Nader, 1982; Huang and Airey, 1998); on the other hand, the critical state appears to be independent of the level of cementation (Coop and Atkinson, 1993; Airey, 1993; Huang and Airey, 1998). Shear at low confining pressures is led by progressive fracture of cement bridges among the grains, which releases local degrees of freedom, allowing fragment reorganization. This progressive loss of the contribution of the cement to the stability of the