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Modeling of granular media submitted to internal underpressure

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ABSTRACT

A conglomerate, composed of granular materials encapsulated in a tight, flexible envelope, and submitted to an internal underpressure is investigated experimentally and modelled numerically. The underpressure level, controlled by a vacuum pump, has a great influence on the properties of the media. The structures filled up with plastic grains and submitted to uniaxial compression tests are examined in this study. The nonlinear behaviour is simulated using the viscoplastic constitutive law of Chaboche. The identification of material parameters is formulated as an optimization problem and solved by means of the evolutionary algorithm. The numerical examples present the robustness of the proposed approach. Possible improvements of the method are discussed.

1. Introduction

A conglomerate, composed of granular materials encapsulated in a tight, flexible envelope, and submitted to an internal underpressure, changes its properties in the function of the vacuum range. The underpressure level, controlled by a vacuum pump, enables us to control the behaviour of such medium. This particular ability could be useful in some specific applications. A direct example of a practical use of this phenomenon is a vacuum mattress – a medical device applied for the immobilisation of patients, especially in a case of vertebra, pelvis or limb trauma. Packing systems for fragile objects, temporarily fixing shapes, semi-active damping of vibrations or insulation panels are examples of possible applications.

Although, the most important factor that influences the mechanical properties of such structures is the underpressure value, the global material features depend also on the dimensions and the shape of a single grain, type of granular material, surface roughness, filling ratio of the structure (grain volume to the envelope volume ratio) and a type of loading. Thus, the preparation of such granular structure gives us the possibility of controlling its global mechanical characteristics (e.g. the Young's modulus or the proof stress) and its behaviour.

In this study, the structures filled up with plastomers' grains and submitted to uniaxial tension are examined experimentally for different underpressure levels. Their nonlinear behaviour is modelled using the viscoplastic constitutive law of Chaboche, requiring determination of several material parameters. The identification of material constants is formulated as an optimization problem and solved by means of the evolutionary algorithm. The investigated subject is original and, besides former conference papers of authors (Bajkowski and Zalewski, 2006a,b), it is difficult to reference other relevant publications.

2. Experimental results

The structures under investigation are granular media encapsulated in a tight, flexible envelope, resistant enough to prevent a perforation by rough grains. The plastic grains investigated in this study are made of Acrylonitrile Butadiene Styrene (ABS), characterized by density 1.05 g/cm^3, Young modulus 1.1–2.9 GPa and elastic limit 18–50 MPa.

A special cylindrical granular specimen, consisting of two rigid discs joined by a thin (0.25 mm) polyvinyl chloride encapsulation, has been developed for the experimental investigation (Fig. 1). The envelope has been connected to the vacuum pump through a valve. The pump was used to generate an internal underpressure and to maintain it constant during the tests. The underpressure causes the stiffening of the structure, and for its suitable value, the baggy granular media becomes a solid like structural material.

The experimental tests have been conducted for constant filling coefficient $N = 0.32$, representing the fraction of the free volume (that is not packed by the grains) with respect to the total space. Uniaxial compression tests have been conducted using the universal tensile testing machine MTS 809 at the constant, strain independent strain rate, carefully determined for a granular structure

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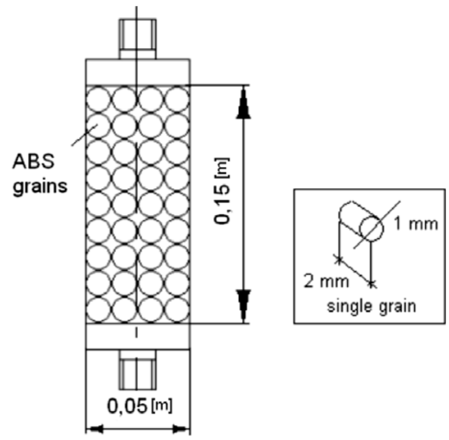

Fig. 1. Schematic of the granular specimen.

on the basis of several experiments (Bajkowski and Zalewski, 2006a,b). The strain rate value $\dot{\varepsilon} = 1 \times 10^{-3}$ [1/s] was found small enough to assume the quasi-static strain rate, corresponding to the elongation of the granular specimen by $\Delta l = 10$ [mm] in time $t = 60$ [s]. Below this threshold value, a stagnation of the viscous phenomenon of the granular samples was observed.

The applied underpressures p, defined as a difference between the atmospheric (0.1 MPa) and the internal pressure, measured experimentally, varied from values close to the atmospheric pressure ($p = 0.01$ MPa) to values approaching vacuum ($p = 0.09$ MPa). The stress–strain graphs, obtained at different internal underpressures for the ABS cylindrical shape grains of 1 mm diameter and 2 mm length, are presented in Fig. 2 (only experimental hardening curves are depicted). The proof strain $\varepsilon = \frac{l - l_0}{l_0}$, expressed as the change in the sample length per unit of the original length, and the conventional stress measure, defined as the ratio of the loading force F to the initial cross-sectional area of the specimen $\sigma = \frac{4 \cdot F}{\pi \cdot d^2}$ have been chosen (d stands for the specimen diameter). The influence of the underpressure level is evident. The hardening curves are located higher for samples with greater internal underpressure. Correspondingly, increased values of Young's modulus, tensile strength or yield point (proof stress) are observable. The detailed description and typical experimental hardening curves for other granular structures can be found in Bajkowski and Zalewski (2006a,b)).

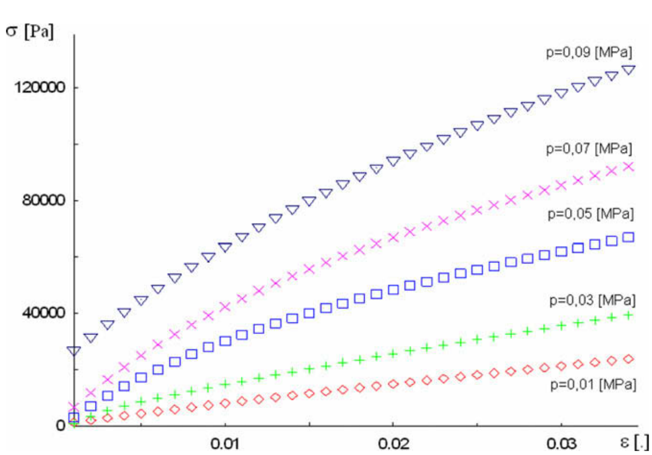

Fig. 2. Tensile test results at different internal underpressures for ABS grains.

3. Viscoplastic constitutive model

The behaviour of the special granular structures investigated is complex and nonlinear. Here only uniaxial hardening curves are presented for ABS grains and a selected strain rate. However, previous works of authors (Bajkowski and Zalewski, 2006a,b) have revealed, that the behaviour of considered structures is analogous to viscoplastic materials. Zalewski (2005) experimentally discovered the sensitivity of the granular conglomerate to the various strain rate and found that higher strain rates generate higher position of hardening curves. In Zalewski (2008) or Zalewski and Skalski (2008) the results of stress-relaxation tests are described. Rheological effects have been observed for all applied types of granules, underpressure values and strain rates. Based on the overall collected experimental data, we have decided to propose the application of a viscoplastic constitutive law to model the behaviour of granular structures submitted to internal underpressure.

The classical Chaboche viscoplastic constitutive law (Chaboche and Rousselier, 1993) has been chosen in this study because of its universality and capacity to capture not only the behaviour of metal alloys but also applied to model polymers, solid propellants and even fabric textiles. In the uniaxial case it can be written as

$$\sigma = k + Q\,(1 - e^{-b \cdot \varepsilon^I}) + K \cdot \dot{\varepsilon}^{I^m}, \quad (1)$$

with σ – stress, ε – strain, ε^I – inelastic strain, $\dot{\varepsilon}$ – strain rate, $\dot{\varepsilon}^I$ – inelastic strain rate. The model is characterized by: k – initial yield limit (the yield point acquired in uniaxial experiment for strain independent strain rate), Q – isotropic hardening parameter (responsible for cyclic hardening effects for $Q > 0$ and softening effects when $Q < 0$), b – isotropic hardening exponent (the parameter responsible for convergence rate of the model to the stabilized cycle), K – strain rate coefficient (the plastic strength function), m – strain rate or viscous exponent. In the presented approach it was assumed that the conglomerate system is isothermal. The formulation (1) was obtained by taking the kinematic hardening function X (Lemaitre and Chaboche, 1990)

$$X = v \cdot \frac{2}{3} \cdot \frac{a}{c} + \left(X_0 - \frac{2}{3} \cdot \frac{a}{c} \right) \cdot \exp\, -c \cdot (\varepsilon^I - \varepsilon_0^I), \quad (2)$$

with $v = \mathrm{sgn}(\sigma - X) = \pm 1$, a and c – constant values, X_0 – the initial kinematic hardening parameter, and ε_0^I – the initial inelastic strain. The isotropic hardening function R was defined as

$$R = Q(1 - \exp(-b \cdot |\varepsilon^I|). \quad (3)$$

The final form of the stress function of the granular material in the uniaxial case

$$\sigma = X(\varepsilon^I, X_0, \varepsilon_0^I) + v \cdot R(|\varepsilon^I|) + v \cdot k + v \cdot K |\dot{\varepsilon}^I|^m, \quad (4)$$

was then simplified to (1) assuming that the parameters ε_0^I and X_0 can be neglected. In the presented approach, the kinematical hardening term was omitted in order to reduce the number of material constants.

4. Identification of material parameters using evolutionary algorithm

Classical procedures of parameter estimation are complicated and time consuming, especially in the case of multi-parameter viscoplastic constitutive models (Zalewski, 2005). They may require complex experimental tests (tensile tests for a wide range of strain rates, cycle loading for obtaining a stabilized loop, etc.), complicated transformations of the mathematical formulation (depending strongly on the applied model) and additional numerical processing. In order to avoid a large part of presented disadvantages, a numerical procedure of parameters identification,