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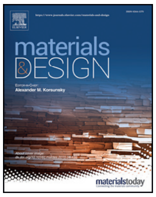

Stochastic continuum model for mycelium-based bio-foam

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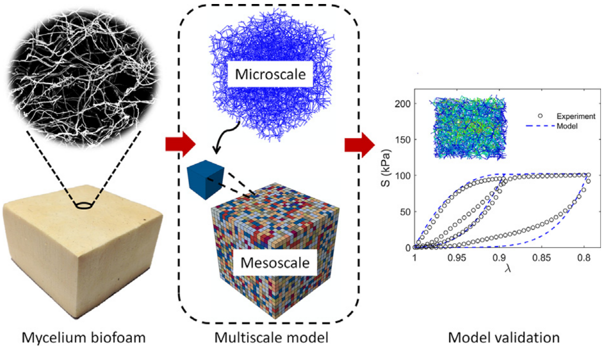
HIGHLIGHTS

- Novel biofoam, developed from the root structure (mycelium) of fungi, is characterized under axial compression.
- The material response is highly nonlinear and controlled by microscopic randomness and density variability.
- Mycelium biofoam exhibits strong stress softening and hysteresis under cyclic loading.
- A multiscale model is presented, capturing the microscale structure and mesoscale density fluctuation of the material.

GRAPHICAL ABSTRACT



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ABSTRACT

Mycelium, the root structure of fungi, grows naturally as a biodegradable filamentous material. This unique material has highly heterogeneous microstructure with pronounced spatial variability in density and exhibits strongly non-linear mechanical behavior. In this work we explore the material response in compression, under cyclic deformation, and develop an experimentally-validated multiscale model for its mechanical behavior. The deformation localizes in stochastically distributed sub-domains which eventually percolate to form macroscopic bands of high density material. This is reflected in the stress-strain curve as strain softening. Cycling at fixed macroscopic strain leads to deformation history dependence similar to the Mullins effect. To capture this behavior, we use a two-scale model. At the micro-scale, a random fiber network is used, while at the macroscale the spatial density fluctuations are captured using a stochastic continuum model. The density-dependent local constitutive behavior is defined by the microscale model. An empirical damage model is incorporated to account for the experimentally observed cyclic softening behavior of mycelium. The model is further validated by comparison with a separate set of experimental results. The model can be used to explore the effect of mesoscale density fluctuations on the overall mechanical behavior and to design mycelium-based products with desired mechanical performance.

1. Introduction

Mycelium is a sustainable alternative to petroleum-based polymeric materials. It grows naturally as the root structure of fungus and self-organizes as a network of tubular filaments, called hyphae, Fig. 1.

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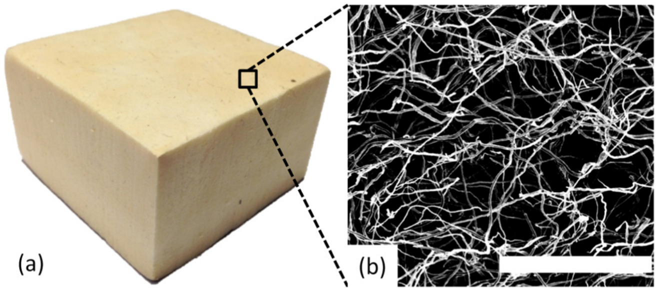

Fig. 1. Illustration of mycelium-based bio-foam: (a) macroscopic structure (50 × 50 × 50 mm) and (b) microstructure of mycelium; scale bar 100 μm.

Mycelium has the potential to emerge as a material of choice for lightweight structures with several advantages such as low density, low production cost, minimal processing energy input and, most importantly, 100% biodegradability. To promote the applications of this novel fungal bio-material, a precise understanding of its deformation behavior is required.

Recent experiments on mycelium indicate that it demonstrates significant non-linear behavior under compression [1]. In particular, mycelium exhibits three distinct regimes under compression, somewhat similar to open cell foams [2]. Linear elastic behavior is observed at small strains. This is controlled by hyphae bending and does not entail significant structural reorganization of the network. A second regime emerges at larger strains, which is associated with fiber buckling and local structural collapse/densification leading to strain stiffening. In the third regime, rapid stiffening is associated, with full compaction and the formation of a large number of inter-fiber contacts. It is observed that the strain distribution is highly heterogeneous due to strong structural disorder and density fluctuations. Deformation localizes at multiple sites which eventually merge into one or multiple bands that percolate through the sample [1].

Mycelium also exhibits significant hysteretic behavior under cyclic compression, including stress softening, or the Mullin's effect, and the occurrence of residual strain, similar to filled and unfilled elastomers [3,4]. When subjected to compressive cycles of constant strain amplitude, the response is softer during reloading compared to the response of the virgin material. This softening diminishes gradually in successive cycles.

The mechanical behavior of mycelium is dictated by the structure of the underlying network and the properties of the constituent fibers – the hyphae. The hypha is a hollow filament and its major structural components are chitin nanofibers, beta-glucans and proteins [5]. Chitin nanofibers form a network which is covalently cross-linked with beta-glucans, and constitutes the structural element of the hypha wall [5,6]. Several researchers studied the mechanical properties of chitin nanofiber-based membranes. Jeffe et al. [7] observed a tensile modulus of 3 GPa and tensile strength of 50 MPa for regenerated chitin membranes. Ifuku et al. [8] extracted chitin nanofiber networks from exoskeletons of crabs and prawns and measured similar values for the modulus (~2.5 GPa) and tensile strength (~45 MPa). Fan et al. [9] reported a tensile modulus of 5 GPa and strength of 140 MPa from chitin nanowhiskers. Mushi et al. [10] observed that properties of the chitin nanofiber network largely depends on the nanofiber volume fraction and the tensile modulus varies from 2.5 to 8.2 GPa for volume fractions ranging from 42% to 78%. The tensile strength varies from 29 to 77 MPa in the same range of volume fractions. Note that the chitin percentage in mycelium is in the range 34 to 68% [11].

In recent years, significant research effort has been devoted to delineate structure-property relations of network-based materials [12]. Several micromechanical models are employed using simplified periodic unit cells or representative volume elements (RVE) of realistic systems to obtain the effective mechanical response. In the small strain regime, network behavior is largely determined by the density, degree of connectivity and the fiber bending-to-axial stiffness ratio. For dense networks with fibers that are relatively stiff in bending, the network undergoes affine deformation. In these conditions the network modulus scales linearly with the density and the fiber axial stiffness. On the other hand, networks of low density, sparse connectivity and/or fibers which are relatively soft in bending, deform in a highly non-affine way. In this case, small strain modulus varies as a power function of the network density (this dependence is quadratic for mycelium [1]) and scales linearly with the fiber bending rigidity.

Network behavior in the collapse/densification regime was also studied using micromechanical models. It is shown [2] that the network softens in this regime due to elastic buckling and/or formation of plastic hinges at fiber-fiber joints. For elastic fibers, the stress-strain curve in this regime has positive slope (much smaller compared to that of the linear regime) which is controlled by the network architecture and structural stochasticity. In particular, a random fibrous network shows larger slope in the collapse/densification regime compared to cellular networks, where fibers are arranged in polyhedral cells [13]. Further, if fibers are elastic-plastic, the network loses stability and shows a more drastic softening behavior with zero or negative stress-strain slope [14].

In contrast to micromechanical models, several phenomenological models were also developed. These consider the network as a continuum material and describe the behavior through empirical constitutive equations without considering microstructural details [15]. Most phenomenological models rely on the hyperelastic model formulation and use suitable forms of the strain energy function to predict experimental observations. A large set of strain energy functional forms are available, including Mooney-Rivlin [16], Arruda-Boyce [17], and Ogden [18] models. Hyperelastic models provide reasonably accurate predictions of the non-linear stress-strain response during compression loading, but cannot capture hysteresis, Mullin's effect and residual strains. To model the stress softening effect, several researchers incorporate additional damage type variables in the hyperelastic model that remain inactive during loading but are activated during unloading based on the maximum strain reached [3,19].

While the above-mentioned microstructurally-detailed models of fibrous materials, as well as other similar works, established the relation between network parameters and its overall properties, they refer to structures with mesoscale homogeneity. Specifically, on scales larger than the size of the respective 'representative volume elements,' the material is considered homogeneous. However, real fibrous materials, including mycelium, exhibit density fluctuations on all scales, up to the macroscopic scale [20]. The effect of mesoscale fluctuations of material properties has been discussed in the literature on stochastic composite materials [21,22], mostly in the context of linear elastic constitutive behavior [23]. Pronounced heterogeneity modifies the global mechanical behavior, promoting softening and localization. Accounting for such mesoscale effects in explicit fiber network models is not feasible since this implies modeling large structures while resolving every fiber in the material. Therefore, a multiscale approach is needed. Developing such representation for mycelium materials is the central objective of the present work.

To this end, we expand our recent work [1] by performing additional experimental characterization of mycelium of different effective densities, and developing a 3D multiscale model that accounts for strain localization and the Mullins effect. An explicit network model is used on the microscale and a stochastic continuum representation is used on the mesoscale. The local constitutive behavior of the continuum is dictated by the local density and the response of the corresponding microscale network model. Ogden's model is used on the continuum scale to represent Mullin's effect observed experimentally. The model is validated by comparison with a separate set of experimental results. The model can be further used to explore the effect of mesoscale heterogeneity on the overall mechanical behavior of the material, and to design the