Soft Mechanical Metamaterials with Unusual Swelling Behavior and Tunable Stress-Strain Curves

Hang Zhang[*], **Xiaogang Guo, Jun Wu, Daining Fang**[#], **Yihui Zhang**[†]

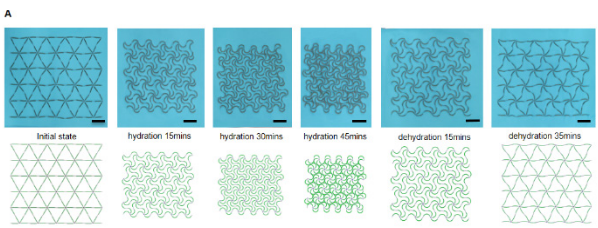
[*] AML, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, P.R. China. (hang-zha16@mails.tsinghua.edu.cn)

[#] Institute of Advanced Structure Technology, Beijing Key Laboratory of Lightweight Multi-functional Composite Materials and Structures, Beijing Institute of Technology, Beijing 100081, P.R. China. (fangdn@bit.edu.cn)

[†] Center for Mechanics and Materials and Center for Flexible Electronics Technology, Tsinghua University, Beijing 100084, P.R. China. (yihuizhang@tsinghua.edu.cn)

Abstract

Soft adaptable materials that change their shapes, volumes and properties in response to changes in ambient conditions have important applications in tissue engineering, soft robotics, biosensing and flexible displays. Upon water absorption, most existing soft materials, such as hydrogels, show a positive volume change, corresponding to a positive swelling. In contrast, the negative swelling represents a relative unusual phenomenon that does not exist in most natural materials. The development of material systems capable of large or anisotropic negative swelling remains a challenge. Here, we combine analytic modeling, finite element analyses (FEA) and experiments to design a type of soft mechanical metamaterials that can achieve large effective negative swelling ratios and tunable stress-strain curves, with desired isotropic/anisotropic features. This material system exploits horseshoe-shaped composite microstructures of hydrogel and passive materials as the building blocks, which extend into a periodic network, following the lattice constructions. The building block structure leverages a sandwiched configuration to convert the hydraulic swelling deformations of hydrogel into bending deformations, thereby resulting in an effective shrinkage (up to around -47% linear strain) of the entire network. By introducing spatially heterogeneous designs, a range of unusual, anisotropic swelling responses were demonstrated, including those with expansion along a direction and simultaneously, shrinkage along the perpendicular direction. The design approach, as validated by experiments, allows the determination of tailored microstructure geometries to yield desired length/area changes. These design concepts expand the capabilities of existing soft materials, and hold promising potentials for applications in a diverse range of areas.



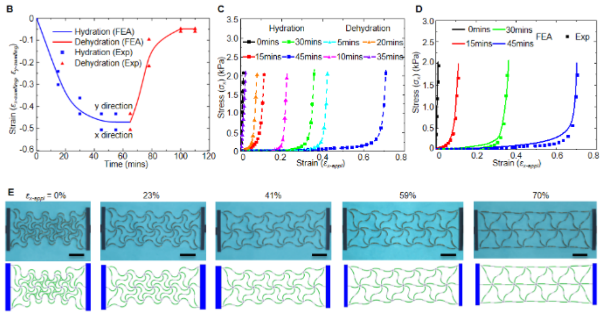


Figure 1. Soft mechanical metamaterials with large negative swelling ratios and tunable stress-strain curves. (A) Experimental (top) and computational (bottom) results on the evolving configurations of a representative network material during the hydration and dehydration processes. (B) Swelling-induced strain components as a function of the processing time for the network material in (A). (C) Measured stress-strain curves of the network materials in (A) at different stages of hydration and dehydration. The square and triangular symbols denote the results during hydration and dehydration, respectively. (D) Calculated stress-strain curves of the network materials at different stages of hydration, in comparison to the experimental results. (E) Experimental (top) and computational (bottom) results on the deformation sequences of a hydrated (~ 45 mins) network material under a uniaxial stretching. Scale bars, 40 mm in (A) and (E).

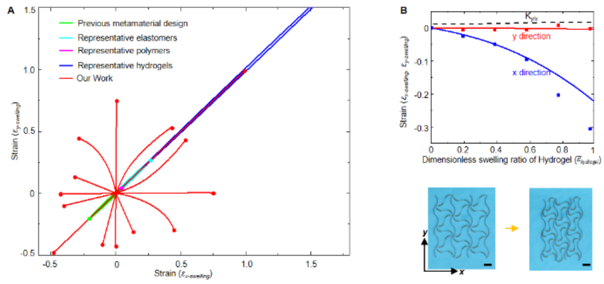


Figure 2. Strategic heterogeneous designs for large anisotropic swellings. (A) Swelling path illustrated in the space of strain components (εx-swelling and εy-swelling) for the network materials designed in the current work, as compared to the traditional soft materials and a metamaterial design reported previously*(1)*. (B) Measured and computed swelling-induced strain components (εx-swelling and εy-swelling) for a design that shrinks only along the x direction and keeps almost undeformed along the y direction during the hydration. The images on the bottom represent the configurations at the initial and final states of hydration. Scale bars, 20mm.

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