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Wet to Shrink: an Approach to Realize Negative Expansion upon Wetting

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Abstract

Composites can be designed to have special properties, and even such properties that are difficult to find in nature. We propose a simple approach to realize negative expansion upon wetting, i.e., contraction upon wetting, using swelling materials. The key parameters in one-dimensional case are investigated, and the possible configurations for two and three-dimensional cases are presented. The feasibility is demonstrated through a simple test.

Keywords

Wetting, contraction, swelling, negative expansion

1. Introduction

Upon sorption, the volume of some materials expands, while their stiffness may reduce. This is the well-known swelling phenomenon, which can be commonly found in nature. Some materials can expand more and quicker than others due to different swelling mechanisms (e.g., [1, 2]). While in some of these materials swelling induced volume expansion is more or less permanent, in some others the volume expansion can be largely recoverable (e.g., [3]).

We can find a number of materials with negative thermal expansion coefficient and/or negative Poisson's ratio in nature (e.g., [4, 5]). But it seems to be rather more difficult to find materials that shrink upon wetting. Materials or composites with the wet-to-shrink feature can be used in many novel applications, for example, to automatically open holes when wetted for water to flood in or out, as actuating materials which response to moisture in an opposite way as those of conventional materials, and as novel cover or cloth materials that become thinner upon wetting.

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To the best knowledge of the authors, there are no existing materials that wet to shrink.

Composites can be designed to have special properties, and even such properties that are difficult to find in nature. The development of composites with negative thermal expansion coefficient and/or Poisson's ratio [6–8] may provide us a clue for realizing contraction upon wetting. Truss-like structure is the traditional configuration for realizing negative thermal expansion coefficient in composites. Different from those thermal responsive (expansion/contraction) materials, here we need to use moisture responsive materials to trigger the shape change. By carefully selecting the geometrical configuration (truss-like structure or similar) and dimensions, using swelling materials one may achieve 'wet to shrink'. Numerous hydrogels have been developed for quick and significant volume expansion upon wetting. Some of them can also recover (deswelling) most of the expansion rapidly (e.g., [9]). They may be used as the actuation material for 'wet to shrink'.

This paper aims to propose a simple approach to develop composites with negative expansion upon wetting in one-dimensional, two-dimensional and three-dimensional cases. In addition, we use a simple example to verify the concept.

2. Basic Concept in a One-Dimensional Case

Figure 1 illustrates the basic concept in a one-dimensional case. The composite is in a sandwich-like shape. The top and bottom layers are relatively much stiffer than the middle part (Fig. 1(a)). Thus, they are considered as rigid elements. The middle part is formed by square-shaped tubes separated by empty space (void). The top and bottom layers are fixed to the top and bottom walls of the square-shaped tubes, respectively. Inside of the tubes, an expansible material (with a high volume expansion ratio upon wetting) is filled in. If the tube is made of a material which can let moisture pass through quickly (i.e., high moisture transportation membrane), the fill-in material can expand more rapidly upon wetting. In addition, the tube is thin but made of a stiff material (i.e., non-stretchable but flexible upon bending). Upon wetting, the shape of the cross-section of the tube changes in order to accommodate the volume expansion of the fill-in material. Since the tube is non-stretchable, and the bending of the top/bottom wall is constrained by the stiff top/bottom layer, the deformation is dominated by the bending of side-walls (Fig. 1(b)).

Figure 2 illustrates the dimensions of a unit cell (cross-section of a tube) before and after wetting. We assume that the width of the tube is one unit, and the original height is H (Fig. 2(a)), and then we take $H/1$ as a parameter in the course of this study, as this is a key ratio for the initial configuration.

Upon wetting, the side wall bends outwards in order to accommodate the volume change in the expansible fill-in material. Since the pressure applied on the side wall can be approximated as a constant, and by ignoring the constraint from the

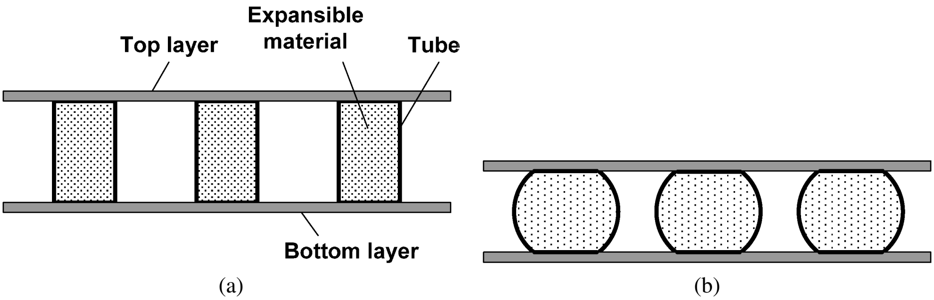


Figure 1. 1-D case. (a) Original shape (dry); (b) after wetting.

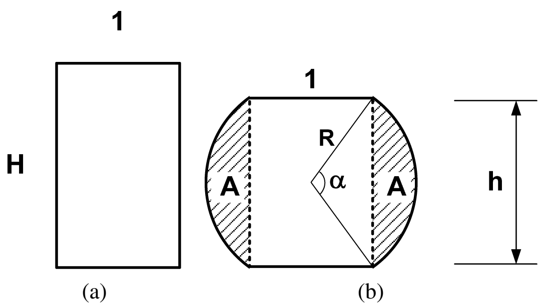


Figure 2. Dimension of one unit cell. (a) Original shape (dry); (b) after expansion upon wetting.

top/bottom layer on bending in the side walls, we may assume that the shape of side wall is about part of a circle with a radii R. As such, one has

$$H = R\alpha, \tag{1}$$

where α is the angle of the arch. The current height (h) is determined by

$$h = 2R\sin\left(\frac{\alpha}{2}\right). \tag{2}$$

So the height change ratio can be worked out as $(h - H)/H$ (taking the initial height H as reference).

The shadowed area shown in Fig. 2(b) can be expressed as

$$A = \frac{R^2}{2}(\alpha - \sin\alpha). \tag{3}$$

Hence, the volume change ratio can be obtained as $(2A + h - H)/H$, taking the initial volume in this 1-D case, area, H ($= H \times 1$), as reference.

Figure 3 shows the volume change ratio *vs* height change ratio curves of six selected $H/1$ ratios, namely 20, 10, 5, 2, 1 and 0.5. In this study, we assume the maximum α is 90° (or $\pi/2$). We can see that with the decrease in height, the required volume change ratio does not increase monotonously. Corresponding to an individual $H/1$ ratio, there is a certain maximum volume change ratio. This maximum volume change ratio defines the maximum change in height. Figure 4 reveals

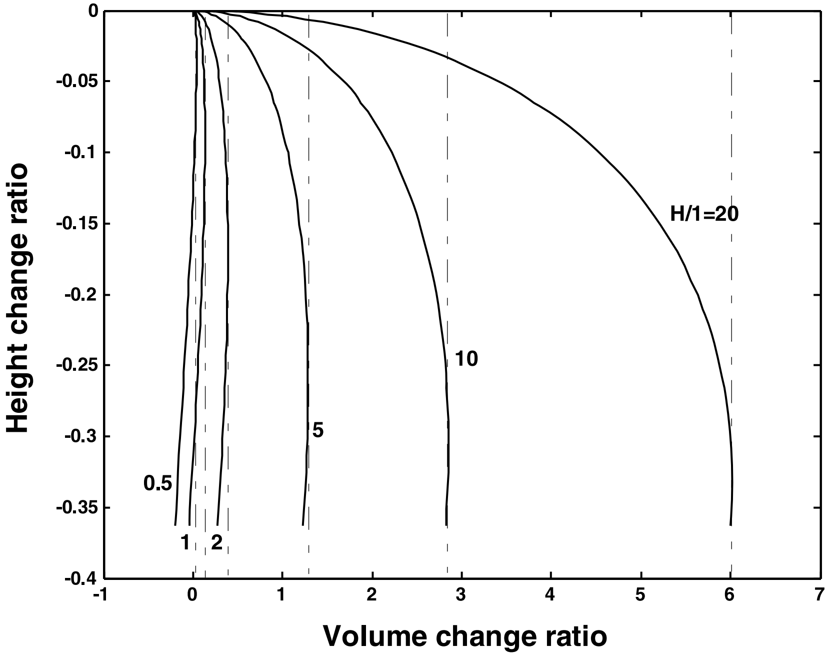


Figure 3. Volume change ratio *vs* height change ratio curves of some selected $H/1$ ratios.

the maximum volume change ratio and the corresponding maximum achievable height change ratio as functions of $H/1$ ratio. It is clear that the maximum height change ratio is limited to about 0.35.

From Fig. 3, we also notice that there is a range in which a slight change in volume can induce a significant decrease in height. This range is identified when the volume change approaches the maximum. This finding indicates that if a small change in height is targeted, we can find an optimized initial shape for the tube cross-section, so that the required volume expansion can be minimized.

Since the expansion is restricted to only in the in-plane horizontal direction in the 1-D case discussed above, the maximum decrease in height is limited. On the other hand, the overall dimension in the horizontal direction is kept untouched. Thus, the change in height is practically one-dimensional.

3. Two- and Three-Dimensional Models and Expansion–Contraction

In a 2-D case, contraction should occur in two transverse directions simultaneously. This can be achieved by utilizing the same structural concept as discussed above in 1-D case. Figures 5 and 6 demonstrate two 2-D configurations.

In Fig. 5, rigid elements (colored areas) are connected by flexible elements (tubes filled with an extensible material). Upon wetting, the flexible elements become short due to the expansion of the fill-in material. Consequently, the rigid elements are pulled closer. The voids should be large enough to provide enough space for

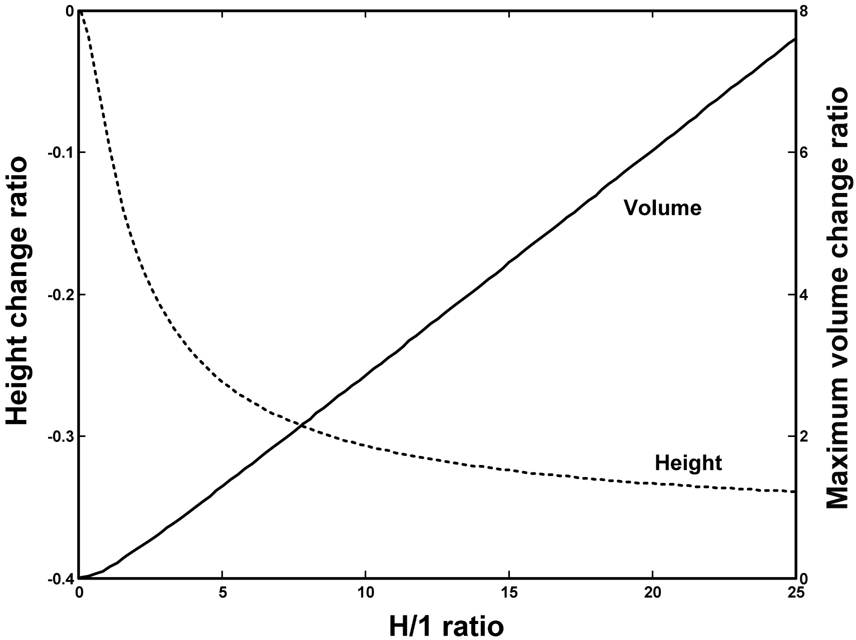


Figure 4. Maximum volume change ratio and corresponding height change ratio against $H/1$ ratio.

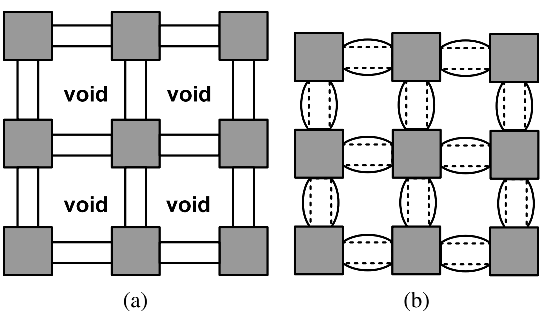


Figure 5. A configuration for two-dimensional case. (a) Original shape; (b) after wetting.

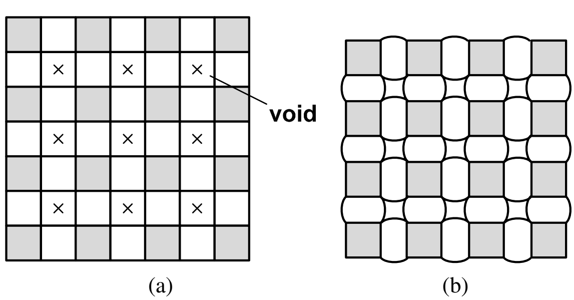


Figure 6. A mesh shaped configuration. (a) Original shape; (b) after wetting.

expansion, so that the maximum contraction in both in-plane directions can be achieved. As the rigid elements take a significant portion of space in the composite, compared with the maximum decrease in dimension achievable in 1-D configuration, the contraction is about proportionally reduced. The structure of Fig. 6 is simpler as all units (void, flexible element and rigid element) are initially of the same size and shape. Again, the shaded areas stand for rigid element (square). However, upon wetting, the bending of side wall is limited to before two adjacent side walls touch each other. Hence, the maximum contraction in this configuration is more or less pre-determined.

The above concept can be further extended into 3-D situation. However, the flexible element needs to be redesigned, as a different type of tube is required. Figure 7 illustrates one possible configuration for a flexible element. The possible design of the flexible element is also presented. In order to achieve large and reversible bending, as shown in Fig. 7(b), the side walls are separate pieces and surround an expansible core. Expansible material is filled into the expansible core, so that upon wetting, moisture can reach the expansible material. Consequently, the expansion of the expansible material causes the expansion of the core in the transverse direction, which causes the bending of side walls.

As a separate issue, one may design a composite in which the height increases continuously upon wetting before a certain point is reached. After this point, the height starts to decrease despite the volume keeps on expanding. Figure 8 illustrates

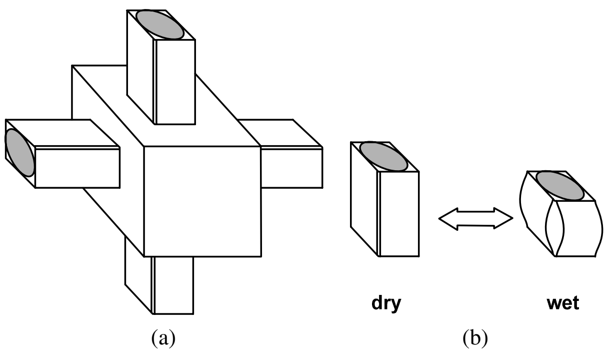


Figure 7. 3-D configuration. (a) Unit cell (not all flexible elements are shown); (b) deformation in a flexible element.

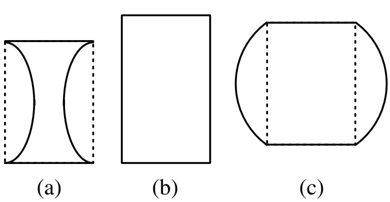


Figure 8. A configuration for expansion–contraction upon wetting. (a) Original shape; (b) maximum height upon wetting; (c) final shape.

one such example. By carefully selecting the fill-in material and optimizing the dimensions, one may realize programmable expansion–contraction upon wetting, and even in the whole wetting/drying process.

With different flexible elements (e.g., size or fill-in material), one can realize different contraction ratios along different directions in a composite, and a proper combination can result in bending and/or twisting upon wetting.

4. Experimental Demonstration

We took a simple example to demonstrate the concept of wetting to shrink using Magic Crystal Jelly (Water Babies) (Note 1), which is water absorbent gel and can expand significantly in size upon immersing into water as shown in Fig. 9. This gel is able to fully recover its original size upon drying.

We made some cuts in the sidewall of a straw and placed one piece of half wetted spherical shaped gel inside in a way as illustrated in Fig. 10(a). Upon further wetting in water, the piece of gel expanded more (Fig. 10(b)). In a real test, we used a 5 mm

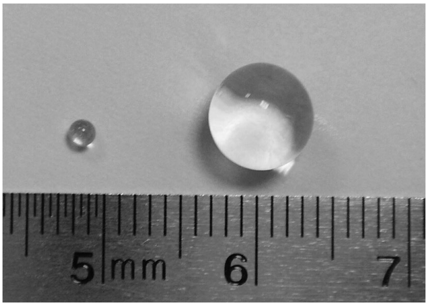


Figure 9. Commercial available spherical shaped hydrogel before (left) and after (right) wetting.

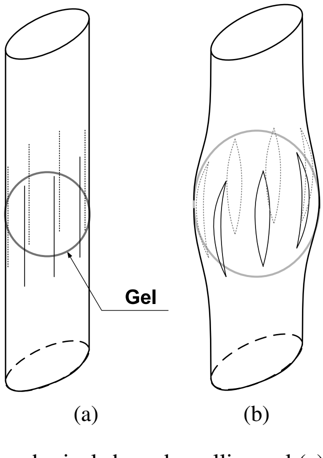
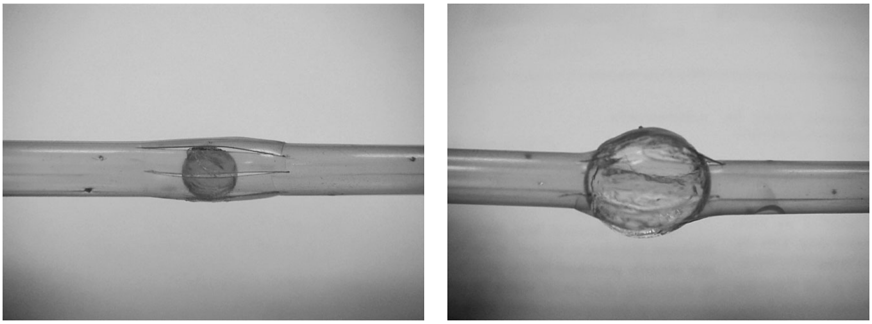


Figure 10. A cut-straw with a spherical shaped swelling gel (a) and after (b) further wetting.



(a) (b)

Figure 11. Swelling of a piece of spherical shaped gel inside a straw. (a) Half-way wetted; (b) fully wetted.

diameter, 0.15 mm thick wall straw (Fig. 11(a)). After it was fully wetted, the straw was 1 mm shorter (Fig. 11(b)).

5. Conclusions

Composites can be designed to have special properties, and even such properties that are difficult to find in nature. In this paper, we propose an approach to realize 'wet-to-shrink' and even extension and then contraction (i.e., in a programmable manner) upon wetting. In 1-D case, we investigate the relationship of $H/1$ ratio–volume change ratio–height change ratio. We find that it is possible to optimize the initial shape of the flexible element so that a small volume expansion can induce a significant contraction. In addition, we find the maximum reduction in height is about one-third of the original one. We also propose the configurations for 2-D and 3-D systems. A composite with anisotropic contraction ratio is also achievable.

Provided the expansible material that triggers the contraction of the composite upon wetting can reverse back into its original volume upon de-wetting (as in some polymers and gels), the composite should be able to return to its original shape.

A simple experiment was carried out to verify the feasibility of the concept. The same concept is applicable for thermal expansion in composites, i.e., shrinking upon heating.

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Notes

1. http://www.mementoenterprise.com/

References

1. T. L. Vigo, Intelligent fibrous substrates with thermal and dimensional memories, *Polym. Adv. Technol.* **8**, 281–288 (1996).
2. S. J. Kim, S. G. Yoon and S. I. Kim, Properties of the interpenetrating polymer network hydrogels composed of poly(vinyl alcohol) and poly(diallyldimethylammonium chloride), *High Perform. Polym.* **14**, 261–269 (2002).
3. H. Okuzaki and T. Kuwabara, Temperature dependence of humido-responsive bending of conducting polymer films, *Synth. Metals* **153**, 101–104 (2005).
4. J. S. Evans, Negative thermal expansion materials, *J. Chem. Soc. Dalton Trans.* 3317–3326 (1999).
5. R. H. Baughman, J. M. Shacklette, A. A. Zakhidov and S. Stafstrom, Negative Poisson's ratio as a common feature of cubic metals, *Nature* **392**, 362–365 (1998).
6. O. Sigmund and S. Torquato, Composites with extremal thermal expansion coefficients, *Appl. Phys. Lett.* **69**, 3203–3205 (1996).
7. N. Gasper, X. J. Ren, C. W. Smith, J. N. Grima and K. E. Evans, Novel honeycombs with auxetic behavior, *Acta Mater.* **53**, 2439–2445 (2005).
8. R. Lakes, A broader view of membranes, *Nature* **414**, 503–504 (2001).
9. W. Xue, S. Champ, M. B. Huglin and T. G. J. Jones, Rapid swelling and deswelling in cryogels of crosslinked poly(N-isopropylacrylamide-co-acrylic), *Euro. Polym. J.* **4**, 703–712 (2004).