The Effects of Negative Poisson’s Ratio and Finite Element Analysis of Polyvinyl Alcohol Hydrogel with Three-Dimension Porous Structure

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Abstract. Based on the assumptions of the preparation process and the microstructure characteristics of polyvinyl alcohol hydrogel with three-dimension porous structure, and compared to the similar hexagonal honeycomb configuration, a kind of novel Centre symmetric honeycomb structure with three sorts of shapes, stack patterns evaluated is constructed. The results show that the entire structure without filling with honeycombs has the negative Poisson's ratio ignoring various configuration parameters. The entire structure filling with honeycombs, the changes of the honeycombs thickness, three different arrange-square, vertical and transverse deformation modes, and the configuration parameters make the entire unit cell possess the negative Poisson’s ratio. When the numerical value of the unit cell thickness is less than 5μm and the honeycombs in the novel Centre symmetric structure take arrange-square shapes, if filling with circular honeycombs, the entire structure should choose the bigger values of the structure parameters $R_2, θ_1$ and $L_2$, the novel Centre symmetric honeycomb structure possess the negative Poisson's ratio; if filling with hexagonal honeycombs, the entire structure should choose the smaller values of the structure parameters $R_2, θ_1$ and $L_2$, the novel Centre symmetric honeycomb structure possess the negative Poisson’s ratio.

Introduction

Materials with negative Poisson's ratios exhibit the unusual property by K.E.Evans[1]in 1991. Recently most investigations are focus on the discussion aspects in the hyper elastic porous silicone rubber [15], aluminum foams materials [16], analysis to the equivalent elastic constants of honeycomb structures [17, 18, 19].Etc. With the academic analysis penetrating deeply, the researches are gradually transformed from simple structure of porous materials to the properties of representative units of porous materials [25], model structure discussion [26], optimum design [27], micro-structure design and analysis for cellular material [28].

There are a few researches about preparation and performance of the hydrogel with Negative Poisson's ratio effect. A series of researches have developed in local laboratory. Milton’s the “Rod-hinge frames” model [11, 12, 13], C.Lira’s RVE concept [29] and the thoughts of the shell-core hydrogel brought forward by Lv[35]and Meng[36]gave us a profound illumination. On that basis, to acquire the porous hydrogel materials with negative Poisson's ratio effect, the theoretic models and the finite element analysis are developed in this work by using FEM software.

The Centre Symmetric Honeycomb Design

For achieving good mechanical strength, the NEW volume element was designed to sandwich structure. The inner parts have three-kind frameworks: one has the similar hexagonal honeycomb
configurations (Fig 1(a)); the other has a kind of re-entrant honeycomb two-dimensional structure in plane, and Stack patterns evaluated is constructed; and the third has circle-shaped frame (Fig 1(b)), and collects generally inside the hydrogel. The swelling time was decided by the influence of the lesser hole-pitch [39] and the interconnected pores [40], and increased the swelling and the deswelling speed [41].

Note: (a) Circle pores; (b) similar hexagonal pores.

Figure 1. Photos of poly vinyl alcohol hydrogel materials and SEM photos of the pores in poly vinyl alcohol hydrogel materials.

Table 1. RVE and NEW geometric parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Formula</th>
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<tbody>
<tr>
<td>a</td>
<td>horizontal cell wall</td>
</tr>
<tr>
<td>b</td>
<td>mono-edge cell wall</td>
</tr>
<tr>
<td>c</td>
<td>internal cell angle 1</td>
</tr>
<tr>
<td>d</td>
<td>base wall angle</td>
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<tr>
<td>e</td>
<td>cell wall thickness</td>
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Table 1. RVE and NEW geometric parameters.

Note: (a) RVE elementary volume; (b) 3D schematic diagram of RVE elementary volume; (c) NEW elementary volume; (d) Amplified image of the inner part in the NEW elementary volume; (e) 3D schematic diagram of NEW elementary volume; (f) Schematic diagram of NEW elementary volume array; (g ~ j) the homogeneous frame of NEW elementary volume in specific conditions.

Figure 2. Various layouts of RVE, NEW.
Compared to RVE, the main oblique cell wall “L” in RVE is considered as the length of half-arc; the value of the length of the base ball is zero; the internal cell angle “θ” and the base wall angle “φ” are describes by the radius of the inside circle “R₁” and the radius of the outside circle “R₂”.

**Finite Element Modeling**

Based on the statements described by Kanyatip T [43] and the analysis results proposed by Wangfei [17] and Fanye [21], for raising the carrying capacity of the NEW elementary volume geometric structure, this work assumes there are filling in regular similar hexagonal honeycomb configurations and a kind of novel Centre symmetric honeycomb structure (Fig 3) with three sorts of shapes [21, 42, 44], Stack patterns evaluated is constructed. By analyzing the changes of the packed structures under the concentrated load, the Poisson’s ratio in certain parameter range can have negative value. The aperture diameter of the cellular and the value of thickness are consulted and set by the realistic materials parameter (Fig 2).

Note: (a) Circle cell;(b) Circle cell with transverse deformation mode;(c) Circle cell with arrange-square deformation mode;(d) Circle cell with vertical deformation mode;(e) The similar hexagonal honeycomb configurations

Figure 3. Filling in different honeycombs topology structure plan sketch.

**Results and Discussions**

**Hollow Model**

It is assumed that there are not filling in any other materials in the NEW elementary volume geometric structure:

Note: (a)The R₃-µcurves.θ₁=φ₁=0, R₁ is regard as constant, R₂ is regard as variable;(b)Theθ₁,φ₁-µcurves.θ₁≠0,φ₁≠0,θ₁ andφ₁ are regard as variable, R₁, R₂ and L are regard as certain fixed value;(c) The R₂-µ curves. R1 =8.75, L₂=1.24, 0₁=φ₁=90° ;(d) The L₂-µ curves. R₁ =8.75,R₂=9.05,θ₁=φ₁=90°; (e) The θ₁-µcurves.θ₁≠0,φ₁≠0, θ₁ and R₂ are regard as certain fixed value;(f) The R₂,θ₁-µcurves.θ₁≠0,φ₁≠0, R₁ and L are regard as certain fixed value.

Figure 4. The curves of hollow model.
Along with the augment of $R_2$, the value of $\mu$ in the NEW elementary volume geometric structure is getting smaller; If not having an inner trapezoid composition in the NEW elementary volume geometric structure, $R_1$, $R_2$ and $L_2$ are fixed values, along with the decrease of $\theta_1$ and $\phi_1$, the value of $\mu$ in the NEW elementary volume geometric structure is getting smaller; $R_1$, $L_2$ are fixed values, along with the decrease of $\theta_1$ and $R_2$, the value of $\mu$ in the NEW elementary volume geometric structure is getting smaller; $R_1$, $L_2$ are fixed values, along with the decrease of $\theta_1$ and $R_2$, the value of $\mu$ in the NEW elementary volume geometric structure is getting smaller.

**Filling in Honeycombs in the NEW Elementary Volume Geometric Structure**

It is assumed that there are filling in circle-shape honeycombs in the NEW elementary volume geometric structure:

**Circle cells.** A. While having the inner trapezia structure,

![Figure 5](image)

Note: The value of $\theta_1$, $\phi_1$, $R_1$, $R_2$ and $L_2$ are fixed value. (a) With the change of the thickness ($t$); (b) with the change of the $R_2$; (c) With the change of the $\theta_1$; (d) With the change of the $L_2$.

Figure 5. The D-$\mu$ curves of model filling in honeycombs.

Along with the decrease of the inside diameter of the cell wall thickness, the value of Poisson's ratio is getting smaller (Fig 5(a)). Expressed as an inequality, for the variation trend of the three deformation modes: $\mu_{Da} < \mu_{Dh} < \mu_{Dv}$. If the circle cell was designed to take the arrange-square deformation mode, the value of the Poisson's ratio is getting smaller along with the increase of the structure parameters $R_2, \theta_1, L_2$ of circle cell in the NEW elementary volume geometric structure, and comparing with the transverse and vertical deformation modes (Fig 5(b-d)).

B. While not having the inner trapezia structure, the Poisson's ratio is getting smaller along with the increase of $R_2$ in the NEW elementary volume geometric structure, and comparing with the transverse and vertical deformation modes (Fig 6).

![Figure 6](image)

Figure 6. The D-$\mu$ curves of model filling in honeycombs with the change of the $R_2$.

**The similar hexagonal honeycombs cells.** A. While having the inner trapezia structure, along with the decrease of the inside diameter of the similar hexagonal cell and the changes of the thickness, if those honeycombs were designed to take different deformation shapes (D) in the
NEW elementary volume geometric structure, the changes of the Poisson's ratio can be seen in the Fig 7:

![Graphs showing changes in Poisson's ratio](image)

Note: The value of $\theta_1$, $\phi_1$, $R_1$, $R_2$ and $L_2$ are fixed value. (a) The inside diameter is 41.5$\mu$m; (b) The inside diameter is 32.5$\mu$m; (c) The inside diameter is 24$\mu$m.

Figure 7. The D-$\mu$curves of model filling in honeycombs.

If the similar hexagonal cell was designed to take the arrange-square deformation mode, the value of the Poisson's ratio is getting smaller along with the decrease of the structure parameters $t, R_2, \theta_1, L_2$ of circle cell in the NEW elementary volume geometric structure, and comparing with the transverse and vertical deformation modes(Fig 8).

![Graphs showing changes in Poisson's ratio](image)

Note: The value of $\theta_1$, $\phi_1$, $R_1$, $R_2$ and $L_2$ are fixed value. (a) with the change of the $R_2$; (b) with the change of the $\theta_1$; (c) with the change of the $L_2$.

Figure 8. The D-$\mu$curves of model filling in honeycombs with the change of the $R_2$, $\theta_1$, $L_2$.

B. While not having the inner trapezia structure,

![Graphs showing changes in Poisson's ratio](image)

Figure 9. The D-$\mu$curves of model filling in honeycombs with the change of the $R_2$.

The Poisson's ratio is getting smaller along with the decrease of $R_2$ in the NEW elementary volume geometric structure, and comparing with the transverse and vertical deformation modes (Fig 9).

**Conclusions**

The present work describes a theoretical and numerical investigation of a kind of hollow model and a model filling in circle or similar hexagonal honeycomb configurations. As for the hollow model and the NEW geometric unit structure model, this honeycomb topology provides six sets of geometry parameters, enabling the material designer to engineering optimized and multifunctional cellular cores. As for the new geometric unit structure model filling in circle or similar hexagonal honeycombs, this honeycomb topology structure provides three kinds of micropores shapes and different deformation modes. Assumed the structure parameters $t$, $R_2$, $\theta_1$ and $L_2$ are variable, along with the changes of honeycombs deformation modes (D), change trends relation schema of the structure parameters, the honeycombs deformation modes (D) and the Poisson's ratio ($\mu$) can be
achieved. The analytical and numerical simulations of the NEW geometric unit structure model show a satisfactory agreement. The analytical formulas provided can be used to perform parametric analysis for the design of the cores in similar and multifunctional honeycomb-construction.

References


