

# Analysis of 2D Auxetic Metamaterial as a Variable Macro and Micro Structural Filter

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**Abstract** – This paper explores the field of Auxetic metamaterials with focus in mechanical perspective. The auxetic structures were made from 3D printable PLA, RTV silicon and lacerated rubber sheets. These structures were experimented upon for calculating and comparing their Poisson's ratio and then they were tested for their compatibility as a mechanical sieve for filtration applications. Auxetic structure thus produced was showing appreciable results in tension while auxetic structure made from hot glue was showing appreciable results in compression. This research work, thus, is an amalgamation of the knowledge of Auxetics and the theory about filtration. This paper further explores the applications of 2D re-entrant auxetic metamaterials as a prospective molecular filtration membrane.

**Keywords**—Auxetics, silicone, casting, sieve, negative poisson's ratio, auxetic filter

## 1. INTRODUCTION

Auxetic cellular structures exhibit negative Poisson's ratios so that, unlike regular cellular structures, they show lateral shrinkage upon axial compression. In 1987, Lakes first discovered the negative Poisson's ratio effect in polyurethane foam with re-entrant structure which is achieved by isotropic permanent volumetric compression of conventional foam. These materials are of interest due to possibility of enhanced mechanical properties such as shear resistance, indentation resistance, fracture toughness compared to conventional materials from which they are made [1]. Materials with NPR produced by transformation of conventional material into re-entrant structure which allows properties like ultra-light weight, high stiffness and negative thermal expansion coefficient [2]. Rocks with microporous cracks have been reported to exhibit poisson's ratio near to -0.1. The effect is abolished under water saturation or hydrostatic pressure [3]. Properties of re-entrant structure made from thermosetting, thermoplastic and copper foams were studied and it was found that re-entrant polymer foams were more resilient than the corresponding conventional foams [4]. In particular, for isotropic materials thermodynamic stability arguments lead to the condition that the Poisson's ratio lies in the interval (-1, 0.5) while for anisotropic materials this interval is unbounded [5]. Negative values of Poisson's ratio can be achieved for specific values of the dimension and orientation of the

perforations. The hexagonal disposition of the perforations makes the medium isotropic in the plane. Using this negative value of Poisson's ratio can be achieved for specific orientation. [6]. Analytical model of 3D re-entrant honeycomb structure has been developed based on deflection in beam [7]. Aluminum based auxetic lattice structure has been fabricated by 3D printing and investment casting and its compressive mechanical behavior was studied. First the structure is 3D printed using photosensitive resin. The mold is prepared from this by plaster slurry. Then photosensitive resins are burnt and aluminum is poured into it. [8]. Auxetic material is manufactured with 3D printing technology using fused deposition modeling (FDM) 3D printer with PLA based upon mathematical model and its validation is checked with experimental results [9]. Use of hierarchical tubes with re-entrant honeycomb structure as reinforced fibers in composite materials result in higher resistance to fiber pull-out. These tubes are manufactured from a tube having auxetic cellular structure and it is used as constructional element for next level of hierarchy [10]. In some laminates composed of fibrous layers it is theoretically possible to achieve poisson's ratio of -0.21 in the direction perpendicular to layers of control of stacking sequence [11]. Thus, auxetic materials have enhanced mechanical properties than the material from which they are manufactured.

One of the prolific uses of auxetic materials in research is in the world of robotics. Auxetic metamaterial is been researched upon and plans are made and already being executed to incorporate auxetic materials in soft robotics. Instead of using actuators and bulky mechanical structures, scientists are trying to using this metamaterial with negative Poisson's ratio to achieve the same functions. These Meta materials show better results in terms of movement, strength, more freedom and flexibility and less bulkiness and thus finer space consumption.

Main objectives of this research are:

- Compute and analyze the Poisson's ratio for the Auxetic structure and the fundamental material used for making the structure.
- To test the auxetic structures for macro filtering properties.

- Extrapolating these results for exploring further applications of this structure as a molecular sieve.

### 1.1 Theory

#### 1.1.1 Poisson's Ratio:

Poisson's ratio is defined as negative of the ratio of lateral and axial strain.

$$\nu = -\frac{\epsilon_{lateral}}{\epsilon_{axial}}$$

For normal materials, due to the opposite direction of lateral and longitudinal strain, we get a positive Poisson's ratio. Yet, there are some materials which exhibit a negative Poisson's ratio. This means that when stretched laterally, the material will show axial elongation as well, thus resulting in the negative ratio. Such materials are called Auxetic materials.

#### 1.1.2 Auxetics:

Auxetic structures, attributing to their property of negative Poisson's ratio, are expected to have mechanical properties such as high energy absorption and fracture resistance.

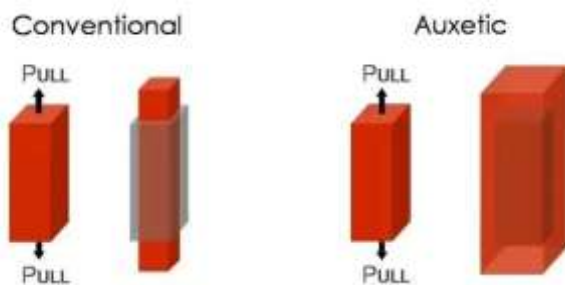


Figure 1 Stresses in Conventional and Auxetic Materials

Auxetic materials have greater energy dissipation during impact and high amplitude dynamic loading, high indentation resistance and uncommon filtering properties. An auxetic filter will only release particles or components of specific dimensions based on its current unit cell dimensions which again depend on the stresses acting on the structure. This gives rise to an accurate molecular sieve.

#### 1.1.3 Membranes:

A membrane blocks specified unnecessary entities from passing through it and only allows the particles or components that we want.

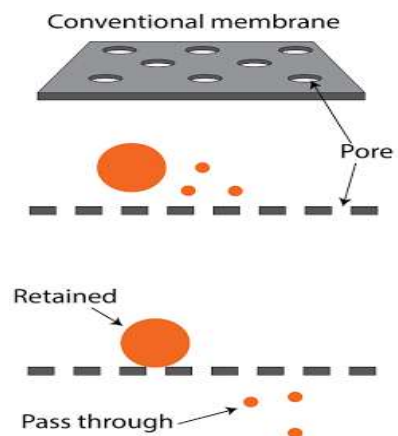


Figure 2 Mechanism of a membrane

[12] We have used the lacerated rubber sheet structure and RTV Silicone auxetic structure as a mechanical macro-filter. Using Auxetics as a filter provides two advantages:

1. We can vary the size of the passageway by giving stress as an input, which is not possible in the conventional membranes having a stringent allowance when it comes to letting the particles pass.
2. Auxetics materials provide mechanical strengths greater than normal membranes. Unlike membranes made from multiple layers of active thin-film polyamide with some support layers, this membrane made from auxetic structures provides greater strength and resistance to wear and tear.

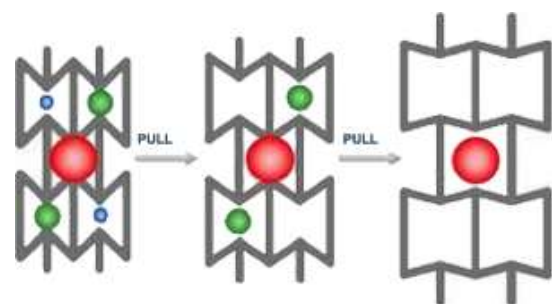


Figure 3 Auxetic Membrane

## 2. Designing and Manufacturing

### 2.1 Calculations and Analysis

Firstly to demonstrate the phenomenon of negative Poisson's ratio, we manufactured a 2D Auxetic structure using an elastic material. Design of the unit cell was fed to the laser cutter and the paper was cut accordingly.

Next we manufactured the same auxetic structure and added some thickness. This structure was 3D Printed

using PLA. The final 3D model was fed to the CAD based 3D Printer. We obtained the following model.

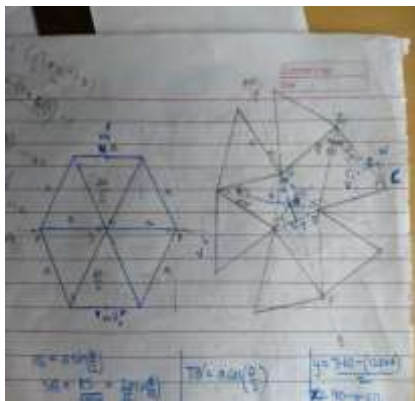


Figure 4.1 Diagram of Stretched Unit cell for Rubber Sheet

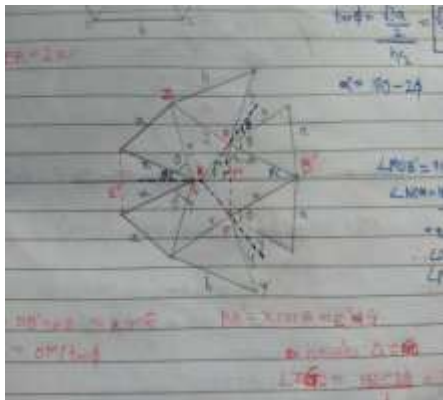


Figure 4.2 Diagram of Stretched Unit cell for Rubber Sheet

RADIUS OF CIRCUMCIRCLE

$$r = \left( \frac{(2a)}{\sqrt{3}} * \sin\left(\frac{\theta}{2}\right) \right)$$

AREA OF CIRCUMCIRCLE

$$A = \frac{4\pi a^2}{3} \sin^2\left(\frac{\theta}{2}\right)$$

$$\text{Lateral strain} = 2a \left( \cos\left(\frac{\theta}{2}\right) + \frac{\sqrt{3}}{2} \sin\left(\frac{\theta}{2}\right) - 1 \right)$$

$$\text{Longitudinal strain} = 2a \left( \cos\left(\frac{\theta}{2}\right) + \sqrt{3} \sin\left(\frac{\theta}{2}\right) - 1 \right)$$

$$\text{Poisson's ratio} = \frac{\left( 1 - \cos\left(\frac{\theta}{2}\right) - \frac{\sqrt{3}}{2} \sin\left(\frac{\theta}{2}\right) \right)}{\left( \cos\left(\frac{\theta}{2}\right) + \sqrt{3} \sin\left(\frac{\theta}{2}\right) - 1 \right)}$$



Figure 5 Auxetic Structure made from Rubber Sheet

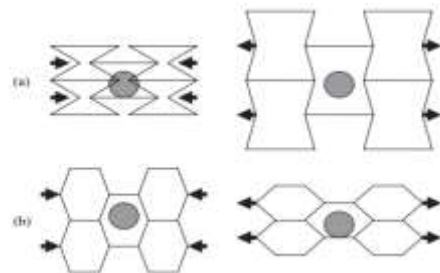


Figure 6 Filtration in Auxetic Structure

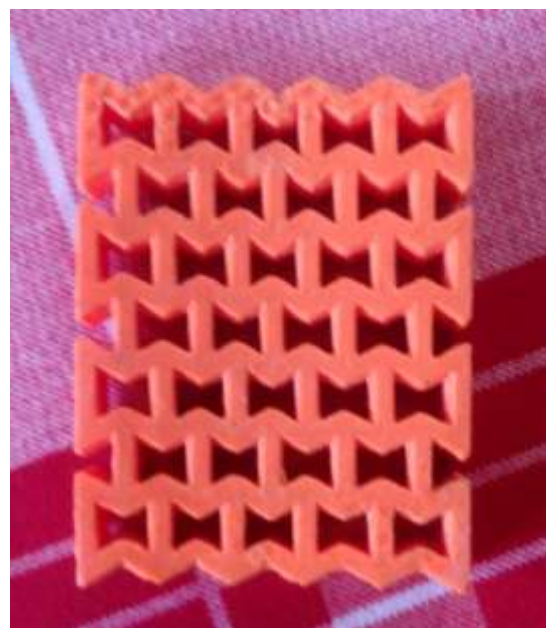


Figure 7 Auxetic Structure made from 3D Printed PLA

Next, the auxetic material having re-entrant honeycomb structure was manufactured by casting of liquid silicon. The mold cavity was produced on 20mm thickness wooden plank. Potter's clay was plastered inside the cavity to make the mold block. It took 12 hours for the block to dry up at room temperature. The mold block was extracted from the wooden planks by separating the two wooden pieces. The procedure was repeated again to make 10 such blocks. The top view of the auxetic structure array shown in Fig. 1 was printed on a paper using 1:1 scale. After that, the 10 blocks were stuck to the paper using Fevicol adhesive. The walls of the mold blocks were coated with talcum powder. Talcum powder helps the hot glue to flow and reach greater depths than without. The outer walls were made using talcum coated cardboard. Hot glue was poured inside the cavity. Cooling process got completed in 10 minutes. Cooling was done at room temperature. The clay blocks were removed from the cast. The casted product was cleaned and the entrapped air bubbles were removed using the hot lead of the glue gun. Touch up was done using hot glue. The dimensions used for this casting process using hot glue were  $h=26\text{mm}$ ,  $l=13\text{mm}$ ,  $\theta=30^\circ$ .

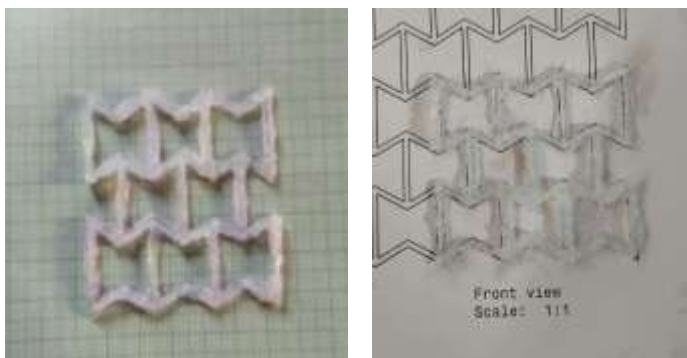


Figure 8 Auxetic Structure made from Reinforced Glue

For the product shown in Fig.2 RTV, silicone sealant was used. A printout showing the top view of the design at 1:1 scale was taken and the silicone gel was applied



directly. The same process was also repeated using hot glue where instead of the RTV silicone sealant hot silicone glue was used.

Figure 9 Auxetic Structure made from RTV Silicone

## 2.2 Testing Procedure

In order to measure the Poisson's ratio during compression and expansion the deformation was recorded by a camera. The longitudinal and lateral deformations were measured by software Image J. To guarantee the measuring precision, the transverse strains of the marked points on the samples and each length were measured at least 3 times. Similarly, the average longitudinal strain was calculated from the longitudinal strains measured from the left and right points. Using the average value of measured data, the Poisson's ratio can be calculated by the following equation (2).

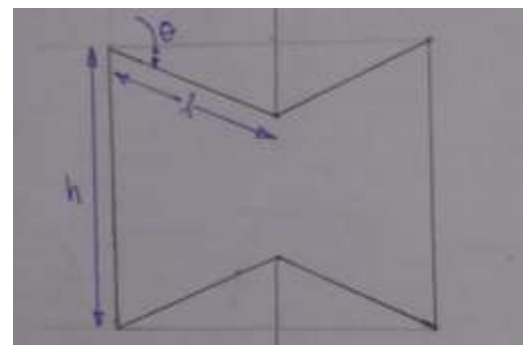
## 3. RESULTS AND CONCLUSIONS

### 3.1 CALCULATIONS

#### Units:

- All the lengths measured are in mm.
- Angles are measured in degrees.
- Tensile strain is shown with '+' sign while compressive strain is shown with '-' sign.

#### Equations used:



$$\mu = \frac{-\cos^2 \theta}{\left(\frac{h}{l} - \sin \theta\right) \sin \theta}$$

$\mu$  = Poisson's ratio

$h$  = height of unit cell

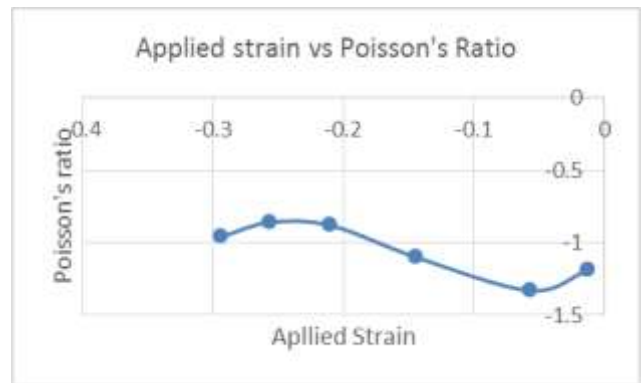
$l$  = length of rib

$\theta$  = angle of rib with horizontal

$$\mu = - \frac{\text{lateral strain}}{\text{longitudinal strain}}$$

TABLE 1 THEORETICAL POISSON'S RATIO

Sr. No.	Simulation			Poisson's ratio
	h	l	$\theta$	
1	24	13	30	-1.1142
2	26	12	30	-0.9
3	26	13	30	-1
4	28	12	30	-0.8181
5	36	20	30	-1.1538
6	38	19	30	-1
7	38	20	30	-1.0714
8.	40	18	30	-0.8709
9.	40	19	30	-0.9344
10	40	20	30	-1



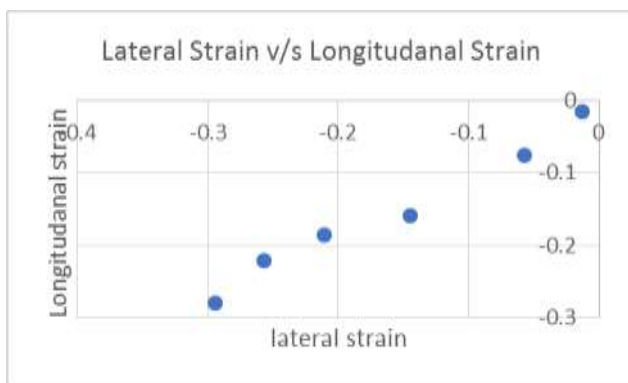
Graph 2 Strain vs Poisson's Ratio

TABLE 2.1 POISSON'S RATIO USING STRAIN VALUES

Sr. No.	Experimental Poisson's ratio of auxetic honeycomb made from RTV Silicone		
	Lateral strain applied	Longitudinal strain	Poisson's Ration
1	0.0210	0.0217	-1.03
2	0.0275	0.0301	-1.09
3	0.0324	0.0268	-0.83

TABLE 2.1 POISSON'S RATIO USING STRAIN VALUES

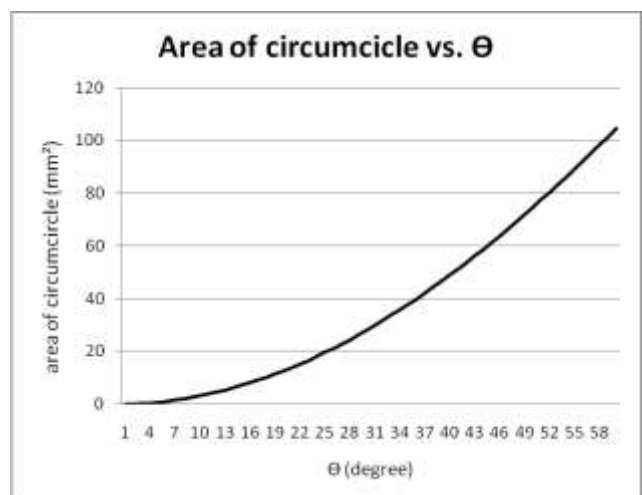
Sr. No.	Experimental Poisson's ratio auxetic structure made from hot glue		
	Lateral strain applied	Longitudinal strain	Poisson's Ration
1	-0.0128	-0.0153	-1.19
2	-0.0570	-0.0763	-1.33
3	-0.1445	-0.1593	-1.10
4	-0.2103	-0.1864	-0.88
5	-0.2568	-0.2220	-0.86
6	-0.2937	-0.2814	-0.96



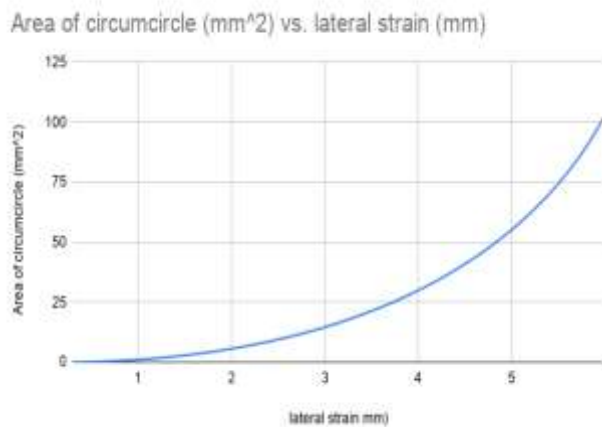
Graph 1 Longitudinal Strain vs Lateral Strain

TABLE 3 ALLOWABLE RADIUS TO LET THE PARTICLE PASS

Sr. No.	Analytical data of size of circular object that can pass through auxetic sieve				
	$\theta$ (deg)	a	lateral strain(mm)	Area of circle (mm <sup>2</sup> )	Radius of circle (mm)
1	1	10	0.150386	0.0318987	0.10076535
2	10	10	1.433476	3.1818568	1.00638783
3	20	10	2.70383	12.630748	2.00511644
4	30	10	3.801394	28.059574	2.98858491
5	40	10	4.717815	48.999537	3.94930844
6	50	10	5.446119	74.814388	4.87997534
7	60	10	5.980762	104.71976	5.77350269



Graph 3 Area of Circumcircle vs Theta angle



**Graph 3** Area of Circumcircle vs Lateral Strain

### 3.2 CONCLUSIONS

2D Auxetic structured were designed, manufactured and experimented on. Behavior of 2D auxetic structure made from silicone was studied under tension and one made from hot glue was studied under compression and its Poisson's ratio was found at different strains. Poisson's ratio was found to be dependent completely upon the dimension of the structure and not the material. Poisson's ratio of silicone is 0.48 but with auxetic honeycomb structure made from silicone helped to achieve Poisson's ratio near to -1.

It was observed that with the increase in strain applied on the auxetic structure in lateral or longitudinal direction, the passageway for the particles widens.

This means that, greater the stress applied on the unit cells, greater is the size or the radius of the particles that are allowed through the auxetic membrane.

This way, auxetic membrane gives us the ability to vary the passageway of the membrane and customize the ability of the membrane to allow particles with varying sizes to pass through it.

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