Deconstructing the auxetic behavior of paper

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What are auxetic materials?

Poisson’s Ratio

\[ \nu_{xy} = -\frac{\varepsilon_y}{\varepsilon_x} \]

x: longitudinal direction
y: lateral direction

<table>
<thead>
<tr>
<th>isotropic</th>
<th>anisotropic</th>
</tr>
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<tbody>
<tr>
<td>( \nu_{xy} )</td>
<td>-1 ~ +0.5</td>
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</tbody>
</table>
Certain types of

- Minerals
- Skins
- Arteries
- Bones

...have been found to be auxetic
**macroscopic auxetic material**

conventional foam

auxetic foam

**microporous expanded PTFE**

UHMWPE

**potential auxetic molecule**


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**Other relevant sources:**

Some applications

Paper as an out-of-plane auxetic material

Page, TREND (1969)
Previous reports

- **Ohrn (1965)**

- **N Stenberg (2002)**


## Material selection

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (μm)</th>
<th>Grammage (gm²)</th>
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</thead>
<tbody>
<tr>
<td>Copy Paper</td>
<td>105±2</td>
<td>75</td>
</tr>
<tr>
<td>Paperboard</td>
<td>270±2</td>
<td>220</td>
</tr>
<tr>
<td>Bamboo Paper</td>
<td>433±7</td>
<td>295</td>
</tr>
<tr>
<td>Cotton Paper</td>
<td>190±3</td>
<td>120</td>
</tr>
<tr>
<td>Filter Paper</td>
<td>178±4</td>
<td>85</td>
</tr>
<tr>
<td>Glassine Paper</td>
<td>52±2</td>
<td>48</td>
</tr>
<tr>
<td>Handsheet SW</td>
<td>542±26</td>
<td>220</td>
</tr>
<tr>
<td>Handsheet HW</td>
<td>586±28</td>
<td>210</td>
</tr>
<tr>
<td>PET Film</td>
<td>144±2</td>
<td>152</td>
</tr>
</tbody>
</table>
Copy Paper

Filter Paper
Experimental setup

- Sample size
  10 cm x 2 cm

- Instron 5566, 10 kN load cell

- Rate: 0.5 mm/min (paper)
  1.0 cm/min (NWs)

- Reported thickness at center of sample*

- 5 samples of each type

*thickness was measured using Mitutoyo micrometer 369-350 at 20-25 kPa
Results (paper)

- Machine direction present, anisotropic
- Marked increase in thickness, $\nu < -2.0$
- Similar production sequence for both → Pulping, bleaching, paper machine, calendaring
Random fiber orientation (filter paper)
- Filter Paper: Moderate increase in thickness before break, made from cotton fibers
- Glassine Paper: Ordinary (+ve) Poisson’s ratio – super-calendering
Results (paper)

Cotton paper

- Machine direction present, anisotropic
- Cotton Paper: Moderate increase in thickness before break

Bamboo paper

- Bamboo Paper: Near zero Poisson’s ratio
Random wet-laying of fibers under hydrostatic pressure
- Largely negative Poisson’s ratios, \( \nu < -4.0 \)
- No paper machining, calendaring orientation or compression
- Close to a cellulose random fiber network
Results (paper)

Sample Name | Poisson’s ratio *
--- | ---
Copy paper | -3.3
Paperboard | -1.1
Bamboo Paper | 0.1
Cotton Paper | -0.3
Filter paper | -0.3
Glassine paper | 1.2
Handsheet SW | -4.8
Handsheet HW | -3.8
PET Film | 0.5

*calculated from linear fit of elastic region

Deformation mechanism

Schematic view of paper.

Unstretched

Stretched

Olov E. Ohrn, Svensk papperstidning, 1965, 68(5), 141-149
\[ l^2 = d^2 + x_0^2 \]

\[ l^2 = (d - dz)^2 + (x_0 + dx)^2 \]

\[ dz = d - \sqrt{d^2 - 2x_0 \cdot dx - dx^2} \]

For \( d = 30 \, \mu m, x_0 = 100 \, \mu m \)
Future work

**Task 1**
Handsheets possibilities

- Changing pulp type
- Varying stock concentration
- Varying compressive forces?
- Possibility of making non-cellulosic paper?

**Task 2**
Imaging (SEM)

- Identification of structural features

**Task 3**
Cross Direction Tests

- For all representative samples
- Lower value of ν anticipated

**Task 4**
Geometrical model

To consider effect of

- Fiber properties (elasticity)
- Network properties (grammage, density)
- Modeling random layout of fibers

Future work
Thank you!

Questions?