Nanocomposite-Coated Scaffold Materials with Tailorable Hydrated Mechanical Behaviour

Acheson, J.¹, Ziminska, M.¹, Goel, S.², Lennon, A.¹, Dunne, N.³, Hamilton, A.⁴

1. School of Mechanical and Aerospace Engineering, Queen’s University Belfast, UK
2. Precision Engineering Institute, Cranfield University, UK
3. School of Mechanical and Manufacturing Engineering, Dublin City University, Ireland
4. Engineering Sciences, University of Southampton, UK
Introduction

- Tissue engineering solutions are an attractive alternative to autograft treatment for bone trauma patients

- Bone tissue scaffold development has challenges:
  - High porosity in conjunction with suitable mechanical properties
  - Limitation in selection of materials

**Thin film nanocomposite coating to tailor mechanical properties of open cell structures**

[Image] Alessandra Giuliani, Synchrotron Radiation and Nanotechnology for Stem Cell Research, Stem Cells in Clinic and Research, 2011
Coating has only been tested under ambient conditions. Testing must be done when submerged to examine efficacy under hydrated conditions.

- **Un-coated**
  - Highly porous
  - Less than desirable mechanical properties

- **Coated**
  - Slightly reduced porosity
  - Tailored mechanical properties to match surroundings
Hydrated Testing Materials and Methods

**Materials**
- Open cell polyurethane foam
- Coated with varying number of quadlayers of:
  - Poly(ethyleneimine)
  - Poly(acrylic acid)
  - Cloisite Na⁺ nanoclay

**Methods**
- Uniaxial compression testing
- SEM
- Surface profilometry
- MicroCT
- Mass and elastic modulus in environments of increasing RH
Adapted Ashby-Gibson Model

Mechanical properties of open cell materials can be **tailored**

How do these coatings act when **hydrated**?

Coated Foam Properties when Wet

INTRODUCTION

MATERIALS AND METHODS

RESULTS

CONCLUSIONS

Quadlayers

<table>
<thead>
<tr>
<th>Number of Deposited Quadlayers (n)</th>
<th>Thickness (µm)</th>
<th>Ambient</th>
<th>Hydrated</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.08 ± 0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>1.31 ± 0.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>2.78 ± 0.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>3.19 ± 0.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>4.90 ± 0.46</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Relative Humidity (%)</th>
<th>Elastic Modulus (MPa)</th>
<th>Mass (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60% RH</td>
<td>0.08 ± 0.00</td>
<td>4.0 ± 0.1</td>
</tr>
<tr>
<td>85% RH</td>
<td>1.31 ± 0.21</td>
<td>6.0 ± 0.2</td>
</tr>
<tr>
<td>90% RH</td>
<td>2.78 ± 0.26</td>
<td>8.0 ± 0.3</td>
</tr>
<tr>
<td>95% RH</td>
<td>4.90 ± 0.46</td>
<td>10.0 ± 0.5</td>
</tr>
</tbody>
</table>

Change in Mass (mg) vs. Time (min)

Elastic Modulus (E) (MPa) vs. Mass (mg)

R² = 0.9883
Mechanism of Mechanical Property Loss

Proposed Solution:

Crosslinking of Coating Design Outline

Two-level factorial design of experiments (DoE) to investigate crosslinking effect

**Table 5.1 Design of Experiment Factors**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Parameter</th>
<th>Low</th>
<th>High</th>
<th>Units</th>
<th>Factor Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Glutaraldehyde Molarity</td>
<td>0</td>
<td>2.5</td>
<td>M</td>
<td>Continuous</td>
</tr>
<tr>
<td>B</td>
<td>Glutaraldehyde Time</td>
<td>30</td>
<td>300</td>
<td>mins</td>
<td>Continuous</td>
</tr>
<tr>
<td>C</td>
<td>Temperature</td>
<td>0</td>
<td>120</td>
<td>°C</td>
<td>Discrete</td>
</tr>
<tr>
<td>D</td>
<td>Temperature Time</td>
<td>60</td>
<td>1500</td>
<td>mins</td>
<td>Continuous</td>
</tr>
<tr>
<td>E</td>
<td>Crosslink Interval</td>
<td>5</td>
<td>30</td>
<td>QL</td>
<td>Discrete</td>
</tr>
</tbody>
</table>

Optimise for output: Hydrated elastic modulus

**Optimal Crosslinked Coated Foams Characterised:**

- Hydrated elastic modulus
- Coating thickness SEM
- Hydrated coated thickness surface profilometry
- Mass and elastic modulus in environments of increasing RH
- FTIR
Optimal Crosslinking:
- Glutaraldehyde Crosslinking at 2.5 M
- Glutaraldehyde treatment time of 30 mins
- Crosslinking coating every 5 quadlayers deposited
Optimal Crosslinked Coated Foams

**INTRODUCTION**

**MATERIALS AND METHODS**

**RESULTS**

**CONCLUSIONS**

**Graphs and Figures:**
- **Thickness (µm):**
  - Un-Crosslinked
  - Crosslinked
- **Elastic Modulus (E) (MPa):**
  - Un-Crosslinked
  - Crosslinked
- **Absorbance (au):**
  - Wavenumber (cm⁻¹)
- **Increase in C=N bonds:**
  - Un-Crosslinked
  - Crosslinked
Conclusions

- Nanocomposite coatings provide significant improvement in elastic modulus, under ambient conditions
- Coating loses almost all of its mechanical properties when hydrated
- Effects of water on coating analogous with water acting as a plasticiser as described by others[1,2]
- Design of Experiments identified optimised crosslinking parameters:
  » Glutaraldehyde treatment at 2.5 M for 30 mins, every 5 quadlayers
- Crosslinked coated foams retained 57% of their ambient mechanical properties when hydrated compared to 1.97% for uncrosslinked coated foams
- Crosslinking of coating allows for tailored hydrated physio-mechanical properties
- Coatings can be used to tailor the mechanical and physical structure of bone tissue scaffold materials to match that of surrounding bone

Acknowledgements

Special Thanks
Dr A Hamilton
Dr M. Ziminska
Prof N Dunne
Dr S Goel
Dr A Lennon