3D Printed Geosynthetics

Dr Gary Fowmes

Prof Neil Dixon
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- Geosynthetic Interfaces Wear and Strength
  - Case Studies
  - Wear Development
  - Digital Analyses: Optical Microscopy, SEM and Profiling
- Rapid Prototyping
  - FFF
  - Laser Sintering
  - Laser Ablation
- Results from prototype interfaces
Case studies of interface displacements

- Case study 1
  - Milegate Quarry Landfill, Hornsea
  - Landfill Cell
  - Stress range approximately 0-200 kPa

- Case Study 2
  - Judkins Quarry, Nuneaton
  - Landfill Cap
  - Stress range approximately 0-50 kPa
Milegate Landfill

Case Study
Materials/Instrumentation
Installation

Zamara et al. 2012, 2014
Extensometers
Fibre optic instrumentation
Fibre optic instrumentation
Fibre optics sensors location

Figure 2. Instrument locations on the slope test panel – schematic view (after Zamara et al. 2012).

- Dome strain gauges on the GM
- Extensometers on the GM & GT
- Pressure cells in clay
- PC 13
- PC 24
- PC 30
- Drainage layer (shredded tires)
- PC bottom
Demec Strains Gauges
Deformation of the geotextile during placement of the 2nd sand veneer obtained from extensometer readings compared to theoretical elongation of the geomembrane sheet for the exposed section. Theoretical elongation are calculated for the lower boundary assuming $\Delta T = 30^\circ C$ and coefficient of thermal expansion equal $1.1 \times 10^{-4}$ cm/cm/$^\circ C$, and higher boundary $\Delta T = 40^\circ C$ and coefficient of thermal expansion equal $1.5 \times 10^{-4}$ cm/cm/$^\circ C$.

<table>
<thead>
<tr>
<th>Sensor ID</th>
<th>Sensor location below the crest/ When covered by the sand layer</th>
<th>Monitored geotextile displacement during placement of the 2nd sand veneer</th>
<th>Theoretical geomembrane elongation due to temp. change for the exposed HDPE sheet length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ext. 1</td>
<td>3.0 m 1st veneer</td>
<td>20 mm</td>
<td>9.9–18.0 mm</td>
</tr>
<tr>
<td>Ext. 2</td>
<td>8.4 m 2nd veneer</td>
<td>50 mm</td>
<td>27.7–50.4 mm</td>
</tr>
<tr>
<td>Ext. 3</td>
<td>13.8 m 3rd veneer</td>
<td>80 mm</td>
<td>45.5–82.8 mm</td>
</tr>
</tbody>
</table>

$\Delta L_{GTX} = L_{GTX} - L_{GMB}$

$\Delta L_{SMB} = L_{SMB} + \Delta L_{SMB}$

Temperature increase

Temperature decrease
Judkins Landfill

Case Study
Demec strain gauges
Top of restoration soils
Summary of in situ and lab measurements

- Displacements measured beyond peak values
- Displacements occur at varying normal stresses
- The overall system is more complex than a shear box typically represents
- Stress paths become important
Analysis of Interfaces

0 Direct Shear
Stress Paths in Geosynthetic Interfaces
Digital IMAGING

- Optical Microscope (OM)
- Field Emission Gun – Scanning Electron Microscope (FEG-SEM)
- 3D Surface Roughness Scanner (SRS)
Wear vs normal stress

Increasing normal stress

Deformation and polishing of the top of the asperity

limited damage present
Further observations

Type of geomembrane influences the depth and nature of interaction with the geotextile.
Rapid Prototyping

- Aim: Take understanding from digital analysis and produce stronger interfaces

- Develop viable rapid prototyping techniques to allow comparison between different materials at the laboratory scale.
Rapid Prototyping

Extruded (FFF) 3D Printing
Laser Sintering
Laser Ablation
Extruded 3D Printing

- Builds up model layer by layer imported from stl files

- Consideration of:
  - Polymers used (HDPE & PP proved problematic)
  - Internal Structure (Layered Structure)

- Accessible costs
- Easy to use
Printed Structure

Shear forces act along weaker interlayer bonds

Shear forces perpendicular to laminations

Parallel layers due to printing process
SLS Process

Builds up model layer by layer
Fine powder bonded by laser
Good spatial resolution
Internal structure less prevalent but still present
SLS Process
Laser Ablation

- Laser used to “cut away” material you don’t want
- CO₂ laser used
- Slow and spatial accuracy inferior to SLS & FFF
Laser Ablation

Selective Laser Sintering (SLS)

Laser Thermal Ablation (LTA)
Laser ABLATION

Shear box test for HDPE geomembranes against clay (50 kPa normal stress)
Results of 3D Printing Trials on Textured Geomembranes

Geomembranes – Geotextile Interfaces
Geomembranes – Geotextile Interfaces

- Printed geomembranes
- Produced from scans on factory GM
- Conical structure
- Smooth base sheet
Geomembranes – Geotextile Interfaces

- Needle punched PP non-woven geotextile
Comparison of Factory HDPE and Laser Sintering

![Shear Stress vs Displacement Graph](Image)

- **LS 50**
- **LS 200**
- **LS 400**
- **Factory HDPE 50**
- **Factory HDPE 200**
- **Factory HDPE 400**

**Shear Stress (kPa)** against **Displacement (mm)**
The diagram illustrates the relationship between normal stress (kPa) and peak shear stress (kPa). The data points are color-coded to represent different materials:

- LS
- Factory HDPE

### Adhesion Friction Angle

<table>
<thead>
<tr>
<th>Material</th>
<th>Adhesion</th>
<th>Friction Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factory HDPE</td>
<td>15.7</td>
<td>24.9</td>
</tr>
<tr>
<td>LS</td>
<td>15.3</td>
<td>27.8</td>
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</tbody>
</table>
Comparison of FFF and Laser Sintering

![Graph showing the comparison between FFF and Laser Sintering. The x-axis represents Displacement (mm), and the y-axis represents Shear Stress (kPa). The graph includes lines for LS 50, LS 200, LS 400, FFF 50, FFF 200, and FFF 400.]
<table>
<thead>
<tr>
<th></th>
<th>Adhesion</th>
<th>Friction Angle</th>
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<tbody>
<tr>
<td>FFF</td>
<td>25.6</td>
<td>26.8</td>
</tr>
<tr>
<td>LS</td>
<td>15.3</td>
<td>27.8</td>
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</table>
Altering Asperity Shape

- Investigation of Hook and Loop Effects

Hebeler et al. (2005)
Altering Asperity Shape

Shear Stress (kPa) vs. Displacement (mm) for different types of asperity shapes: LS Spike 50, LS Spike 200, LS Spike 400, LS Small Hook 50, LS Small Hook 200, LS Small Hook 400, LS Large Hook 50, LS Large Hook 200, and LS Large Hook 400.
### Table

<table>
<thead>
<tr>
<th></th>
<th>Adhesion</th>
<th>Friction Angle</th>
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<tbody>
<tr>
<td>LS Spike</td>
<td>15.3</td>
<td>27.8</td>
</tr>
<tr>
<td>LS Small Hook</td>
<td>56.8</td>
<td>21.4</td>
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<tr>
<td>LS Large Hook</td>
<td>44.5</td>
<td>23.8</td>
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Altering Asperity Spacing

![Graph showing the relationship between shear stress and displacement for different asperity spacings.](Image)
### Table

<table>
<thead>
<tr>
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<th>Asperities</th>
<th>Adhesion</th>
<th>Friction Angle</th>
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<tbody>
<tr>
<td>LS Spike (7mm)</td>
<td>160</td>
<td>22.3</td>
<td>27.4</td>
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<tr>
<td>LS Spike (10mm)</td>
<td>116</td>
<td>15.3</td>
<td>27.8</td>
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<tr>
<td>LS Spike (13mm)</td>
<td>83</td>
<td>13.8</td>
<td>26.4</td>
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</tbody>
</table>
Altering Asperity Height

Shear Stress (kPa)

Displacement (mm)
<table>
<thead>
<tr>
<th>Asperity Height</th>
<th>Adhesion</th>
<th>Friction Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4 mm</td>
<td>15.9</td>
<td>25.6</td>
</tr>
<tr>
<td>1 mm</td>
<td>15.3</td>
<td>27.8</td>
</tr>
<tr>
<td>1.6 mm</td>
<td>19.8</td>
<td>27.7</td>
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</table>
Results of 3D Printing Trials on Textured Geomembranes

Geomembranes – Sand Interfaces
Geomembranes – Sand Interfaces

0 Uniformly graded SAND
0 No compaction carried out
Comparison of Factory HDPE and Laser Sintering

![Graph comparing shear stress and displacement for different processes and materials.](image-url)
<table>
<thead>
<tr>
<th>Material</th>
<th>Adhesion</th>
<th>Friction Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factory HDPE</td>
<td>0</td>
<td>39.5</td>
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<tr>
<td>LS</td>
<td>0</td>
<td>41.64</td>
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Dialation diagram (sand, 400 kPa)

- Dialation (mm)
- Displacement (mm)

Lines:
- LS
- HDPE
Comparison of Factory HDPE and Laser Sintering

Shear Stress (kPa) vs. Displacement (mm)
Results of 3D Printing Trials on Textured Geomembranes

Geomembranes – Clay Interfaces
# Geomembranes – Clay Interfaces

- Liquid limit 34.0%
- Plastic limit 17.2%
- Plasticity index 16.8%

- Placed at ~17% ±0.5
- Hand compaction

<table>
<thead>
<tr>
<th>Location</th>
<th>Soil Description</th>
<th>Job ref</th>
<th>pf</th>
<th>Sample no.</th>
<th>Borehole/Pit no.</th>
<th>Depth m</th>
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</table>

<table>
<thead>
<tr>
<th>Sieve aperture size, ( \mu m )</th>
<th>212</th>
<th>425</th>
<th>1,18</th>
<th>5</th>
<th>6.3</th>
<th>10</th>
<th>20</th>
<th>37.5</th>
<th>63</th>
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<tbody>
<tr>
<td>BS sieve aperture size, ( \mu m )</td>
<td>63 um</td>
<td>150</td>
<td>300</td>
<td>600 um</td>
<td>2</td>
<td>3.35</td>
<td>6.3</td>
<td>14</td>
<td>28</td>
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</table>

<table>
<thead>
<tr>
<th>Particle size, ( \mu m )</th>
<th>0.002</th>
<th>0.006</th>
<th>0.012</th>
<th>0.018</th>
<th>0.024</th>
<th>0.030</th>
<th>0.036</th>
<th>0.042</th>
<th>0.048</th>
<th>0.054</th>
<th>0.060</th>
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<tbody>
<tr>
<td>Particle size, mm</td>
<td>0.002</td>
<td>0.006</td>
<td>0.012</td>
<td>0.018</td>
<td>0.024</td>
<td>0.030</td>
<td>0.036</td>
<td>0.042</td>
<td>0.048</td>
<td>0.054</td>
<td>0.060</td>
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<table>
<thead>
<tr>
<th>Clay</th>
<th>Fine</th>
<th>Medium</th>
<th>Coarse</th>
<th>Silt</th>
<th>Sand</th>
<th>Fine</th>
<th>Medium</th>
<th>Coarse</th>
<th>Fine</th>
<th>Medium</th>
<th>Coarse</th>
<th>Cobble</th>
<th>Boulder</th>
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<tr>
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</tbody>
</table>
Geomembranes – Clay Interfaces
Influence of Asperity Height

![Graph showing the influence of asperity height on peak shear stress for different pressures.]

- Peak Shear Stress (kPa)
- Asperity Height (mm)
- 50 KPa
- 200 Kpa
- 400 Kpa
Influence of Spacing
Limitations

- Accurate polymer analogy is challenging
- Printing large flat sheets requires specialist printers
- Printed materials typically much stiffer than geosynthetics
- Internal structure differs from geosynthetics
Potential Applications

0 Allows rapid testing of geometric configurations

0 Allows comparison of geometric variables, shape and dimensions
Summary

- Printing, Sintering and Ablation present significant prototyping potential to the geosynthetics industry.

- A variety of techniques available:
  - Consider the properties in which you are interested.
  - Internal and Chemical structure important to consider.

- Costs likely to be prohibitive to manufacturing scale at present – however this is a rapidly developing field.
Acknowledgements

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- Liwei Fu
- Alex Zaharescu
- Lewis Darwin
- Tom Nolan
- Olajuwon Odunowo
Thanks for listening

Any question?