Introduction to Wood Properties and Wood Products

Puu-25.5000

The wood fibre: composition, ultra-structure and properties

16th September 2015
Wood: Nature’s Cellular Composite Material
Objectives

• To provide an introduction to the structure of wood at different levels of organisation:
  – Gross structure of wood (visible to the naked eye)
  – Microstructure of wood (visible under a light microscope)
  – The cell wall (visible by electron microscopy)
  – Chemical composition (chemical techniques)

• Providing background to:
  – Appearance
  – Properties
  – Behaviour
Chemical composition
Chemical composition

• Three main structural polymers
  – Cellulose
  – Hemicelluloses
  – Lignin

• Analogous to fibre-reinforced-plastics

• Additional polymeric compounds known as “extractives” (because they can be extracted from the wood, i.e. they are not “bound” to the cell wall)
  – Generally these have a range of properties, e.g. some are more hydrophobic than others and so tend to be soluble in different solvents

• Inorganic material – ash, large amount of silica
## Chemical composition

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass</th>
<th>Polymeric state</th>
<th>Molecular derivatives</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Softwood (%)</td>
<td>Hardwood (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cellulose</td>
<td>42±2</td>
<td>45±2</td>
<td>Crystalline, highly oriented, large linear molecule</td>
<td>Glucose</td>
</tr>
<tr>
<td>Hemicellulose</td>
<td>27±2</td>
<td>30±5</td>
<td>Semicrystalline, slightly branched, smaller molecule</td>
<td>Galactose Mannose Xylose</td>
</tr>
<tr>
<td>Lignin</td>
<td>28±3</td>
<td>20±5</td>
<td>Amorphous, large 3-D molecule, not fully elucidated</td>
<td>Phenylpropane</td>
</tr>
<tr>
<td>Extractives</td>
<td>3±2</td>
<td>5±4</td>
<td>Principally compounds soluble in organic solvents (e.g. water, toluene, ethanol)</td>
<td>Terpenes, polyphenols, stillbenoids</td>
</tr>
</tbody>
</table>

*(Adapted from Dinwoodie, 2000)*
Cellulose

- General structure \((C_6H_{10}O_5)_n\)
- Based on glucose molecule \((C_6H_{12}O_6)\)
- Smallest repeating unit is cellobiose (two anhydroglucopyranose units)
- Long thin chain molecule, containing 8000-10000 units per cellulose chain in secondary wall, 2000-4000 in primary cell wall
- Cellulose form the basic structural component of the cell all. The molecules aggregate to form highly crystalline structures through intermolecular bonding, forming the basis for the microfibril, the basic building block of the cell wall
Intermolecular bonding
Inter- and intra- molecular hydrogen bonding
Properties of cellulose

• The Young’s modulus of cellulose has been estimated to be in the region of 135 GPa (similar to Aramid fibre and greater than glass fibre!)

• Very high tensile properties are seen in fibres like flax, hemp and ramie which have a high proportion of cellulose (>80%), oriented nearly parallel with the fibre axis

• Cellulose therefore provides the structural strength of wood and can be thought of as the ultimate “fibre reinforcement” (using the analogy with fibre-reinforced composites) of the wood cell wall
Hemicelluloses

- Range of sugar molecules (e.g. Galactose, glucose, mannose, arabinose)
- Degree of polymerisation (number of units) lower than cellulose (~200)
- Mainly linear but sometimes branched
- Lower degree of crystallisation
- Young’s modulus of hemicellulose ~8 GPa (<< cellulose)
Lignin

- Complex 3-D molecule composed of short, branched molecules
- Structure of lignin not fully understood, as removal from wood affects its structure
- With hemicellulose, lignin forms the “matrix” to cellulose’s “reinforcement”
- Lignin more hydrophobic than hemicellulose and mediates moisture
- Young’s modulus of lignin ~4 GPa (similar to unreinforced polymers like epoxy, unsaturated polyester)
Possible lignin structure
Structure of lignin

Another possible lignin structure!
The microfibril

- The basic fibrous building block of the cell wall
- Composed of a backbone of cellulose, surrounded by a sheath of hemicellulose and lignin

Models for the structure of microfibrils (Dinwoodie, 2000)
The cell wall
Ultrastructural wood

Microfibrils

Cell wall structure
Cell wall structure

• Cell wall composed of the **primary** and **secondary** walls

• Secondary wall composed of three layers, known as \( S_1, S_2 \) and \( S_3 \) layers

• Region between cells known as the **middle lamella**, composed of a lignin-pectin complex. It does not have any microfibrils
Cell wall cross section

Primary

S1

S3

S2

Middle lamella
Cell wall structure

- Primary wall
- Outer layer (S1)
- Middle layer (S2)
- Inner layer (S3)
- Secondary wall
- Middle lamella
Lamellar structure

<table>
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<tr>
<th>Wall layer</th>
<th>Approx. thickness (%)</th>
<th>Angle to fibre axis (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>3</td>
<td>random</td>
</tr>
<tr>
<td>S1</td>
<td>10</td>
<td>50-70</td>
</tr>
<tr>
<td>S2</td>
<td>85</td>
<td>10-30</td>
</tr>
<tr>
<td>S3</td>
<td>2</td>
<td>60-90</td>
</tr>
</tbody>
</table>

(Source: Dinwoodie, 2000)

- Microfibrils in primary wall loosely packed random arrangement
- S1 layer: 4-6 concentric lamellae in left and right hand spirals (S and Z helix)
- S2 layer: 30-150 lamellae, all in Z helix
- S3 layer: few lamellae
- Warty layer inside
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$S_2$ layer and wood properties

- Since ~85% of secondary wall is consists of the $S_2$ later, mechanical and other properties are dominated by the winding angle of this layer.
Summary

• Wood is structured at many levels - chemical, ultra-structural, micro-structural and macro-structural

• Features at all level affect the properties and behaviour of wood
Literature and further reading

• Society of Wood Science and Technology: http://www.swst.org/teach/set2/struct1.html
