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UNIVERSITY OF CAMBRIDGE

Dissemination of IT for the Promotion of Materials Science (DoITPoMS)
About DoITPoMS

History

DoITPoMS (Dissemination of IT for the promotion of Materials Science) was set up in 2000, as a joint venture involving the Department of Materials Science and Metallurgy at the University of Cambridge, and five partner institutions: Institutute for Materials Research, University of Leeds; London Metropolitan Polymer Centre, London Metropolitan University; Manchester Materials Science Centre, University of Manchester/UMIST; Department of Mechanical Engineering, Oxford Brookes University; Department of Engineering Materials, University of Sheffield. Close links also exist with the UK Centre for Materials Education and with the MATTER project, both based at the University of Liverpool.

ALL ABOUT WOOD AND IT STRUCTURE

This document has taken extracts from research carried out by DoITPoMS to try and explain why wood reacts as it does to its environment.

The basic unit of wood structure is the plant cell, which is the smallest unit of living matter capable of functioning independently. The cell has many functions, such as the manufacture of proteins, polysaccharides and mineral deposits. A plant cell varies in diameter from 10–100 µm. The main difference between the plant and animal cell is that plant cells have a cell wall outside the plasma membrane, which is 0.1 to 100 µm thick. This makes the cells rigid, among other effects prohibiting the locomotion typical of animals. The cell wall supports the cell membrane, as internal pressure in the cell can be as high as 1 MPa. The plasma membrane acts as a selective barrier enabling the cell to concentrate the nutrients it has gathered from its environment while retaining the products synthesized within the cell for its own use. It is also able to excrete any waste products from the cell. The membrane is formed from amphipathic molecules i.e. one end is hydrophilic (water liking) and the other end is hydrophobic (water disliking). The nucleus is the most prominent organelle in cells and contains the genetic information (DNA) necessary for control of cell structure and function. In the cell the endoplasmic reticulum synthesises proteins and the Golgi apparatus sorts them; the proteins are then stored within the fluid *cytosol*. Chloroplasts contain energy-converting systems that make ATP by capturing and using the energy from sunlight. Mitochondria produce ATP from larger energy-storage molecules, such as glucose. Finally the vacuoles can store nutrients and waste products, increase the cell size if necessary, and control turgor pressure.
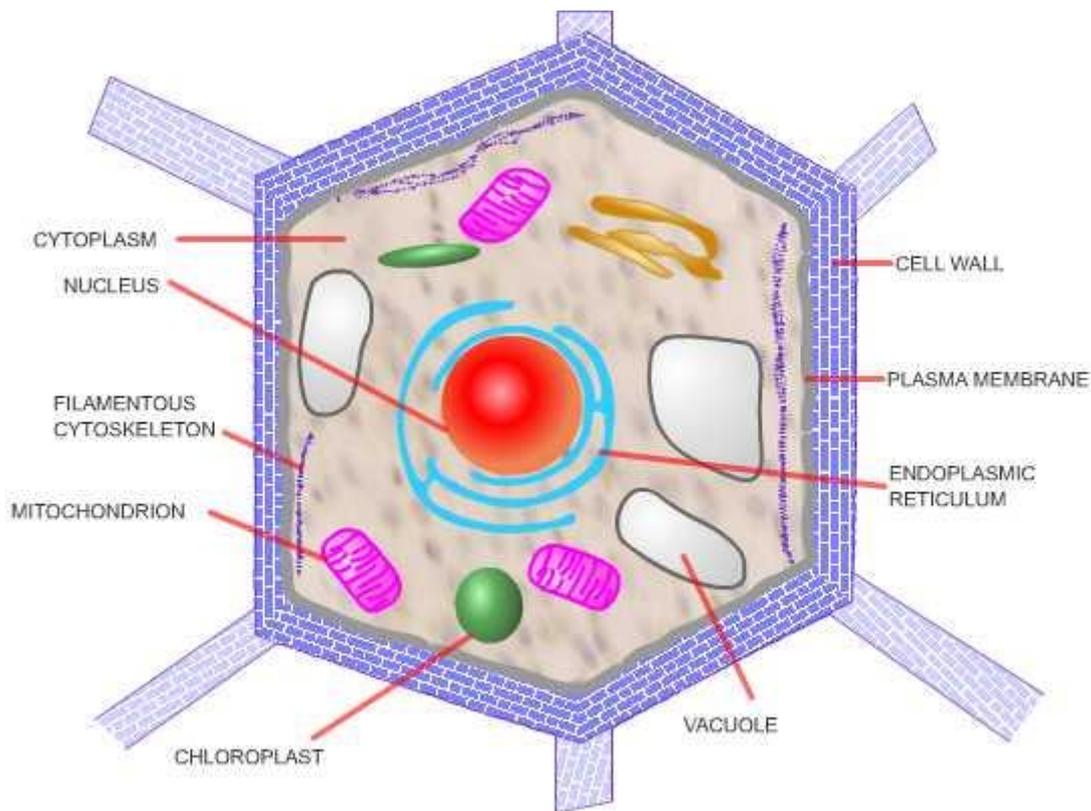
A plant cell

An extracellular matrix called the cell wall, which acts as a supportive framework, surrounds the plant cell. It is made of a network of cellulose microfibrils embedded in a matrix of lignin and hemicellulose, which are examples of polysaccharides. Cellulose is a polymer of 8,000 to 10,000 monomers of anhydroglucose in the form of a flat 6-membered ring. The individual polymers are aligned in parallel and cellulose is up to 90% crystalline. Cell secretions form the matrix, and cellulose and lignin comprise the bulk of a tree's biomass.
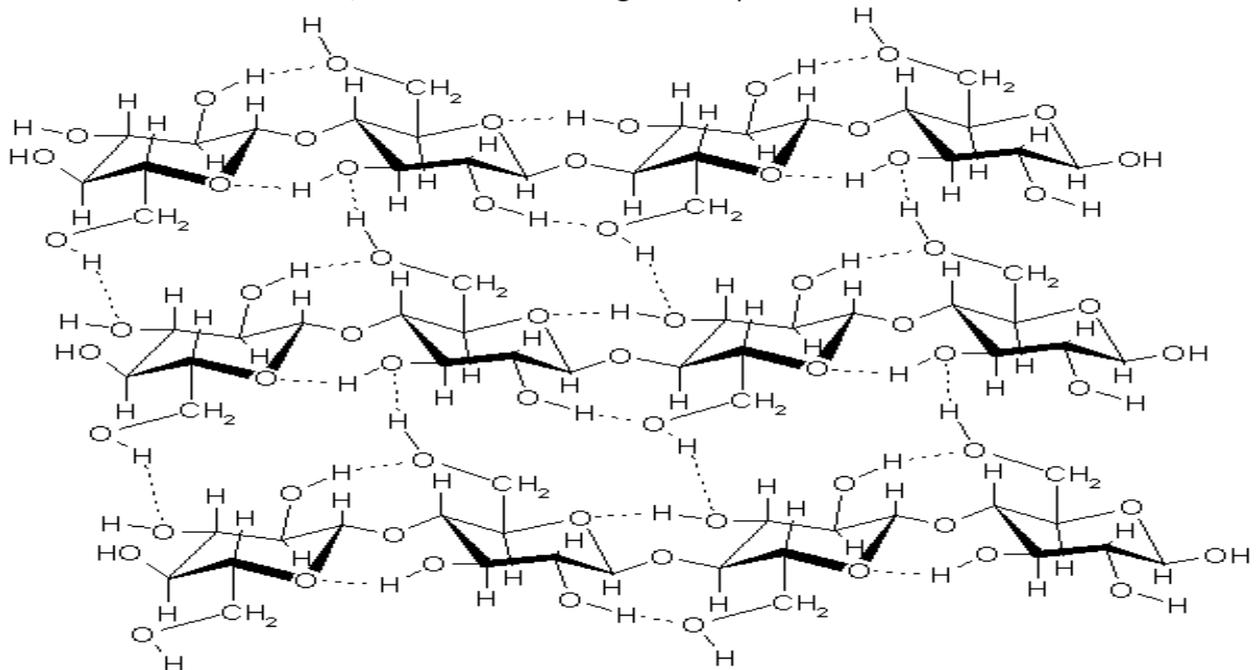
The structure of cellulose

The tubular cell wall has a layered structure:
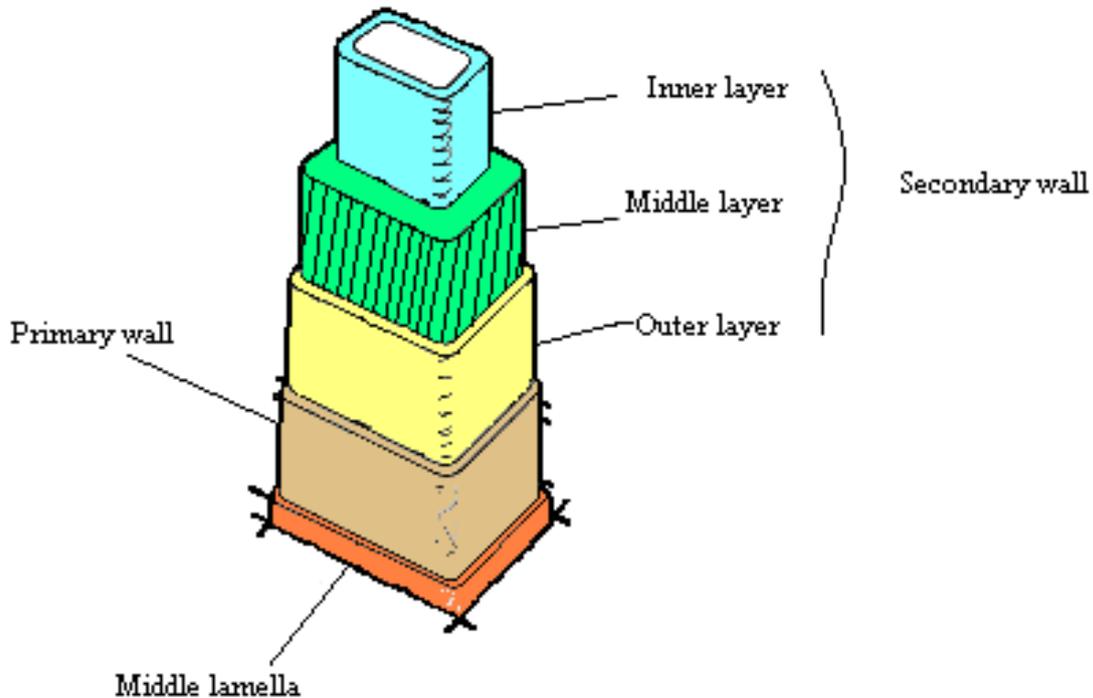
Cell wall schematic

Further cells are aligned parallel to the cell shown. The middle layer is the thickest and most important, and the orientation of the cellulose microfibrils is significant. The orientation of the microfibrils has only been shown for this layer. The cell wall is approximately 50% cellulose fibrils. To toughen the structure, the fibrils are aligned at 10 to 30° to the tree trunk axis in the middle layer of the cell wall.

The open space in dry wood is approximately 50%, but can be as high as 92% in balsa wood. In green wood (freshly cut timber with over 19% moisture content) the amount of open space is less different, as some of the space is filled with water.

Wood has extreme *anisotropy* because 90 to 95% of all the cells are elongated and vertical (i.e. aligned parallel to the tree trunk). The remaining 5 to 10% of cells are arranged in radial directions, with no cells at all aligned tangentially. The diagram below shows a cut-through of a tree trunk:
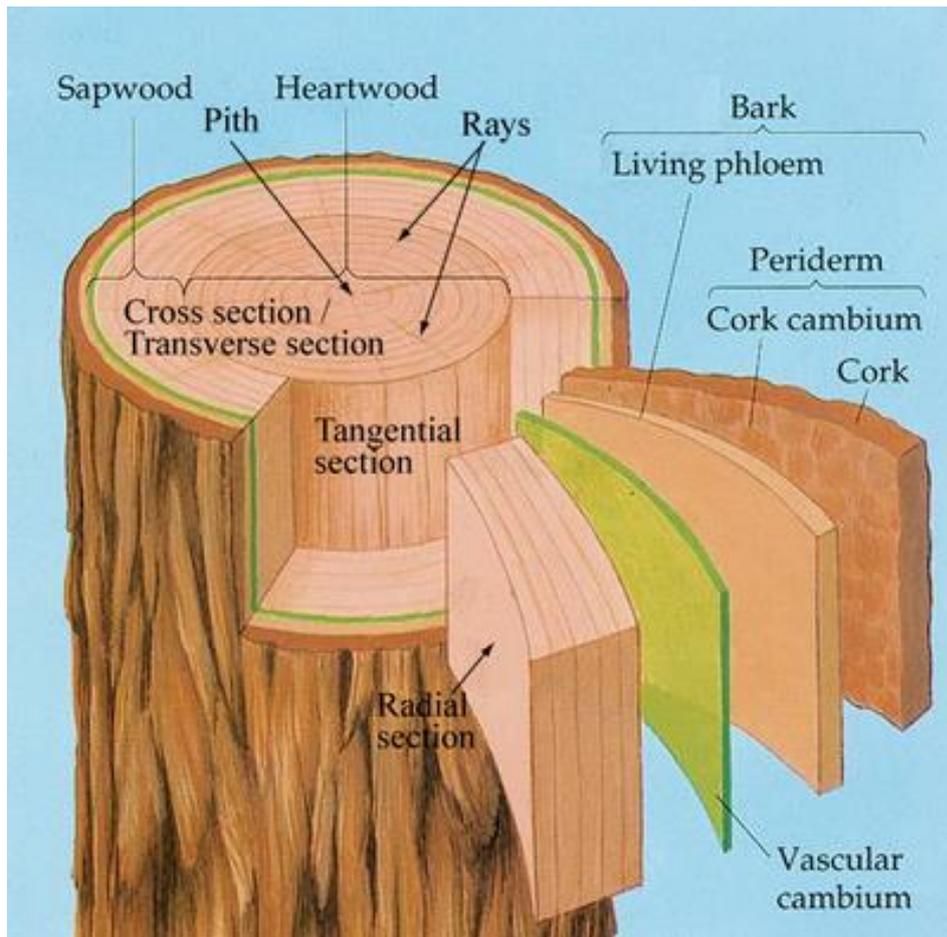
A cut-through of a tree trunk

In the trunk there are three main sections, the *heartwood*, which is physiologically inactive, the *sapwood*, where all conduction and storage occurs, and the*bark*, which protects the interior of the tree trunk. The two main types of tree, *softwoods* and *hardwoods*, have distinct internal structures. *Coniferous* trees are softwoods, with vertical cells, tracheids, 2 to 4 mm long and roughly 30 μm wide. These cells are used for support and conduction; they have an open channel and a thin cell wall:

Cross-section of tracheid cell typical of a softwood

The storage cells, parenchyma, are found in the radial direction. Scots pine is an example of a softwood tree. Below is shown a 3D model of the trunk interior of Scots pine made from micrographs of sections cut in the tangential, radial and transverse planes:

The structure of the tree trunk has now been discussed at both the cellular and macroscopic scale. At the level of the complete structure, there is a further point of interest: the tree is pre-stressed. The centre of tree trunk is in compression, and the outer layers are in tension. The stressing is achieved as the inner sapwood shrinks as it dries and becomes heartwood. As the heartwood has lower moisture content it is better able to resist compression.
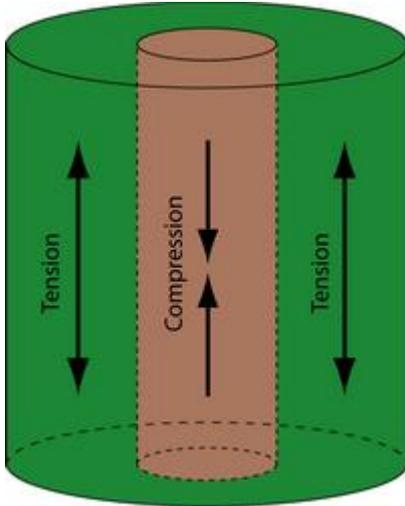
Regions of tree trunk in compression and tension

When a tree grows, the new cells grow at the edge of the tree from the vascular cambium. At the beginning of the growing season, in spring, the cells that grow are large due to the greater amount of moisture available. Throughout summer, the moisture available decreases and the cells also decrease in size as a result. By winter cells can no longer grow, and cells at the edge of the sapwood region near the central heartwood dry out and die. This sequence is evident as annual growth rings. This process is used to date trees by *dendrochronology*. In a good growing year, the growth ring will be wider than that in a bad growing year. By working out the sequence of good and bad years it is possible to match this sequence to the tree, as long as it is more than fifty years old when felled, and hence find the age of the tree. Close examination of the last growth ring then pinpoints the actual season that the tree was cut down. This technique was used to date the oldest-known timber track-way in the world, Sweet Track in the Somerset levels, to the winter of 3807 to 3806 BC.

Broad-leaved trees are called hardwoods. The vertical cells in hardwoods are mainly fibres, which are 1 to 2 mm long and 15 mm wide. These are thick-walled with a very narrow central channel and are for support only.
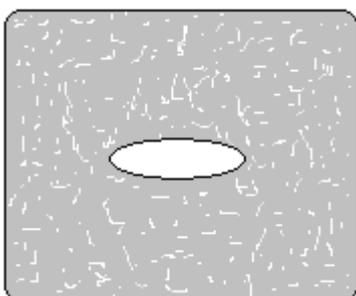
Cross-section of fibre cell found in hardwoods

These cells are unsuitable for conduction, and so the tree needs vessels for this purpose. Vessels are either xylem, which are dead cells that carry water and minerals, or phloem, which are live cells and transport energy sources made by the plant. Vessels are 0.2 to 1.2 mm long, open-ended and are stacked vertically to form tubes of less than 0.5 mm in diameter. Hardwoods also have a small number of tracheid cells, and parenchyma cells are still present radially for storage. Both balsa and greenheart wood are examples of hardwoods.

Water's effect on the mechanical behaviour of wood

The mass of water in a freshly felled tree is 60 to 200% of the dry mass of the tree. In dried out timber there is only roughly 10 weight percent water content. However timbers tend to achieve equilibrium with the surrounding air, settling to a moisture content of 22 to 23% in moist, water-saturated air. The effect of water on wood must therefore be considered. Combining and repeating the previous two experiments with the three-point bending equipment can help to demonstrate the effect. Some wood samples are soaked in water for 24 hours. This should ensure that they have a similar level of water content as green (newly felled) timber. The deflections of the wood samples are noted as the mass on the pan is increased in 100 g increments up to 600 g in order to calculate the Young's modulus of the wood. The mass is then increased further until the failure load is reached. At this point the failure load and maximum displacement of the beam centre are noted. This should allow a measurement of the strength of the wet wood samples.

The stiffness and strength of the wet samples are worked out using the methods shown previously. By following this method and repeating for three samples of balsa, Scots pine and greenheart the following results were obtained:

	Greenheart	Scots pine	Balsa
Stiffness (GPa)	16.1±1.7	6.0±0.7	2.2±0.7
Strength (MPa)	112±3	47±4	11±3

Evidently increasing the water content of wood by soaking wood samples in this way lowers the stiffness and strength of the wood. When dry timber has its water content increased to the levels found in green timber, the cell walls fill with water. This causes the cell walls to expand and a dimensional change occurs. Water's presence dramatically softens the cell walls. The hydrogen bonds between different polymer chains in the crystalline cellulose microfibrils can break. Hydrogen bonds form with water instead, as it is a small, polar molecule and so can get in between the polymer chains. Stronger hydrogen bonds are formed between cellulose and water than between cellulose and cellulose, making hydrogen bonding with water more favourable. This softens the cellulose microfibrils as they are no longer so strongly bonded to each other, making it easier to untangle and hence stretch the fibres. This leads to a decrease in the stiffness of wood.

As water is expanding the cell wall, there are also fewer cellulose microfibrils per unit area. Hence the strength of the wood decreases as, for a given applied stress, the load per fibre is greater. This makes the fibres more likely to break, leading to a crack in the wood sample, causing earlier sample failure.

The graph below shows how the compressive strength of a sample of Scots pine changes as the water content increases. Under compression, there is a very marked weakening effect as water reduces the bonding between fibres, making cell walls easier to buckle.
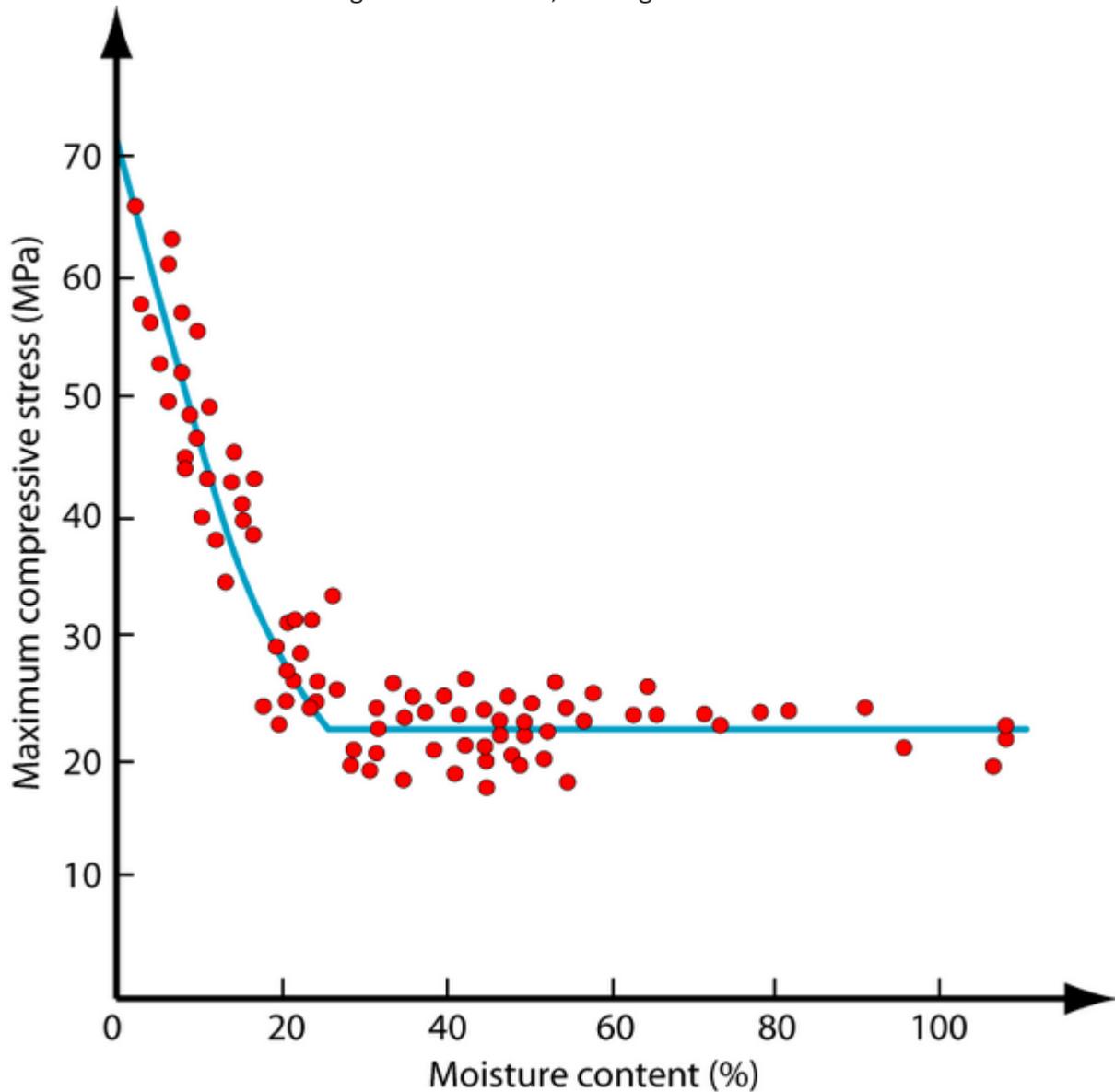
Longitudinal compressive strength of timber as a function of its moisture content [1].