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MECHANICAL PROPERTIES AND MICROSTRUCTURAL CHARACTERISTICS OF HARDWOOD

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Motivation

HARDWOOD MICROSTRUCTURE

Herein, we aim at investigating microstructure-stiffness relationships for hardwood, since these wood species feature certain highly variable microstructural characteristics that govern the anisotropic material behavior observed in macroscopic mechanical experiments. Particularly, **vessels**, which are large cylindrical cells running in stem direction, and **ray cells**, which are oriented in the radial direction, are present in a considerable amount. According to the distribution of vessels and the corresponding pattern in the stem cross-section, hardwood species are classified into '*ring porous*' and '*diffuse porous*'. Except for the ray cells, all wood cells are oriented in the stem direction and build a honeycomb structure. Microstructural characteristics on lower hierarchical levels, influencing the macroscopic mechanical response, are the so-called **microfibril angle**, which defines the orientation of the stiff cellulose fibrils in the otherwise amorphous and soft cell wall material, and the cell wall chemical composition, particularly the amount of cellulose.

MATERIAL

In order to experimentally investigate influences of micro-characteristics on the macro-stiffness, we selected five European species (Common ash, European oak, beech, European plane, lime) and five tropical hardwood species (teak, virola, manil, ipé, satiné), such that a broad variation in these microscopic parameters is given [1]:

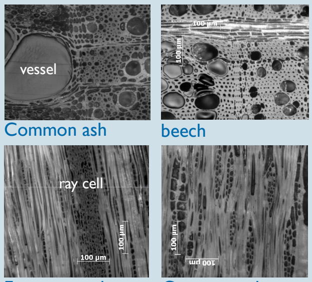
ring / diffuse porous:
e.g. Common ash / beech

vessel volume fraction:
from 8 v% to 29 v%

mass density:
from 0.343 g/cm³ to 0.990 g/cm³

ray cell volume fraction:
from 9 v% to 31 v%

microfibril angle:
from 0° to 25°.

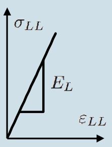


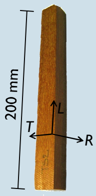
Common ash · beech · European oak · Common ash

Methods – macro- and micromechanical tests

MACROSCOPIC STIFFNESS

Quaistatic tensile tests



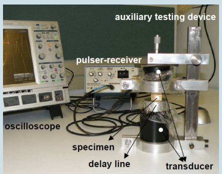


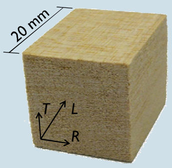
displacement-controlled uniaxial tension, strains measured with clamp-on strain transducers

$$E_L = \Delta\sigma_{LL} \,/\, \Delta\varepsilon_{LL}$$

Young's modulus E_L

Ultrasonic (US) tests [2]





US wave (100 kHz frequency) propagation velocity in three anatomical directions,

$v_i = l_i \,/\, t_i$, with $i \in [L,R,T]$

$C_{iiii} = \rho\, v_i^2$

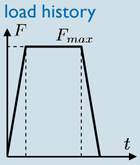
l_i … sample dimension
t_i … time of flight
ρ … mass density

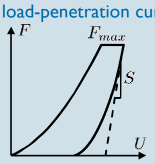
stiffness tensor components C_{LLLL}, C_{RRRR}, C_{TTTT}

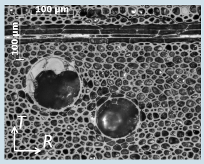
MICROSCOPIC STIFFNESS

Nanoindentation tests [3]

load history · load-penetration curve







initial slope of unloading curve

$$S = dF \,/\, dU|_{U=U_{max}} = \frac{2}{\sqrt{\pi}}\sqrt{A_c(U_c)}$$

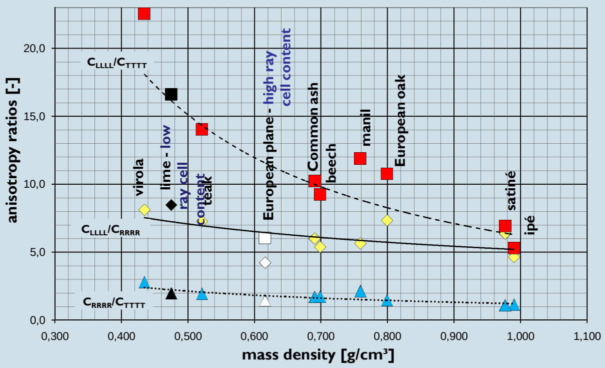
$$M = \sqrt{\pi}/(2\sqrt{A_c})\,S$$

A_c … contact area
U_c … contact depth

indentation modulus M

Results – microstructure-stiffness relationships

ANISOTROPY RATIOS



density increase → **C_{LLLL}/C_{TTTT} and C_{LLLL}/C_{RRRR} decrease,**

which can be explained by the overlinear increase of transversal stiffnesses with density, whereas longitudinal stiffness increases linearly with density [4].

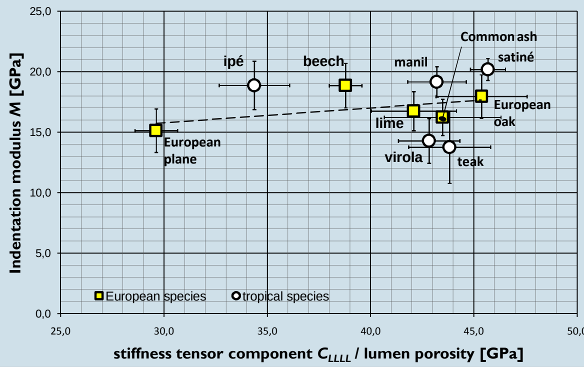
density increase → **C_{RRRR}/C_{TTTT} decreases,**

which reveals that there is less cell wall bending for thick walled cells.

ray cell increase → **C_{LLLL}/C_{TTTT} and C_{LLLL}/C_{RRRR} decrease,**

which underlines that a high ray cell content (e.g. European plane) leads to a reduced longitudinal stiffness.

INDENTATION MODULUS



Indentation modulus $M \neq$ long. Young's modulus of cell wall

As a general trend, indentation modulus of the S2 layer increases with increase in cell wall stiffness, although, there is no strong correlation. This underlines that the indentation modulus is a function of the anisotropic stiffness of the cell wall material, which in turn is strongly influenced by the microfibril angle and the chemical composition of the cell walls.

References:
[1] R. Wagenführ (2007) Fachbuchverlag Leipzig (in German)
[2] V. Bucur (2006) Springer Verlag Wien, Heidelberg, New York
[3] W. Oliver and G. Pharr (1992) J. Mat. Res., 7(6):1564–1583.
[4] T. K. Bader et al. (2010) Acta Mech. DOI 10.1007/s00707-010-0368-8