Shrinkage and density

Physical and Mechanical Properties of Wood Practicum

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Izola, 2026

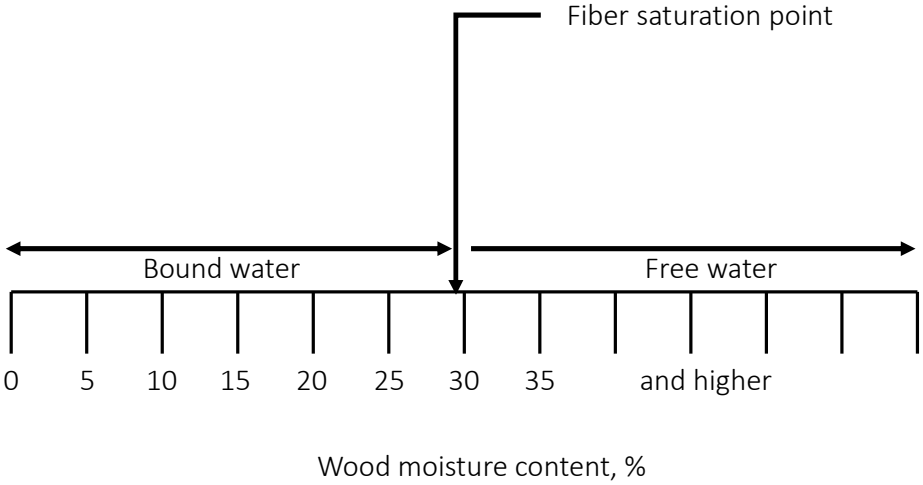
Recap: wood moisture content

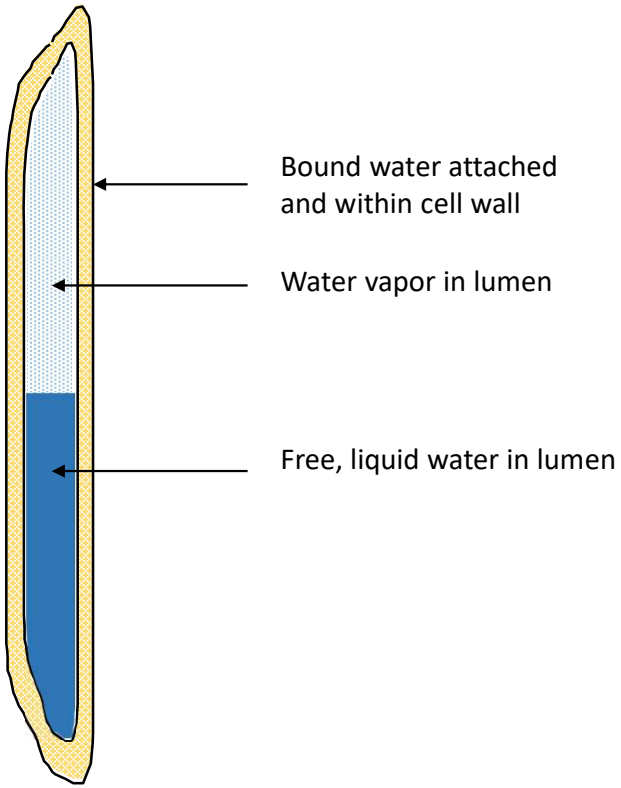
- How much **water** is present **in wood relative to the oven-dry mass**?
- Oven-dry – **Wood moisture content (MC): 0%**

$$\boldsymbol{MC} = 100\ x\ \frac{\boldsymbol{Wet}\ weight\ of\ wood\ -\ \boldsymbol{Oven\ dry}\ weight\ of\ wood}{\boldsymbol{Oven\ dry}\ weight\ of\ wood}$$

Recap: Fiber saturation point (FSB)

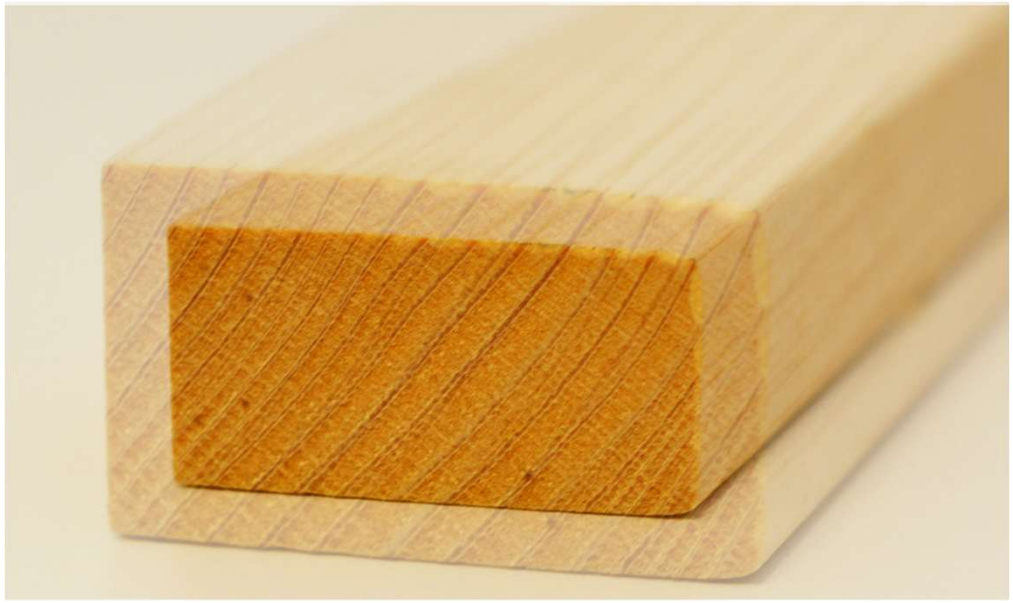
- The moisture content at which wood cell walls are **fully saturated with bound water**, but **no free liquid water** is present in the cell lumina (typically around 30% MC)





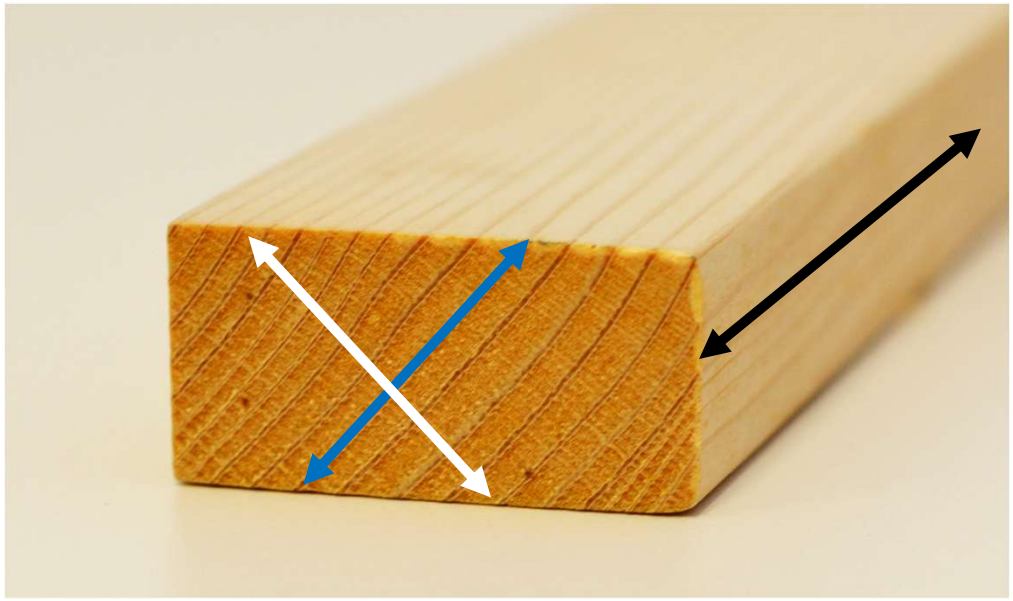
Shrinkage and swelling

- Wood **shrinks and swells below the fibre saturation point** (FSP)
- **Shrinkage**: when bound water is removed from the cell walls
- **Swelling**: when bound water is absorbed into the cell walls



Shrinkage and wood direction

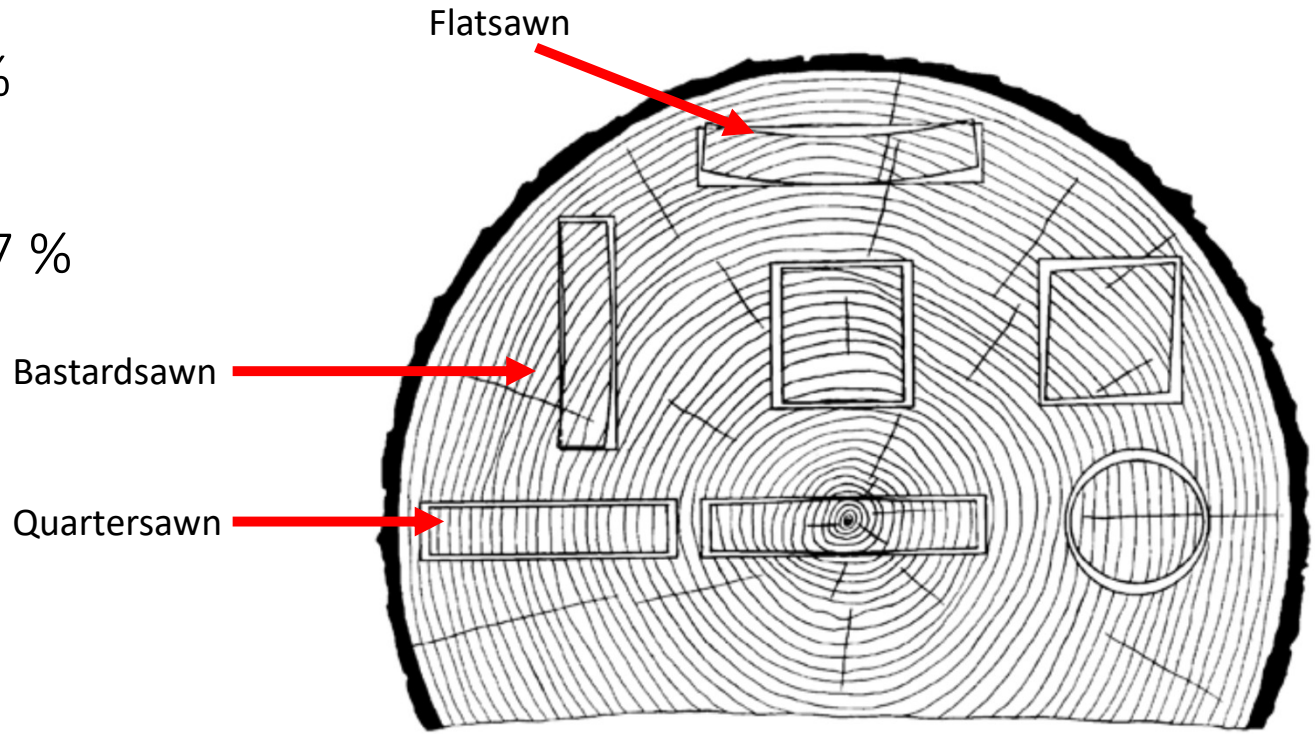
- Longitudinal > 0.2 %
- Radial = about 4 %
- Tangential = about 7 %



- Typical total shrinkage values from green to oven-dry conditions

Normal shrinkage and wood direction

- Longitudinal > 0.2 %
- Radial = about 4 %
- Tangential = about 7 %



Source: Wood Handbook

Shrinkage and sweeling

- Longitudinal shrinkage < 0.2 %
  - We often neglect this
  - Higher in juvenile wood, compression wood, tension wood
- Radial shrinkage is significant
- Tangential shrinkage is 1.5 to 2 times greater than radial shrinkage

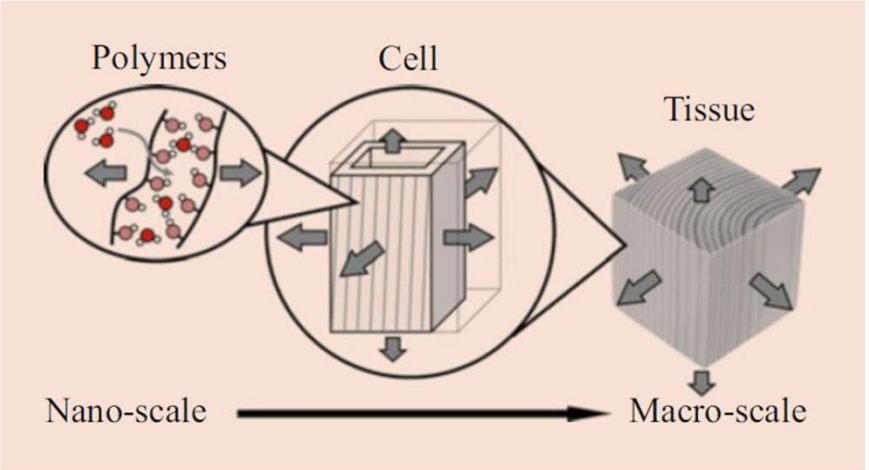


Fig. 7.12 Schematic illustration of dimensional changes in wood on several length scales

Swelling / shrinkage vs MC

- At the same MC, swelling can differ slightly depending on whether wood is absorbing or releasing moisture (sorption hysteresis)

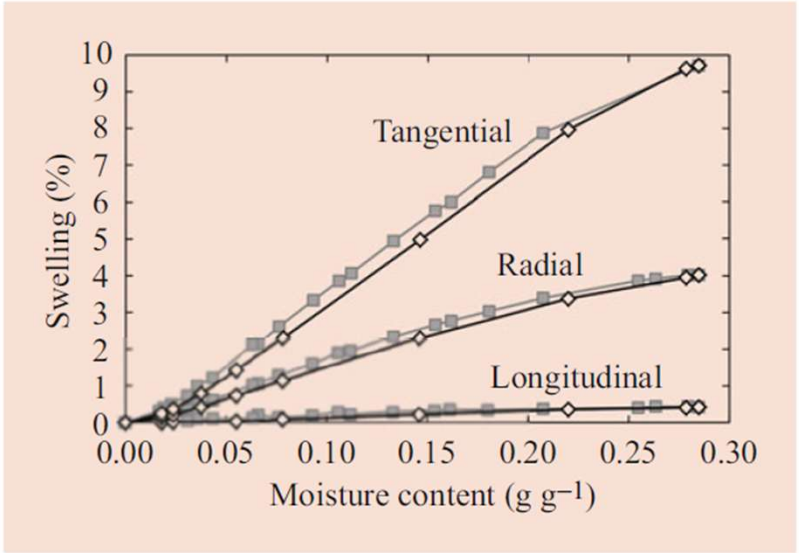


Fig. 7.16 Swelling (S_{sw}) in the longitudinal, radial, and tangential directions as function of equilibrium moisture content at 25 °C during absorption (open diamonds) and desorption (closed squares) from non-saturated condition. Experimental results for spruce [172]

Source: Wood Handbook

Volumetric shrinkage

- Definition: The reduction in the total volume of wood as it loses bound water during drying

- Considers dimensional changes in all three directions: longitudinal, radial and tangential

$$S_v = 100\ x\ \frac{V_{green} - V_{oven\ dry}}{V_{green}}$$

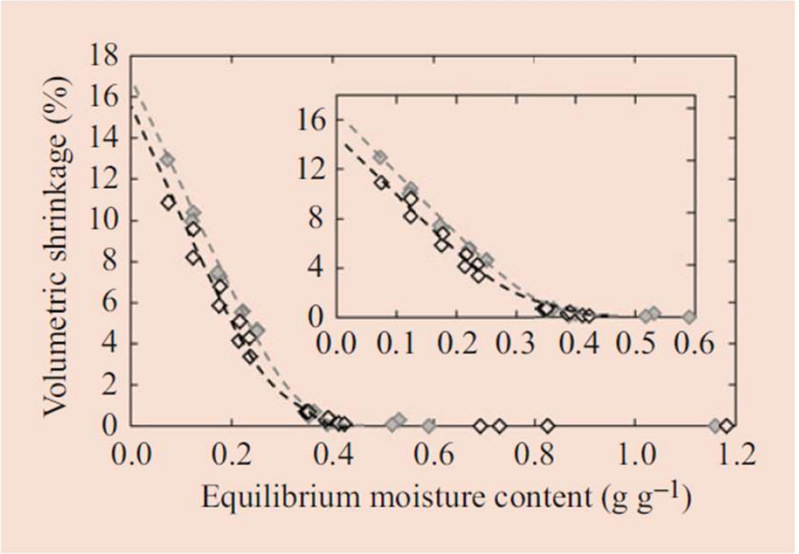
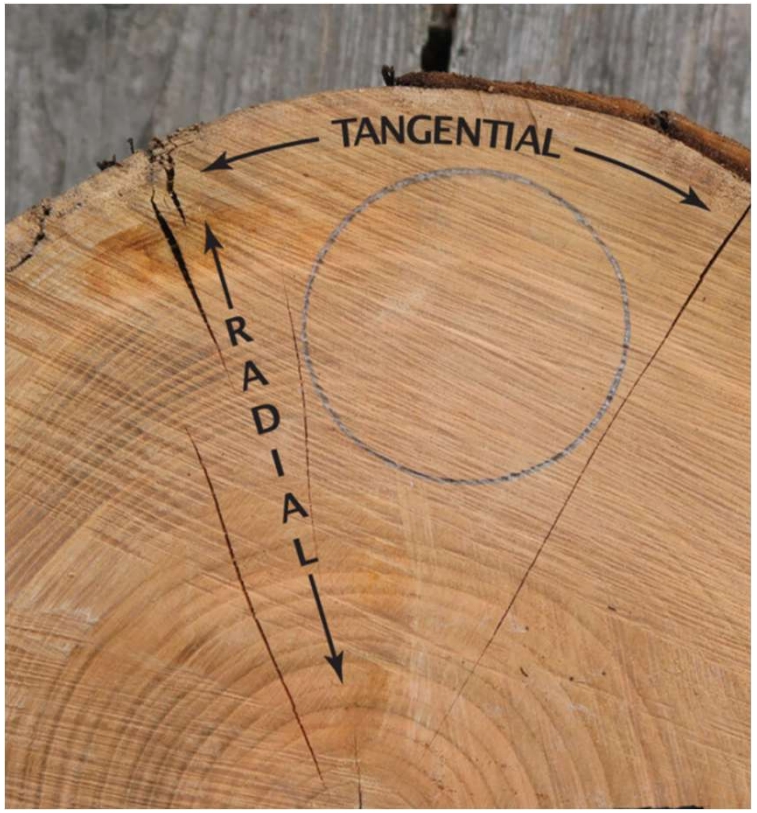


Fig. 7.15 Volumetric shrinkage (S_{sh}) of beech (*Fagus grandifolia* Ehrhart) (black, open diamonds) and yellow birch (*Betula alleghaniensis* Britton) (gray, closed diamonds) as function of equilibrium moisture content in desorption from water saturation in the hygroscopic and over-hygroscopic moisture range. (Based on experimental data [55, 169])

Cracks

- Wood loses moisture and starts shrinking below the FSP
- Tangential shrinkage > radial shrinkage
- Unequal shrinkage creates internal stresses in the wood
- Radial cracks (checks) form when tensile stresses exceed the wood's strength perpendicular to the grain
- Uneven drying can further increase these stresses and accelerate cracking



Shrinkage values of wood

- Table 4-3 in the wood handbook lists shrinkage values for US domestic woods
- These values are used as a starting point to calculate shrinkage and dimensional changes

Table 4–3. Shrinkage values of domestic woods

Species	Shrinkage[a] (%) from green to ovendry moisture content		
	Radial	Tangential	Volumetric
Hardwoods			
Alder, red	4.4	7.3	12.6
Ash			
Black	5.0	7.8	15.2
Blue	3.9	6.5	11.7
Green	4.6	7.1	12.5
Oregon	4.1	8.1	13.2
Pumpkin	3.7	6.3	12.0
White	4.9	7.8	13.3
Aspen			
Bigtooth	3.3	7.9	11.8
Quaking	3.5	6.7	11.5
Basswood, American	6.6	9.3	15.8
Beech, American	5.5	11.9	17.2
Birch			
Alaska paper	6.5	9.9	16.7
Gray	5.2	—	14.7
Paper	6.3	8.6	16.2
River	4.7	9.2	13.5
Sweet	6.5	9.0	15.6
Yellow	7.3	9.5	16.8
Buckeye, yellow	3.6	8.1	12.5
Butternut	3.4	6.4	10.6
Cherry, black	3.7	7.1	11.5
Chestnut, American	3.4	6.7	11.6
Cottonwood			
Balsam poplar	3.0	7.1	10.5
Black	3.6	8.6	12.4
Eastern	3.9	9.2	13.9
Elm			
American	4.2	9.5	14.6
Cedar	4.7	10.2	15.4
Rock	4.8	8.1	14.9
Slippery	4.9	8.9	13.8
Winged	5.3	11.6	17.7
Hackberry	4.8	8.9	13.8
Hickory, pecan	4.9	8.9	13.6
Hickory, true			
Mockernut	7.7	11.0	17.8
Pignut	7.2	11.5	17.9
Shagbark	7.0	10.5	16.7
Shellbark	7.6	12.6	19.2
Holly, American	4.8	9.9	16.9
Honeylocust	4.2	6.6	10.8
Locust, black	4.6	7.2	10.2
Madrone, Pacific	5.6	12.4	18.1
Magnolia			
Cucumbertree	5.2	8.8	13.6
Southern	5.4	6.6	12.3
Sweetbay	4.7	8.3	12.9
Maple			
Bigleaf	3.7	7.1	11.6
Black	4.8	9.3	14.0
Red	4.0	8.2	12.6
Silver	3.0	7.2	12.0
Striped	3.2	8.6	12.3
Sugar	4.8	9.9	14.7
Oak, red			
Black	4.4	11.1	15.1
Laurel	4.0	9.9	19.0
Northern red	4.0	8.6	13.7
Pin	4.3	9.5	14.5
Scarlet	4.4	10.8	14.7
Southern red	4.7	11.3	16.1
Water	4.4	9.8	16.1
Willow	5.0	9.6	18.9
Oak, white			
Bur	4.4	8.8	12.7
Oak, white—con.			
Chestnut	5.3	10.8	16.4
Live	6.6	9.5	14.7
Overcup	5.3	12.7	16.0
Post	5.4	9.8	16.2
Swamp, chestnut	5.2	10.8	16.4
White	5.6	10.5	16.3
Persimmon, common	7.9	11.2	19.1
Sassafras	4.0	6.2	10.3
Sweetgum	5.3	10.2	15.8
Sycamore, American	5.0	8.4	14.1
Tanoak	4.9	11.7	17.3
Tupelo			
Black	5.1	8.7	14.4
Water	4.2	7.6	12.5
Walnut, black	5.5	7.8	12.8
Willow, black	3.3	8.7	13.9
Yellow-poplar	4.6	8.2	12.7
Softwoods			
Cedar			
Yellow	2.8	6.0	9.2
Atlantic white	2.9	5.4	8.8
Eastern redcedar	3.1	4.7	7.8
Incense	3.3	5.2	7.7
Northern white	2.2	4.9	7.2
Port-Orford	4.6	6.9	10.1
Western redcedar	2.4	5.0	6.8
Douglas-fir,			
Coast[b]	4.8	7.6	12.4
Interior north[b]	3.8	6.9	10.7
Interior west[b]	4.8	7.5	11.8
Fir			
Balsam	2.9	6.9	11.2
California red	4.5	7.9	11.4
Grand	3.4	7.5	11.0
Noble	4.3	8.3	12.4
Pacific silver	4.4	9.2	13.0
Subalpine	2.6	7.4	9.4
White	3.3	7.0	9.8
Hemlock			
Eastern	3.0	6.8	9.7
Mountain	4.4	7.1	11.1
Western	4.2	7.8	12.4
Larch, western	4.5	9.1	14.0
Pine			
Eastern white	2.1	6.1	8.2
Jack	3.7	6.6	10.3
Loblolly	4.8	7.4	12.3
Lodgepole	4.3	6.7	11.1
Longleaf	5.1	7.5	12.2
Pitch	4.0	7.1	10.9
Pond	5.1	7.1	11.2
Ponderosa	3.9	6.2	9.7
Red	3.8	7.2	11.3
Shortleaf	4.6	7.7	12.3
Slash	5.4	7.6	12.1
Sugar	2.9	5.6	7.9
Virginia	4.2	7.2	11.9
Western white	4.1	7.4	11.8
Redwood			
Old growth	2.6	4.4	6.8
Young growth	2.2	4.9	7.0
Spruce			
Black	4.1	6.8	11.3
Engelmann	3.8	7.1	11.0
Red	3.8	7.8	11.8
Sitka	4.3	7.5	11.5
Tamarack	3.7	7.4	13.6

[a]Expressed as a percentage of the green dimension.
[b]Coast type Douglas-fir is defined as Douglas-fir growing in the States of Oregon and Washington west of the summit of the Cascade Mountains. Interior West includes the State of California and all counties in Oregon and Washington east of but adjacent to the Cascade summit. Interior North includes the remainder of Oregon and Washington and the States of Idaho, Montana, and Wyoming.

Maximum swelling and swelling coefficient

Table 7.4 Maximum swelling and linear swelling coefficient, that is, percent swelling per 0.01 g g^{-1} moisture content change, of various wood species [170, 171]

	Maximum swelling (%)			Swelling coefficient (% per g g^{-1})	
Species	Longitudinal	Radial	Tangential	Radial	Tangential
Softwoods					
Norway spruce	0.2–0.4	3.7	8.5	0.19	0.36
Scots pine	0.2–0.4	4.2	8.3	0.19	0.36
Larch	0.1–0.3	3.4	8.5	0.14	0.30
Douglas fir	0.1–0.3	5.0	8.0	0.15	0.27
Western Red Cedar	0.2–0.6	2.5	5.3	0.10	0.20
Hardwoods					
Obeche	0.2–0.3	3.5	6.2	0.10	0.18
Beech	0.2–0.6	6.2	13.4	0.20	0.41
Dark Red Meranti	0.2–0.3	4.3	10.7	0.17	0.32
Oak	0.3–0.6	4.6	10.9	0.18	0.34
Iroko	0.2–0.7	3.5	5.5	0.19	0.28
Black poplar	0.2–0.4	3.4	8.9	0.10	0.28
Teak	0.2–0.3	2.7	4.8	0.16	0.26

- **Swelling coefficient**: how much wood expands for each 1 percentage-point increase in moisture content
- Approximately linear within the 5–20% MC range

Swelling: exercise

- *Scots pine*
- **Flat sawn and Quartersawn**
- 50 mm thick x 100 mm width x 3000 mm long

- **MC change: from 0% to green (fully swollen)**



Flatsawn

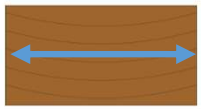


Quartersawn

Species	Maximum swelling (%)			Swelling coefficient (% per g g^{-1})	
	Longitudinal	Radial	Tangential	Radial	Tangential
Softwoods					
Norway spruce	0.2–0.4	3.7	8.5	0.19	0.36
Scots pine	0.2–0.4	4.2	8.3	0.19	0.36

Swelling: exercise - solution

$$\Delta MC = oven\ dry\ (MC\ 0\%)\ to\ fully\ swollen \geq FSP$$

Flatsawn: 

Maximum swelling: tangential 8.3 %

Quartersawn: 

Maximum swelling : radial 4.2 %

Δw: Width change

w_i: initial width

S: total swelling in the relevant direction (%)

$$\Delta w = w_i \times \frac{S}{100}$$

$$\Delta w = 100\ mm \times \frac{8.3}{100}$$

$$\boldsymbol{\Delta w = 8.30\ mm}$$

$$\Delta w = w_i \times \frac{S}{100}$$

$$\Delta w = 100\ mm \times \frac{4.2}{100}$$

$$\boldsymbol{\Delta w = 4.20\ mm}$$

Limiting dimensional change

- Drying before use
- Construction/assembly
- Coatings
- Chemical bulking
- Chemical cross linking
- Heat treatment

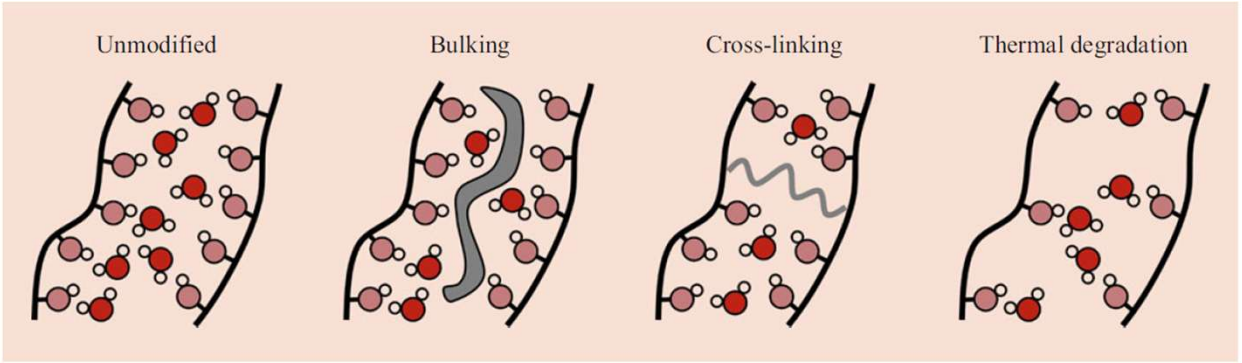


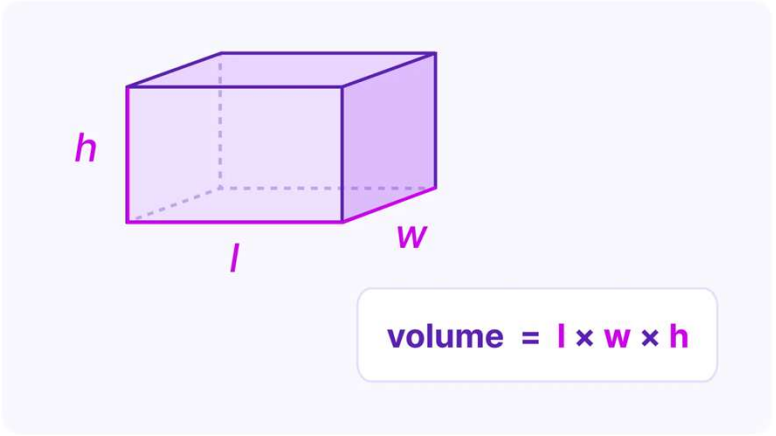
Fig. 7.9 Schematic illustration of three general types of chemical modification: bulking, cross-linking, and thermal degradation

Density

- Density is the **mass** of wood **per** unit **volume**

$$\rho = \frac{m}{V}$$

- Where m = mass (kg) and V = volume (m^3)



- Common units: kg/m^3 or g/cm^3
- 1 g/cm^3 = 1,000 kg/m^3

Different types of wood density

Density types	Conditions	Formula
Density at specified MC ρ(mc)	Mass and volume at the same moisture content	$\rho(mc) = m(mc) / V(mc)$
Oven-dry density ρ_o	Oven-dry mass and oven-dry volume	$\rho_o = m_o / V_o$
Basic density R	Oven-dry mass and fully swollen (green) volume	$R = m_o / V_{max}$
Cell-wall density ρ(cw)	Oven-dry mass and solid cell-wall volume, excluding pores	$\rho(cw) = m_o / V(cw)$

Density at x% MC

- The density in a normal climate
  - 20°C and 65% relative humidity(RH) is referred to as normal density
- The equilibrium moisture content (EMC) in a normal climate is on average 12% for most European wood

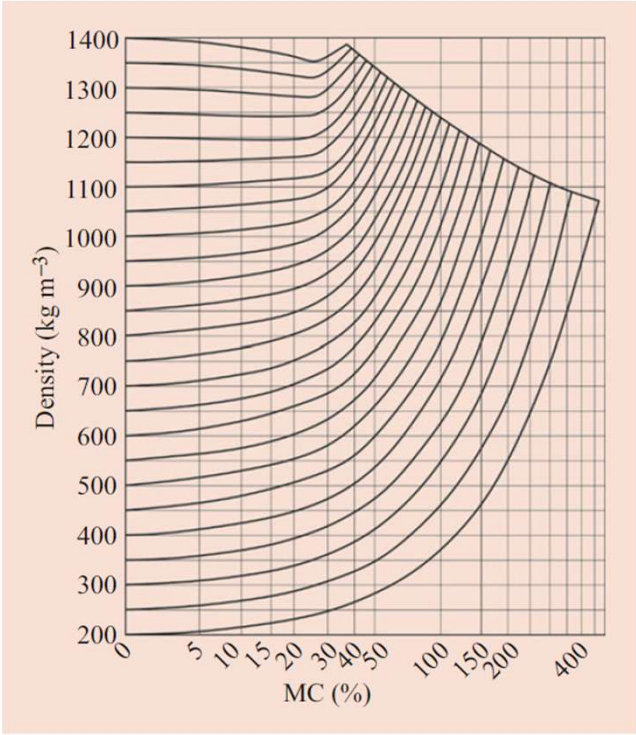


Fig. 6.3 Influence of moisture content (MC) on wood density [12]

Density of different wood species

- Wood is a porous material, consisting of solid cell walls and empty spaces
- The density of dry wood cell-wall material is approximately 1,500 kg/m³
- Wood density mainly depends on the proportion of cell-wall material and void space

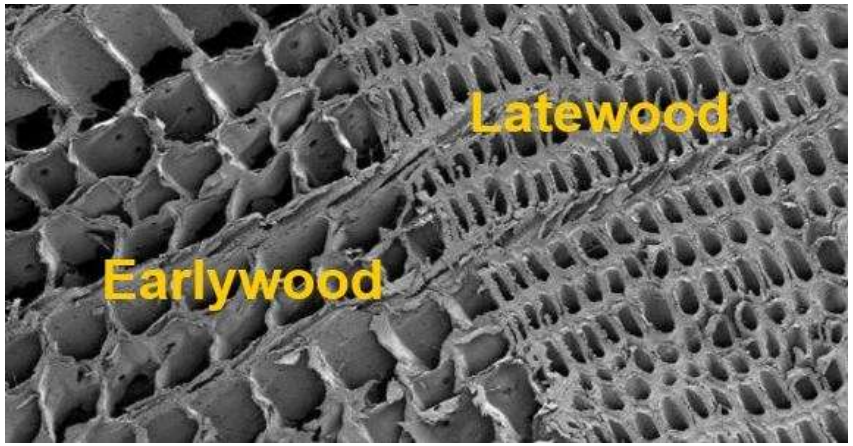
Table 6.1 Mean values ($\bar{x}$) and range of variation (x_{min}, x_{max}) of oven-dry density and mean value of basic density of selected species (according to Knigge and Schulz [13])

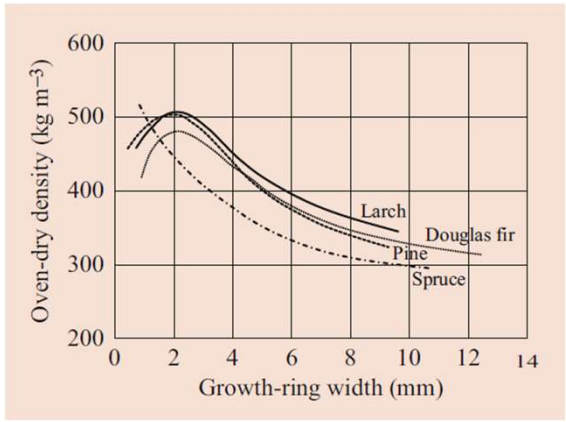
Species	Oven-dry density (kg m^{-3})	Basic density (kg m^{-3})
	x_{min}, $\bar{x}$, x_{max}	$\bar{x}$
Softwood		
Eastern white pine	310...370...460	339
Grand fir	280...420...610	332
Norway spruce	370...430...540	377
Douglas fir	360...470...630	412
Scots pine	300...490...860	431
European larch	400...550...820	487
Hardwood		
Balsa	70...130...230	121
Black polar	270...370...650	377
Sycamore maple	480...590...750	522
Elm	440...640...820	556
Common ash	410...650...820	564
Common oak	380...640...900	561
European beech	540...660...840	554
Lignum vitae	1200...1230...1320	1045

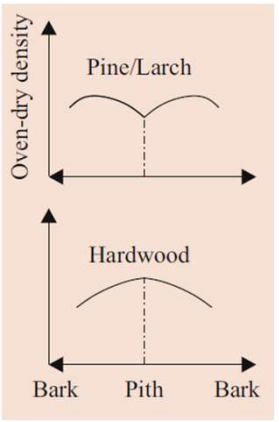
*The basic density is the quotient of the mass of the oven- dry wood and the volume of the maximum swollen wood

Why does wood density vary?

- Influence of the wood species
- Influence of growing conditions and location
- Influence of structural parameters
  - Earlywood and latewood
  - Growth-ring width
  - Heartwood/sapwood
  - Wood from branches, roots, and reaction wood (tension and compression wood)





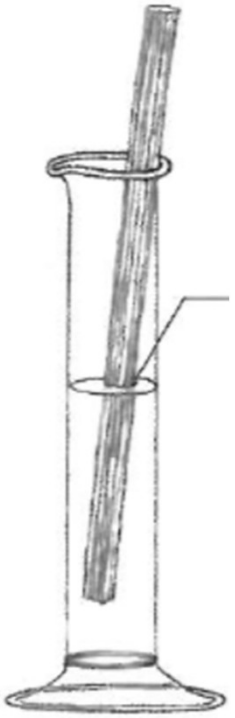


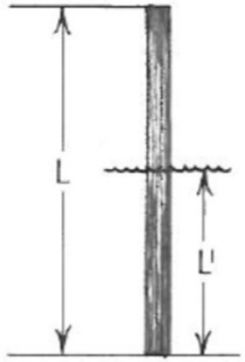
Specific gravity

- Definitions
  - Density of wood substance in relation to the density of water
  - Mass of wood substance over the mass of an equal volume of water

$$SG = \frac{\rho_{wood}}{\rho_{water}} = \frac{500\,\frac{kg}{m^3}}{1000\,\frac{kg}{m^3}} = 0.5$$

- No unit
- Must include MC when stating SG





$$SG = \frac{L'}{L}$$

Determination of specific gravity by flotation based on Archimedes' principle

Specific gravity and density

Table 4–5. Expressions for specific gravity and density of wood[a]

	Symbol	Mass basis	Volume basis
Specific gravity	G_0	Ovendry	Ovendry
	G_b (basic specific gravity)	Ovendry	Green
	G_{12}	Ovendry	12% MC
	G_x	Ovendry	x% MC
Density	ρ_0	Ovendry	Ovendry
	ρ_{12}	12% MC	12% MC
	ρ_x	x% MC	x% MC

[a] x is any chosen moisture content.

Source: Wood Handbook

Density of wood, SG, and MC

Table 4–6a. Density of wood as a function of specific gravity and moisture content (SI)

Moisture content of wood (%)	Density (kg m^{-3}) when the specific gravity G_x is																				
	0.30	0.32	0.34	0.36	0.38	0.40	0.42	0.44	0.46	0.48	0.50	0.52	0.54	0.56	0.58	0.60	0.62	0.64	0.66	0.68	0.70
0	300	320	340	360	380	400	420	440	460	480	500	520	540	560	580	600	620	640	660	680	700
4	312	333	354	374	395	416	437	458	478	499	520	541	562	582	603	624	645	666	686	707	728
8	324	346	367	389	410	432	454	475	497	518	540	562	583	605	626	648	670	691	713	734	756
12	336	358	381	403	426	448	470	493	515	538	560	582	605	627	650	672	694	717	739	762	784
16	348	371	394	418	441	464	487	510	534	557	580	603	626	650	673	696	719	742	766	789	812
20	360	384	408	432	456	480	504	528	552	576	600	624	648	672	696	720	744	768	792	816	840
24	372	397	422	446	471	496	521	546	570	595	620	645	670	694	719	744	769	794	818	843	868
28	384	410	435	461	486	512	538	563	589	614	640	666	691	717	742	768	794	819	845	870	896
32	396	422	449	475	502	528	554	581	607	634	660	686	713	739	766	792	818	845	871	898	924
36	408	435	462	490	517	544	571	598	626	653	680	707	734	762	789	816	843	870	898	925	952
40	420	448	476	504	532	560	588	616	644	672	700	728	756	784	812	840	868	896	924	952	980
44	432	461	490	518	547	576	605	634	662	691	720	749	778	806	835	864	893	922	950	979	1,008
48	444	474	503	533	562	592	622	651	681	710	740	770	799	829	858	888	918	947	977	1,006	1,036
52	456	486	517	547	578	608	638	669	699	730	760	790	821	851	882	912	942	973	1,003	1,034	1,064
56	468	499	530	562	593	624	655	686	718	749	780	811	842	874	905	936	967	998	1,030	1,061	1,092
60	480	512	544	576	608	640	672	704	736	768	800	832	864	896	928	960	992	1,024	1,056	1,088	1,120
64	492	525	558	590	623	656	689	722	754	787	820	853	886	918	951	984	1,017	1,050	1,082	1,115	1,148
68	504	538	571	605	638	672	706	739	773	806	840	874	907	941	974	1,008	1,042	1,075	1,109	1,142	1,176
72	516	550	585	619	654	688	722	757	791	826	860	894	929	963	998	1,032	1,066	1,101	1,135	1,170	1,204
76	528	563	598	634	669	704	739	774	810	845	880	915	950	986	1,021	1,056	1,091	1,126	1,162	1,197	
80	540	576	612	648	684	720	756	792	828	864	900	936	972	1,008	1,044	1,080	1,116	1,152	1,188		
84	552	589	626	662	699	736	773	810	846	883	920	957	994	1,030	1,067	1,104	1,141	1,178			
88	564	602	639	677	714	752	790	827	865	902	940	978	1,015	1,053	1,090	1,128	1,166				
92	576	614	653	691	730	768	806	845	883	922	960	998	1,037	1,075	1,114	1,152	1,190				
96	588	627	666	706	745	784	823	862	902	941	980	1,019	1,058	1,098	1,137	1,176					
100	600	640	680	720	760	800	840	880	920	960	1,000	1,040	1,080	1,120	1,160	1,200					
110	630	672	714	756	798	840	832	924	966	1,008	1,050	1,092	1,134	1,176	1,218						
120	660	704	748	792	836	880	924	968	1,012	1,056	1,100	1,144	1,188	1,232							
130	690	736	782	828	874	920	966	1,012	1,058	1,104	1,150	1,196	1,242	1,288							
140	720	768	816	864	912	960	1,008	1,056	1,104	1,152	1,200	1,248	1,296								
150	750	800	850	900	950	1,000	1,050	1,100	1,150	1,200	1,250	1,300	1,350								

Source: Wood Handbook

Outlook

- Density influences almost all properties of wood

- **Mechanical properties**:
  - Strength generally increases with density
- **Moisture**:
  - Higher density means lower porosity and generally less space for free water
- **Thermal properties:**
  - Thermal conductivity increases with density

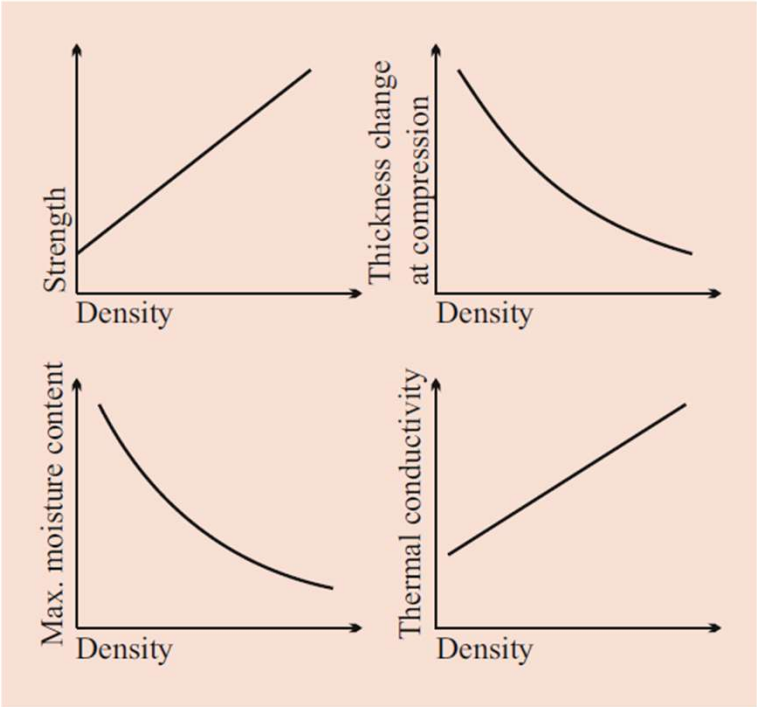


Fig. 6.22 Schematic representation of the influence of bulk density on selected properties of wood and wood-based materials

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