Eur. J. Wood Prod. (2013) 71:91–99
DOI 10.1007/s00107-012-0641-8

ORIGINALS ORIGINALARBEITEN

Investigations on the physical and mechanical behaviour of sycamore maple (*Acer pseudoplatanus* L.)

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Received: 19 March 2012 / Published online: 30 October 2012

Abstract Physical and mechanical properties of sycamore maple (*Acer pseudoplatanus* L.) were extensively investigated as basis for three-dimensional material modelling for structural simulations (e.g., with finite element method) based on this species. The physical properties of swelling, water absorption, water vapour resistance and thermal conductivity were tested and the mechanical properties of tensile, bending and compression strength and of Young's modulus (static and dynamic) as well as of Poisson's ratio, shear strength, shear modulus and fracture toughness were determined. The tests were carried out for most of the features depending on moisture content and also in all three anatomical main directions: longitudinal, radial and tangential.

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Untersuchungen zum physikalischen und mechanischen Verhalten von Bergahorn (*Acer pseudoplatanus* L.)

Zusammenfassung Die physikalischen und mechanischen Eigenschaften von Bergahorn (*Acer pseudoplatanus* L.) wurden eingehend untersucht, um eine Grundlage für eine dreidimensionale Materialmodellierung für Struktursimulationen (z.B. mit der Methode der finiten Elemente), basierend auf dieser Holzart, zu schaffen. Bei den physikalischen Eigenschaften wurden das Quellen, die Wasseraufnahme, der Wasserdampfdiffusionswiderstand und die Wärmeleitfähigkeit geprüft sowie bei den mechanischen Eigenschaften die Zug-, Biege- und Druckfestigkeit, der Elastizitätsmodul (statisch und dynamisch), die Poissonzahl, die Scherfestigkeit, der Schubmodul und die Bruchzähigkeit bestimmt. Die Untersuchungen wurden in den meisten Fällen feuchteabhängig durchgeführt und ebenso in allen drei anatomischen Hauptrichtungen: längs, radial und tangential.

1 Introduction

Sycamore or great maple (*Acer pseudoplatanus* L.) is one of the most common hardwoods in Central Europe. Already, its population in Switzerland adds up to 11.8 Mio m^3 according to the Swiss National Forest Inventory (Brändli 2010) and appears on the third position after beech (73.3 Mio m^3) and ash (14.8 Mio m^3). Due to the successive alteration of the forests culminating in a higher fraction of hardwood, a stronger forestry use of these wood species is required (Krackler et al. 2010).

Therefore, hardwood is among conventional applications like parquetry and interior joinery, furniture- and musical instrument-making more and more applied for wood constructions (glulam). Thereby, well-founded knowledge of the material properties of these species is even more necessary, and the calculation and simulation of material behaviour are increasingly carried out with the finite element method (for example, for calculation of boards). Therefore, among the strength properties, the complete elastic parameter set according to the generalised Hooke's law (3 moduli of elasticity (MOE), 3 shear moduli (G) and 6 Poisson's ratios within the three main directions longitudinal (L), radial (R) and tangential (T)) are required. In addition, the influence of moisture on the elastic and strength parameters has to be evaluated, and heat and moisture transport parameters (sorption, diffusion, thermal conductivity) as well as shrinkage and swelling are required. Analogously, the influences of grain angle (LR, LT) and ring angle (RT) on the parameters mentioned above have to be known. Ideally, also the parameters of the plastic deformation have to be known since this topic is increasingly studied (e.g., Schmidt 2009; Hering 2011). According to Eq. (1), the total strain consists of mechanical stresses and climatically induced stresses and is composed additively:

$$\varepsilon_{tot} = \varepsilon_{el} + \varepsilon_m + \varepsilon_{ms} + \varepsilon_{ve} + \varepsilon_{pl} \quad (1)$$

where $\varepsilon_{\mathrm{tot}}$ is the total strain, $\varepsilon_{\mathrm{el}}$ the elastic strain, ε_{m} the moisture induced strain, $\varepsilon_{\mathrm{ms}}$ the mechanical-sorptive strain, $\varepsilon_{\mathrm{ve}}$ the viscoelastic strain and $\varepsilon_{\mathrm{pl}}$ the plastic strain.

Altogether, very complex measurements are required to allocate all essential data for a numerical simulation. Supplementary, bonding, surface coating and overlay material as well as defects within the material like cracks and burrowing passages of wood insects influence the material behaviour.

Selected property parameters of hardwood have been published amongst others by Kollmann (1951), Bodig and Jayne (1993), Szalai (1994), Pozgaj et al. (1997), Sell (1997), Wagenführ (2007), Kurjatko (2010) and Ross (2011). But complete data sets for the three main wood directions rarely exist, which are sufficient for static calculations and modulations in wood construction and also for calculations on multi-layered boards, parquet or musical instruments with the finite element method. Mostly, investigations on tension, compression and bending are carried out only parallel to the grain, and the parameters for the other main directions (R, T) which are required for finite element calculations, as well as the influences of grain and ring angle are lacking. Equally, the influence of the load type (tension, compression, bending) and of MC on the elastic constants and the Poisson's ratio are scarcely investigated. Also for the rheological characteristics (creep, relaxation, mechanical-sorptive effects), the parameters are lacking for most parts. Certainly, Hering (2011) and Ozyhar et al. (2012) recently enforced detailed investigations on beech wood. For softwood, most investigations were carried out on Norway spruce as the most commonly used wood for construction (e.g., Neuhaus 1981). For sycamore maple, Wedel (1964) determined in detail swelling, tension, compression, bending, impact bending and shear properties in fibre direction (Table 1). Popper and Niemz (2009) tested and simulated the sorption of sycamore maple on the basis of the Hailwood–Horrobin model. A detailed description of the applications of sycamore maple is found by Wedel (1964) and Sonnabend (1989, 1990).

The aim of this work is to generate a preferable complete dataset of the physical and mechanical properties of sycamore maple. For the present, the rheological and mechanical-sorptive as well as plastic properties are left out whereupon continuing investigations are intended.

2 Materials and methods

2.1 Material

All test specimens for the determination of the physical and mechanical properties were cut from logs of a sycamore tree (*Acer pseudoplatanus* L.) of Eastern Switzerland with

Table 1 Mechanical parameters of sycamore maple in fibre direction from different references
Tab. 1 Mechanische Kennwerte von Bergahorn in Faserrichtung aus verschiedenen Literaturquellen

	Kollmann (1951)	Wedel[a] (1964)	Sell[b] (1997)	Wagenführ (2007)
Raw density (kg/m^3)	630	600 (650)[c]	610-660	530-630-790
Tensile strength (N/mm^2)	80	126 (131)	80-140	82-114
Bending strength (N/mm^2)	58-110-162	102 (108)	85-135	50-95-140
Compression strength (N/mm^2)	33-57-83	53 (55)	46-62	29-49-72
MOE (N/mm^2)	6300-9200-14900	10500 (10900)	9100-12000	6400-9400-15200
Impact bending strength (kJ/m^2)	64	52 (67)	64	65

[a] Values of Norway maple (*Acer platanoides* L.) in brackets
[b] Mixed values from sycamore and Norway maple
[c] Density at normal climate

a mean normal density of 626 kg/m^3 (at a MC of about 12 %) and oven-dry density of 563 kg/m^3.

The following physical properties were tested:

- Swelling
- Water absorption
- Water vapour resistance
- Thermal conductivity

The following mechanical properties were tested at the climates 20/35 (20 °C and 35 % relative humidity), 20/65, 20/85 and 20/95:

- Bending strength with static and dynamic MOE
- Tensile strength
- Compression strength
- MOE and Poisson's ratio from tensile and compression tests
- Dynamic MOE and shear modulus
- Shear strength
- Fracture toughness K_{IC}

2.2 Methods

2.2.1 *Determination of the physical properties*

2.2.1.1 Swelling The swelling ratio (differential swelling) was determined in L-, R- and T-directions between the climates 20/35 and 20/93 according to DIN 52184 1979-05. 34 specimens sized 20 mm (R) × 20 mm (T) × 100 mm (L) were used for the L-direction and 35 specimens sized 50 mm (R) × 50 mm (T) × 10 mm (L) for the R- and T-directions.

2.2.1.2 Water absorption The water absorption coefficient was determined in L-, R- and T-directions on cubes with a side length of 50 mm according to DIN EN ISO 15148 2003-03 (specimen number see Table 2). Four sides were varnished with a synthetic resin lacquer so that the water absorption took place only in one direction. The specimens were conditioned in normal climate (20/65) prior to the test. Then, the specimens were put on a grid 5 ± 2 mm deeply in a water bath and weighed after 5 and 20 min and 1, 2, 4, 8, 11 and 24 h. Thereof, the water absorption coefficient was determined according to Eq. (2) by means of a linear regression through the measured data (x-values: $t^{0.5}$, y-values: Δm)

$$A_w = \frac{\Delta m}{\sqrt{t}} \tag{2}$$

A_w Water absorption coefficient [kg/(m^2 s$^{0.5}$)]

Δm Mass gain per face area [kg/m^2]

t Time [s]

Table 2 Physical properties of sycamore maple
Tab. 2 Physikalische Kennwerte von Bergahorn

	Direction	No.	ρ (kg/m^3)	Mean value	V (%)
q (%/ %)	L	34	610	0.01	42
	R	35	600	0.20	12
	T	35	600	0.37	9.7
μ_{dry} (−)	R	6	620	45	2.1
	T	6	620	103	4.0
μ_{wet} (−)	R	6	630	15	2.8
	T	6	620	28	4.6
A_w [kg/(m^2 s$^{0.5}$)]	L	14	600	0.054	25
	R	15	600	0.0032	9.9
	T	17	600	0.0023	18
λ_{10} [W/(m K)]	–	4	650	0.143	6.9

q swelling ratio, μ_{dry}, μ_{wet} water vapour resistance factors at dry and wet conditions, A_w water absorption coefficient, λ_{10} thermal conductivity at 10 °C, *L* longitudinal, *R* radial, *T* tangential, *V* coefficient of variation, ρ density (climate: 20/65)

q differentielle Quellung, μ_{dry}, μ_{wet} Wasserdampfdiffusionswiderstandszahlen im trockenen (dry) und feuchten (wet) Bereich, A_w Wasseraufnahmekoeffizient, λ_{10} Wärmeleitfähigkeit bei 10 °C, *L* in Faserrichtung, *R* radial, *T* tangential, *V* Variationskoeffizient, ρ Rohdichte (Klima: 20/65)

2.2.1.3 Water vapour resistance The water vapour resistance factor was determined according to DIN EN ISO 12572 2001-09 in R- and T-direction at dry (20 °C—65/0 % RH) and wet (20 °C—65/100 % RH) conditions. Six specimens with a cross-section of 140 mm and a thickness of 20 mm were tested per climate and direction.

2.2.1.4 Thermal conductivity Thermal conductivity was tested perpendicular to the grain on four solid-wood boards (size: 500 × 500 × 20 mm) with the guarded hot plate apparatus λ-Meter EP500 (Lambda-Messtechnik GmbH, Dresden) according to ISO 8302 (1991). The specimens were conditioned at the climates 20/35, 20/65, 20/85, 20/95 and oven-dried. After each conditioning, thermal conductivity was measured at three temperatures (10, 20 and 30 °C) each with a temperature difference of 10 K between the hot and the cold plate and a surface pressure of 2,500 N/m^2. The fitted thermal conductivity at 10 °C was then determined by the evaluation software EP 500_PC 5.14 with a linear regression through the values at the three temperatures.

2.2.2 *Determination of the mechanical properties*

2.2.2.1 Bending strength and static and dynamic MOE Bending strength and static modulus of elasticity (MOE) were determined according to DIN 52186 1978-06 on 18-26 specimens sized 20 mm (R) × 20 mm

(T) × 400 mm (L). Previously, sound velocity and eigenfrequency were tested on the same specimens using an ultrasound device (BP-V, 50 kHz, Steinkamp, Bremen) and an impulse excitation tester (Grindosonic MK 5 'Industrial', Lemmens N. V., Belgium). Then, the dynamic MOE was calculated from sound velocity (c) and density (ρ) with the basic relation:

$$E = \rho \cdot c^2 \quad (3)$$

and from eigenfrequency (first flexural mode) according to the method of Görlacher (1984).

2.2.2.2 Tensile strength Tensile strength was determined parallel to the grain according to DIN 52187 1979-05. Perpendicular to the grain, 95 mm long dog-bone-shaped specimens (cross-sectional area: max. 28 × 28 mm, min. 14 × 14 mm) were used according to Hering et al. (2012). 13–16 specimens were tested per direction and climate.

2.2.2.3 Compression strength Compression strength parallel to the grain was determined according to DIN 52185 1976-09 and perpendicular to the grain according to DIN 52192 1979-05. Deviating from the norm, reduced specimen size (15 × 15 × 45 mm) was employed. 16–21 specimens were tested per direction and climate.

2.2.2.4 MOE and Poisson's ratio from tensile and compression tests MOE and Poisson's ratio were determined on the tensile and compression test specimens by means of a video image correlation system (Vic 2D, LIMESS Messtechnik und Software GmbH, Krefeld) for the determination of the longitudinal and transverse elongation. The method is described in detail by Keunecke et al. (2008) and Hering et al. (2012). The Poisson's ratio was determined according to

$$\mu_{ij} = -\frac{\varepsilon_i}{\varepsilon_j} \quad (4)$$

where μ_{ij} is Poisson's ratio, ε_i the transverse elongation and ε_j the longitudinal elongation.

2.2.2.5 Dynamic MOE and shear modulus Dynamic MOE and shear modulus were determined on cubes with a side length of 10 mm by means of ultrasound. 36–42 specimens were tested per climate. The tests were carried out using an Epoch XT device (Olympus NDT Inc., USA) with an Olympus A133S transducer (2.27 MHz) for longitudinal waves (determination of MOE) and a Staveley S-0104 transducer (1 MHz) for transverse waves (determination of G) and the coupling agent Ultragel II (Sonotech, USA). The MOE was determined according to Eq. (3) and the shear modulus (G) according to

$$G_{ij} = c_{ij}^2 \cdot \rho \quad (5)$$

where c is the sound velocity and ρ the density. Thereby, as for the calculation of G from sound velocity, the directions of wave propagation (first index) and oscillation (second index) are exchangeable for an orthotropic material, the values of G_{ij} and G_{ji} were averaged. For more details see Keunecke et al. (2007).

2.2.2.6 Shear strength Shear strength was tested parallel (shearing planes: LT, LR) and perpendicular to the grain (shearing planes: RL, TL) on cubes with a side length of 50 mm according to DIN 52187 1979-05. 8–10 specimens were tested per direction and climate.

2.2.2.7 Fracture toughness K_{IC} Fracture toughness K_{IC} was determined according to DIN EN ISO 12737 2011-04 on compact specimens at RL, TL, RT and TR directions (first index = direction normal to the crack plane, second index = direction of crack propagation). 5–14 specimens were tested per direction and climate.

The static tests were carried out with a Zwick Z010 universal testing machine (Zwick GmbH & Co. KG, Ulm) for tension and compression perpendicular to the grain as well as fracture toughness and a Zwick Z100 machine for tension, bending and compression parallel to the grain as well as shearing.

3 Results and discussion

3.1 Physical properties

The physical properties of sycamore maple are shown in Table 2.

3.1.1 Swelling

Differential swelling was determined for the directions L:R:T at a ratio of 1:20:37. Perpendicular to the grain, the values are about one-third higher than literature data. Sell (1997), for example, stated 0.15 %/% for R and 0.27 %/% for T which are similar to the values of Wagenführ (2007). This demonstrates the high natural variability of this species.

3.1.2 Water absorption

The water absorption coefficient is highly influenced by the direction. Parallel to the fibre, the measured value is 24 times higher than in T-direction and 16 times higher than in R-direction. Whereas the values perpendicular to the grain are similar to the values of other hardwoods like beech or ash, the value in fibre direction is two to four times higher (Sonderegger et al. 2012). Perpendicular to the grain, the water absorption coefficient is higher in R-direction than in T-direction what is mainly influenced by the rays.

3.1.3 Water vapour resistance

The water vapour resistance factor is highly influenced by the direction and is in T-direction twice as high as in R-direction both at dry and wet conditions (Table 2). This may be attributed to the influence of the rays in the R-direction. At dry conditions, the value in both directions is about thrice as high than at wet conditions.

3.1.4 Thermal conductivity

The thermal conductivity perpendicular to the grain accounts for 0.143 W/(m K) at 10 °C after conditioning at normal climate (20/65) and is slightly lower than the value in Kollmann (1951) for wood in general at a density of 650 kg/m^3 and clearly lower than the values of maple in Sell (1997) with 0.16–0.18 W/(m K). The thermal conductivity increases with increasing temperature at about 0.3 % per 1 K and with increasing MC at about 1.4 % per 1 % MC change (Fig. 1).

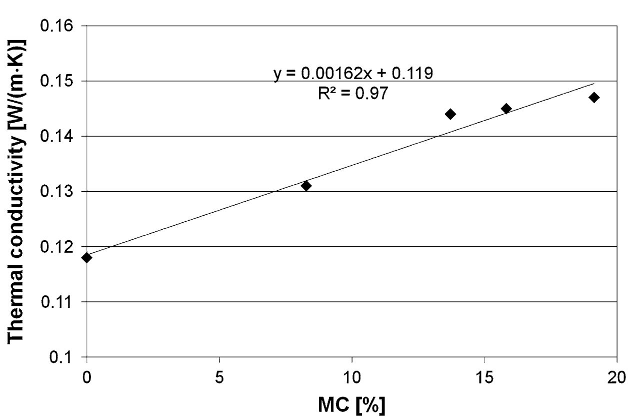

Fig. 1 Thermal conductivity perpendicular to the grain depending on moisture content (MC)
Abb. 1 Wärmeleitfähigkeit senkrecht zur Faserrichtung in Abhängigkeit von der Holzfeuchte (MC)

3.2 Mechanical properties

3.2.1 Tensile, bending and compression tests

Table 3 and Figs. 2 and 3 show the test results. The strength is highly influenced both by the test mode and the wood direction. Parallel to the fibre, the ratio of tensile strength to bending and compression strength is at normal climate about 1.8:1.7:1 and corresponds well with the literature data of Table 1. The influence of MC within the tested RH-range is least for tensile strength (reduction of about 10 %) whereas bending strength is reduced by about one-third and compression strength by about 40 % (Fig. 2a). Perpendicular to the grain, in contrast only small differences exist between tensile and compression strength. All values are reduced with increasing MC by about one-third (Fig. 2b). For the wood directions at normal climate, the strength ratio of L, R, T is 13:1.8:1 for tension and for compression it is 6:1.5:1.

In contrast to strength, the MOEs parallel to the fibre show rather different ratios with regard to the test mode (Fig. 3a). The highest MOE was determined at compression whereas bending MOEs were similar to tensile MOEs except for the climate 20/35. An explanation of the high compression MOE may be the influence of the bimodularity of the material (Conners and Medvecz 1992) which

Table 3 Mechanical properties of sycamore maple at climate 20/65
Tab. 3 Mechanische Kennwerte von Bergahorn bei Klima 20/65

	Direction	No.	ρ (kg/m^3)	Mean value	V (%)
σ_t (N/mm^2)	L	15	630	112	20
	R	14	630	16.2	8.8
	T	15	630	8.9	7.2
σ_b (N/mm^2)	L	18	630	102	7.8
σ_c (N/mm^2)	L	19	660	61.5	6.1
	R	16	660	15.4	4.7
	T	21	660	10.3	5.4
MOE_t (N/mm^2)	L	15	630	11,500	24
	R	15	630	1,210	10
	T	15	630	690	3.8
MOE_b (N/mm^2)	L	18	630	10,900	16
MOE_c (N/mm^2)	L	15	660	14,500	22
	R	19	660	1,140	15
	T	16	660	790	3.9
τ (N/mm^2)	LT	10	630	17.9	5.6
	LR	9	610	14.3	2.0
	RL	9	650	7.3	12
	TL	9	590	6.6	11
K_{IC} (MPa m$^{0.5}$)	RL	6	670	1.08	18
	TL	9	620	0.70	11
	RT	6	690	0.91	11
	TR	7	590	0.54	17

σ strength in tension (t), bending (b) and compression (c), *MOE* modulus of elasticity, τ shear strength, K_{IC} critical stress intensity factor, *L* longitudinal, *R* radial, *T* tangential, ρ density, *V* coefficient of variation

σ Festigkeit bei Zug (t), Biegung (b) und Druck (c), *MOE* Elastizitätsmodul, τ Scherfestigkeit, K_{IC} Bruchzähigkeit, *L* in Faserrichtung, *R* radial, *T* tangential, ρ Rohdichte, *V* Variationskoeffizient

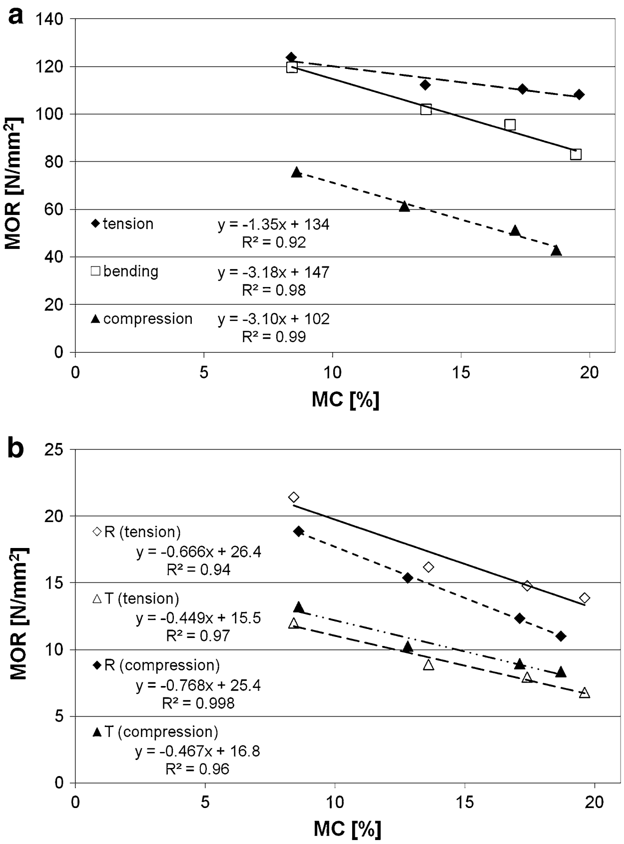

Fig. 2 MOR in L-direction (**a**) and in R- and T-direction (**b**) depending on moisture content (MC)
Abb. 2 Festigkeiten (MOR) in L-Richtung (**a**) sowie in R- und T-Richtung (**b**) in Abhängigkeit von der Holzfeuchte (MC)

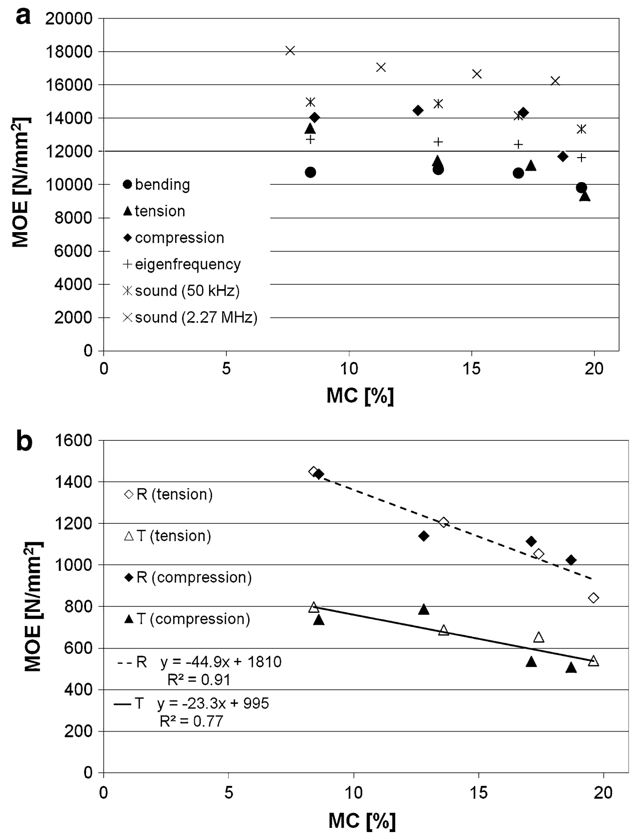

Fig. 3 Modulus of elasticity (MOE) in L-direction (**a**) and in R- and T-direction (**b**) depending on moisture content (MC)
Abb. 3 Elastizitätsmodul (MOE) in L-Richtung (**a**) sowie in R- und T-Richtung (**b**) in Abhängigkeit von der Holzfeuchte (MC)

differs according to the wood species. Conners and Medvecz (1992) show similar behaviour for yellow poplar where the compression MOE (in contrast to the tensile MOE) increases from 6 to 12 % MC and exceeds the tensile MOE by between 6 and 18 % MC. The dynamic MOEs determined from eigenfrequency and sound velocity are clearly higher with a ratio of 1.17 and 1.36, respectively (mean value over all climates) compared to bending MOE. This effect is amongst others influenced by the wood species and wood quality. The ratios are slightly higher than the ones determined for different hardwoods and softwoods in Niemz et al. (1997). For the MOE determined from sound velocity (2.27 MHz) on the cubic specimens, the ratio was again clearly higher with 1.61. The influence of MC on MOE is with the exception of tension lower compared to strength. For bending and compression, the MOE remains constant or even increases with increasing MC until a climate of 20/85. Perpendicular to the grain, there are only small differences between

Table 4 Modulus of elasticity (MOE) and shear modulus (G) at normal climate (20/65) calculated from ultrasound of cubic specimens and its sensitivity from MC (ω) according to equation MOE (or G) = A + B · ω
Tab. 4 E-Modul (MOE) und G-Modul (G) im Normalklima (20/65) ermittelt aus Ultraschallmessungen an Würfelproben sowie deren Abhängigkeit von der Holzfeuchte (ω) gemäß der Gleichung MOE (bzw. G) = A + B · ω

	Direction	Moduli (N/mm^2)	V (%)	A	B	R^2
MOE	L	17,100	3.7	19,100	−160	0.95
	R	2,910	7.6	3,610	−58.1	0.96
	T	1,740	10.4	2,030	−24.2	0.98
G	LR	1,680	14.6	1,720	−10.9	0.43
	LT	1,070	12.0	1,150	−7.69	0.85
	RT	366	9.8	414	−4.68	0.97

A, B parameters, *V* coefficient of variation, R^2 coefficient of determination

A, B Parameter, *V* Variationskoeffizient, R^2 Bestimmtheitsmaß

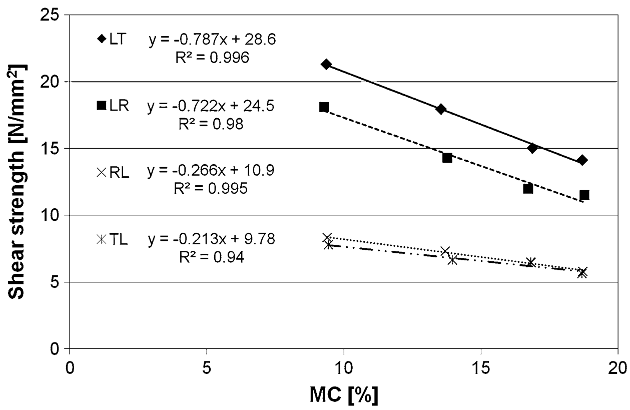

Fig. 4 Shear strength depending on moisture content (MC)
Abb. 4 Scherfestigkeit in Abhängigkeit von der Holzfeuchte (MC)

tensile and compression MOE (Fig. 3b). The decrease of MOE with increasing MC is similar to the decrease in strength.

3.2.2 Dynamic MOE and shear modulus

Table 4 shows the dynamic MOE and shear moduli determined from the sound velocities on the cubic specimens. Whereas the MOEs in all directions have clearly higher values (up to 2.5 times higher) than the MOEs of the static tests (due to the specimen size and height of the test frequency as well as the non-consideration of the lateral contraction influence), the shear moduli are arranged within the expectancy range. Hering et al. (2012) described similar effects on beech wood. The ratio of the MOEs in the directions L:R:T account for 9.8:1.7:1 and of the shear moduli in the shearing planes LT:LR:RT for 4.5:2.9:1. Thereby, the clearly higher values in R-direction than in T-direction can be attributed to the reinforcing effect of the rays.

3.2.3 Shear strength

The shear strength depends strongly on the test direction (Table 3). Parallel to the grain, the values were two to three times higher than perpendicular to the grain and in the LT-plane clearly higher than in the LR-plane. Perpendicular to the grain, the values of the two measured shearing planes hardly differ. Hering (2011) measured similar values by trend but all in all slightly smaller values for beech wood. For all tested directions, a strong correlation exists between shear strength and MC. Thereby, shear strength decreases with increasing MC stronger parallel to the grain than perpendicular to the grain (Fig. 4).

3.2.4 Poisson's ratio

Table 5 shows the Poisson's ratio (μ) at normal climate (20/65) determined from the tension and compression tests, the dependence on MC by means of a linear regression and comparative literature data. At normal climate, the values from the tension and compression tests differ only little except for the RL and LR directions. The mean Poisson's ratios from tension and compression over all climates coincide quite well with values determined by Stamer and Sieglerschmidt in Kollmann (1951) for sycamore maple and with values of Bodig and Jayne (1993) for hardwood. The influence of MC on Poisson's ratio is not uniform so that the values increase or decrease depending on the direction. Certainly, the coefficient of determination is partially very small too. In contrast, Hering et al. (2012) observed for beech a decrease of Poisson's ratio with increasing MC in all directions.

Table 5 Poisson's ratio (μ) at normal climate (20/65) for tension and compression and its sensitivity from MC (ω) according to equation $\mu = A + B \cdot \omega$
Tab. 5 Poissonzahlen (μ) im Normalklima (20/65) für Zug und Druck sowie deren Abhängigkeit von der Holzfeuchte (ω) gemäß der Gleichung $\mu = A + B \cdot \omega$

	Tension					Compression					Mean	Literature data	
Direction	μ [−]	V (%)	A	B	R^2	μ (−)	V (%)	A	B	R^2	μ (−)	μ^a (−)	μ^b (−)
RL	0.49	15	0.502	−0.0013	0.20	0.34	44	0.276	0.0060	0.22	0.42	0.49	0.37
TL	–	–	–	–	–	0.42	31	0.470	−0.0022	0.32	0.44	0.47	0.50
TR	0.65	4.3	0.434	0.0168	0.98	0.68	11	0.594	0.0071	0.98	0.69	0.76	0.67
LR	0.059	36	0.048	0.0010	0.93	0.16	32	0.239	−0.0082	0.74	0.091	0.074	0.044
RT	0.38	9.7	0.312	0.0049	0.97	0.40	6.9	0.411	−0.0013	0.31	0.39	0.44	0.33
LT	0.043	30	0.056	−0.0010	0.83	0.049	53	0.161	−0.0055	0.46	0.061	0.041	0.027

A, B parameters, *V* coefficient of variation, R^2 coefficient of determination

A, B Parameter, *V* Variationskoeffizient, R^2 Bestimmtheitsmaß

[a] Sycamore maple (MC = 9.6): Stamer and Sieglerschmidt in Kollmann (1951)

[b] Hardwood: Bodig and Jayne (1993)

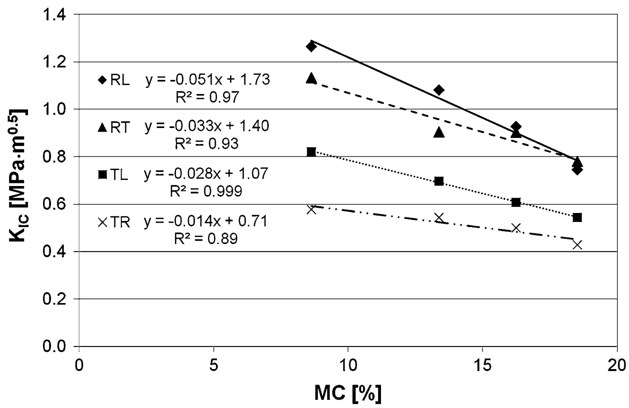

Fig. 5 Fracture toughness (K_{IC}) depending on moisture content (MC)
Abb. 5 Bruchzähigkeit (K_{IC}) in Abhängigkeit von der Holzfeuchte (MC)

3.2.5 Fracture toughness

Table 3 shows the fracture toughness K_{IC} of the different loads at climate 20/65. The values are very high compared with other wood species like oak and beech and also higher compared to sugar maple (Stanzl-Tschegg et al. 2011) and are in the RL and TL directions similar to ash (Reiterer et al. 2002). The tests in the RL and RT directions result in clearly higher values compared to the TL and TR directions which can be attributed to the influence of the rays. The fracture toughness within a crack plane was higher for a crack propagation in fibre direction than perpendicular to the grain what is in contrast with the behaviour of different soft woods (Stanzl-Tschegg et al. 2011). All K_{IC} values are highly influenced by MC with the highest percentage decrease in the RL and TL directions (Fig. 5). In contrast, Logemann and Schelling (1992) found only a low influence of MC for spruce in the TL direction.

4 Conclusion

A broad dataset of physical and mechanical properties in the three main directions was established for the wood of sycamore maple. Up to now, such complex datasets for hardwoods have been hardly available but become more and more important parallel to the increasing silvicultural availability of these species. The dataset allows within the elastic range the calculation and simulation of multi-layered and three-dimensional wood structures with finite element methods. Still, investigations have to be carried out to determine the rheological properties and the mechanical-sorptive behaviour. Equally, further research is needed to analyse the plastic behaviour which particularly is important by compression perpendicular to the fibre. Investigations by Hering (2011) and Schmidt (2009) could provide a basis.

Acknowledgments The authors thank the Händel-Haus foundation, Halle for the co-financing of this work.

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