Fundamentals of Wood Moisture Content Measurement

Overview
• Wood Structure
• Wood moisture content
• Measurement methods
  • Direct measurement methods
  • Ovendry method
  • Indirect measurement methods
  • Conductance method
  • Capacitance method
  • Electric moisture meters – a comparison
  • Checklist for usage of electric moisture meters
  • Hygrometrical method

Wood Structure

Macroscopic View
• a cross section of a tree trunk shows different wood tissue areas
• green wood always contains water
• sawn wood (timber, boards, beams ...) is cut from the trunk part between cambium and pith, i.e., the xylem, covering sapwood and heartwood
• more visible details are growth rings or annual rings consisting of earlywood and latewood

Typical attributes ...
• inhomogeneous,
• anisotropic,
• porous and
• hygroscopic material

Main anatomical directions of wood
L — longitudinal, T — tangential, R — radial

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Wood Structure

Microscopic View

White Oak: ring-porous hard-wood species, clearly defined annual rings, vessels partially closed by tyloses, latewood vessels radially oriented, very wide and large rays

Birch: EW/LW-transition continuously, diffuse-porous, fine undulated rays

White Oak, clearly defined growth ring border by vessel size, vessels partially filled with tyloses, very large earlywood vessels (200x 200x)

Softwood - SEM-Picture

Spruce: clearly separated EW/LW zones, very large earlywood vessels by vessel size, vessels partially filled with tyloses, S2 region

Morphology of cellulose in the cell wall

- Elementar fibril – Microfibril – Fibril
- Bundles of cellulose-macromolecules with amorphous and crystalline regions and absorbed and attached water molecules
- Particular orientation of fibrils in different cell wall layers = fibril angle

Wood Structure

Microscopic View

Softwood - SEM-Picture

Lignified heartwood section with layered wall structure and intercellular spaces (250x 250x)
Wood Structure

**Chemical composition of wood**

- Carbon (C): 49%
- Hydrogen (H): 6%
- Oxygen (O): 44%
- Nitrogen (N): < 1%
- Inorganic elements (Na, K, Ca, Mg, Si): < 1%

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**Molecular composition of wood**

- **Main Components**
  - Extractives: 5%
- **Resins**
  - Polyaccharides: 45–61%
- **Lignin**
  - 6–91%
- **Cellulose**
  - 40–50%
- **Hemicelluloses**
  - 6–27%

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**Wood Moisture Content**

**Moisture content**

- Green wood and wood in use always contains more or less water
- Water in wood exists as liquid water, as water vapour (a part of humid air) and/or as bound water
- Limit states:
  - Absolute dry (\(u = 0\%\)), oven dried, as dry as a bone
  - Water-saturated (\(u_{\text{sat}}\)), depending on void volume

\[
\begin{align*}
\text{Bound water} & = u_{\text{sat}} \times \text{Free water} \\
\text{Hygroscopic range} & = \text{Swelling and or shrinking of wood}
\end{align*}
\]

**Definition**

\[
u = \left( \frac{m_2 - m_1}{m_2} \right) \times 100 = \left( \frac{m_0 - m_1}{m_0} \right) \times 100 \%
\]

with:
- \(m_1\): mass oven dried wood sample
- \(m_2\): mass wet wood sample
- \(m_0\): mass water in wood sample

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**Wood Water Content**

**Water content**

- Is the amount of water in wet materials related to the mass of the wet substance – in contrast with mc the reference quantity is the absolute dry sample mass
- Limit states:
  - Absolute dry (\(x = 0\%\))
  - Water-saturated (\(x < 100\%\))

**Definition**

\[
x = \left( \frac{m_0 - m_1}{m_0} \right) \times 100 = \left( \frac{m_2 - m_1}{m_2} \right) \times 100 \%
\]
Measurement of Material Moisture Content

Water content or moisture content determination
- physical methods
- chemical methods (analytical methods)

Classification of measurement methods

Direct Measurement Methods
- Thermogravimetric Methods
- Analytical Methods

Indirect Measurement Methods
- Electrical Methods
- Optical Methods
- Radiometric Methods
- Thermal Methods
- Acoustical Methods

KEYLWERT
Classification of measurement methods
Kupfer et al. 1997

Oven Dry Method ... acc. to DIN EN 13 183-1:2002

Required equipment
- Suitable balance, accuracy 0.1% of sample weight
- Drying chamber / dry box, temperature range (103 ± 3) °C
- Suitable cutting tools for sampling, e.g. saw, knife ...
- Airtight container for samples, e.g. plastic bags ... if no balance is available when taking samples
Oven Dry Method … acc. to DIN EN 13183-1:2002

Measuring procedure
1. Sampling (any shape) and immediate mass determination \( m_1 \) [g], weighing accuracy 0,1 % of \( m_1 \).
2. Oven drying in heating chamber at (103 ± 3)° C until constant weight
3. Const. weight is achieved, when the mass difference between two sequential weighings at an interval of 6 h is less than 0,1 % of \( m_1 \) [g]
4. Calculation: \[ u = \frac{m_2 - m_0}{m_0} \cdot 100 \text{ [%]} \]
   \( \forall \) for field tests or if no balance is available samples should be stored temporarily in airtight plastic bags with suitable closures

Accuracy ± 0,1 % mc !

Possible errors … despite of errors in reading the balance or the thermometer, set point errors of the equipment etc. …
1. Initial weight inaccurate due to moisture losses during sampling
   \( m_1 \) to low \( \Rightarrow \) determined mc < true mc
2. Constant weight not achieved at final weight determination
   \( m_0 \) to high \( \Rightarrow \) determined mc > true mc
3. Wood species containing resin \( m_0 \) to low due to loss of volatile components of the extractives \( \Rightarrow \) determined mc > true mc

Remedial measures:
\( \forall \) „Drying“ in vacuum, decreasing boiling point with \( p_{\text{abs}} \) < 1 bar !
\( \forall \) Chemical Drying by means of suitable desiccants, e.g., \( \mathrm{P}_2\mathrm{O}_5 \)
in an exsiccator at ambient room temperature

Advantages
- low requirements concerning measurement technology
- relative inexpensive method

The oven dry method acc. to DIN EN 13183-1 is the reference method for juridical disputes regarding wood moisture content problems

Disadvantages
- destructive testing method
- time consuming (20 ... 60 h)
- thorough accurate sampling required
- restricted accuracy due to volatile extractives (absolute error up to 5 ... 10 %) and beginning thermal degradation (hydrolysis) with drying at required temperature
- constant final weight – absolute dry state – will never be achieved ...

Absolute water content in humid air at 100°C > 0 kg/kg !

Direct measurement methods
Oven Dry Method using Infrared Radiation

Required equipment and procedure

- Suitable balance (accuracy 0.1% of sample weight) with integrated infrared heating device; gauge scale is directly indicating material moisture content
- Representative sampling of wood chips or particles directly taken from truck load or wood yard (e.g., chain saw dust) ... raw materials for wood based panels industry
- Predefined amount of wooden particles, e.g., ... 60...120 g, are irradiated by the IR-bulb until the final state, i.e., constant weight is attained
- Sufficient accuracy for moisture content determination, e.g., in the wood based panel industry, where the raw material is purchased on dry weight basis

* Not to be confused with the infrared-reflection or the infrared-absorption method: both are indirect measurement methods, used, e.g., in wood based panel industry.

Oven Dry Method using Infrared Radiation

**Equipment**

Moisture Tester ULTRA X 2081

Moisture Tester ULTRA X 2081

(http://www.apinstruments.de/... 05.10.2006)

Direct measurement methods

Indirect Measurement Methods

- Electrical Methods
  - Capacitance Method
  - Microwave Method
- Radiometric Methods
  - Neutron ray Method
  - X-ray Method
- Ultrasonic Methods
  - Ultrasonic Absorption Method
- Thermal Methods
  - Infractrometric Method
  - Nuclear Resonance Method
- Neutron ray Methods
  - Time-Domain Reflectometry
  - Amplitude Domain Reflectometry
  - Frequency Domain Reflectometry
- Nuclear Methods
  - Neutron-activation Method
- Other Methods
  - Material Neutron Activation Method
  - Material Equilibration Method

(Kupfer et al. 1997)
Conductance Method

**Electric conductance ... electric resistance of wood**

\[ R = \rho \frac{l}{A} \]

Some typical conductance values (at 25°C)

- silver: 62·10⁻⁸ S/m
- aluminium: 37·7·10⁻⁸ S/m
- iron: 9·93·10⁻⁸ S/m
- brass: 15·5·10⁻⁸ S/m
- stainless steel: 1·4·10⁻⁷ S/m
- sea water: ~ 5·10⁻⁵ S/m
- drinking water: ~ 5·10⁻⁴ S/m (at 25°C)
- distilled water: ~ 5·10⁻⁵ S/m (at 25°C)

**Conductance Method**

\[ R = \frac{\rho l}{A} \]

\[ \rho = \frac{R A}{l} \]

**Indirect measurement methods**

- moisture meters
- diagram

**Empirical testing**

- In the range 0 ≤ u ≤ u₀ (%FSP) the electric resistance varies between about 10⁷ and 10¹¹ Ω (≤ 10⁹ Ω ... 10ⁱ² Ω)
- In a semi-logarithmic scale the relation between wood moisture content and resistance is almost linear
- Above u₀ (%FSP) this dependency decreases rapidly

**Checklist for use of moisture meters**

- Some typical conductance values
- Non-conductor

**Empirical determination**

\[ R_0 = \frac{1}{u} \]

\[ R_0 = 100 \mathrm{M} \Omega \]

\[ u = (15 \pm 1) \% \]
Conductance Method

Temperature influence: $R = f(u, \theta, \delta)$

- Electric conductance increases as temperature of wood increases, opposite to the temperature effect on resistance in metals.
- For $u > 10\%$ the conductance is roughly doubled for $\Delta T = 10\,^\circ\mathrm{C}$.

Temperature correction is absolutely necessary for accurate $mc$ measurement (acc to W. L. James 1988).

Grain angle influence: $R = f(u, \theta, \delta)$

According to W. L. James (1988):
- Conductance parallel to grain $\approx 2 \, k_e$
- Conductance perpendicular to grain $k_e$
- Conductance $k_{\text{eff}} = 0.065 \, k_e$
- Conductance $k_{\text{eff}} = 0.5 \, k_e$

Other factors influencing $R = f(u, \theta, \delta, \ldots)$

Wood density, content of extractives, porosity etc. also may have an influence on the measurement result with the conductance method. In practice this requires:
- at least grouping similar wood species according to comparable properties leading to a specific calibration functions for the group, or,
- an individual calibration curve for each individual wood species.
**Conductance Method**

**Electric resistance and wood moisture content**

- Series connection of $R_i$
- Parallel connection of $R_i$

$$R_{tot} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}}$$

With non-insulated pin electrodes, the wettest layers determine the measurement result. Attention has to be paid to rewetted surfaces (= rain, condensation, spray water).

**Conductance Method acc. to DIN EN 13 183-2:2002**

**Conductance-type moisture meters**
- Portable instruments, battery-operated
- Direct reading-meter: analogue or digital
- Calibrated in % mc for individual species (spec. group)
- Species selection according to external table or built-in selection of reference function (curve)
- Built-in correction for true wood temperature
- Measurement direction || or ⊥ to grain

**Limiting conditions**
- Repeatability: conductance measurement only in the range $4 \leq u \leq 22$% ± linear relation between resistance and mc
- Accuracy: within this range ± 1.0...1.5% absolute
- Extended range up to FSP ($u_{fs}$) with decreasing accuracy
- Above FSP ($u_{fs}$) significantly limited measurement repeatability; an indicated mc-reading is more or less a rough guess!

**Conductance Method acc. to DIN EN 13 183-2:2002**

**Conductance-type moisture meters**
- Sample = resistance in an electric circuit; contact via suitable electrodes:
  - Surface-contact electrodes
  - (Penetrating) pin-type electrodes
  - Nail-like pins without insulation
  - Insulated pins
  - Flat, insulated pin electrodes
Conductance Method acc. to DIN EN 13 183-2:2002

Conductance-type moisture meters
Some features of the Brookhuis FMD6:
- Different calibration lines for wood and other building materials – programmable calibration line
- Temperature correction for wood from -40 ... +90°C, steps ΔT = 1K
- Measuring range 5% – 99% (wood) and 0% – 99% (building materials)
- Measuring accuracy 0.2% (reference material)
- Measuring depth depends on pin length
- Memory function – storage up to 75 reports / 2000 measuring values
- Automatic clock
- Built-in statistics (avg., min., max., Std., CV)
- Data transfer / communication with PC via serial interface and particular software

Possible faults and measurement errors due to...
- No or wrong temperature adjustment and wood species selection
- Liquid water on sample surface ⇒ high conductance ⇒ high indicated mc
- Measurement parallel / perpendicular to grain ⇒ small differences between indicated mc
- Moisture content more / less above fibre saturation (FSP)
- Meter in bad maintenance condition
- Damaged pin-shaft insulation
- Bent / twisted pins
- Corroded pins – if not from stainless steel
- Damaged cables and / or connectors
- Low battery

Indirect measurement methods

Capacitive Method

Material behaviour in an electromagnetic field
- Alternating current circuit
- Dielectric constant / permittivity of a material
  \[
  \varepsilon = \frac{\varepsilon_{\text{air or vacuum}}}{\varepsilon_{\text{wet material}}} \quad [\text{[-]}]
  \]
  \( \varepsilon \), a measure, how much electric potential energy is stored in the material when it is placed in a particular electric field
- Wood (oven dry): \( \varepsilon = 2.5 \, \varepsilon_0 \)
- Water: \( \varepsilon = 80 \varepsilon_0 \)
- Temperature and frequency dependence of \( \varepsilon \)
- Significant material density influence on measurement

\( \varepsilon_0 \): Permittivity of vacuum
\( \varepsilon_0 = 8.854 \times 10^{-12} \text{F/m} \)
\( \varepsilon_r \): Relative permittivity
\( \varepsilon = \varepsilon_0 \varepsilon_r \)
\( \varepsilon \): Dielectric constant
\( A \): m² capacitor area
\( d \): Plate distance
\( C \): Capacitance
Capacitive Method

Dielectric constant
- dielectric constant / permittivity of water depends on the water condition, e.g.,
  - free water, adsorbed water, ice, water vapour ...

Effect of moisture content
- ε ↑ with mc
- with decreasing frequency the effect of mc is much greater
- ε linear relation between mc and log ε at all frequencies; slope of this relation with 1/f

Effect of density
- ε ↑ nearly linear with ↑ ρ
- ρ = f(mc) ...
- ρ = f(p)

Power factor
- a dielectric material in an oscillating electric field at constant frequency will absorb energy from the field power proportional to the product of the frequency and the power factor resp. the loss factor d₀

\[ d₀ = \tan δ = \frac{1}{\kappa} \cdot \frac{R}{C} \cdot f \]

Relative permittivity of some substances at 18°C and 50 Hz, if not otherwise indicated

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Capacitive Method

Dielectric constant and power factor (acc. to W. L. James 1988)

Effect of moisture content
- ε ↑ with mc
- with decreasing frequency the effect of mc is much greater
- ε linear relation between mc and log ε at all frequencies; slope of this relation with 1/f

Effect of density
- ε ↑ nearly linear with ↑ ρ
- ρ = f(mc) ...
- ρ = f(p)

\[ d₀ = \tan δ = \frac{1}{\kappa} \cdot \frac{R}{C} \cdot f \]
Capacitive Method

Dielectric constant and power factor

Effect of density on capacitance moisture meter readings

Regressions for mc readings and actual mc for Scots Pine at different densities (acc. to Panhuis, Tarpallanen 2000, p. 28)

Effect of temperature

- \( \varepsilon \) \( \uparrow \) or \( \downarrow \) with \( \uparrow \) \( \vartheta \) depending on mc and f

Effect of species

- Species with comparable densities have similar electric properties, exceptions are, e.g., species with large concentrations of soluble salts and other electrolytes ...

Capacitive Method acc. to DIN EN 13 183-3:2002

Capacitance-type meters (from W. L. James 1988)

- The wood specimen is penetrated by the electric field associated with the capacitor of the frequency determining circuit of an oscillator when the electrode of the meter contacts the wood.
- The frequency of the oscillator is changed according to the effect of the specimen on the capacitance of this capacitor, i.e., according to the dielectric constant of the specimen.
- A frequency discriminator generates a signal, read on a meter, proportional to the changes in frequency. Using the relation between dielectric constant and moisture, the meter can be calibrated to read moisture content.
Capacitive Method acc. to DIN EN 13 183-3:2002

**Power-loss type moisture meters** (from W. L. James 1988)

- The wood specimen is penetrated by the electric field radiating from an electrode that is coupled to a low-power oscillator in the meter.
- Power absorbed by the specimen loads the oscillator and reduces its amplitude of oscillation, which is in turn indicated by the meter dial. Since the loss factor depends on moisture content, the meter dial can be related to percent moisture.

**Capacitive-admittance type moisture meters** (from W. L. James 1988)

- The electrode of this meter is a capacitive element in a resistance-capacitance bridge circuit. When a wood specimen contacts the electrode, its capacitance and losses (admittance) are increased so that the bridge is unbalanced in proportion to the dielectric constant and loss factor of the specimen. The meter dial reads the amount of bridge imbalance, which can be related to the moisture content of the wood specimen causing the imbalance.
Electric moisture meters - Summary

A comparison between both methods

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<th>Capacitive method</th>
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<td>At least two electrodes have to be driven into the material - measurement depth, damage to material and any surface coatings</td>
<td>Non-destructive testing, sensor only touches surface, measurement depth = 25...30 mm, plane surface for sufficient electrode contact required</td>
</tr>
<tr>
<td>Measurement of wetted layer in the sample – non-isolated pin electrodes, local mc determination with isolated pin electrodes – mc profile determination</td>
<td>Only average mc determination over measurement depth</td>
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<tr>
<td>More time consuming measurement – electrode placement</td>
<td>Fast – applying electrodes, low contact pressure</td>
</tr>
<tr>
<td>Temperature correction required</td>
<td>Below 5...40°C temperature correction not strictly required</td>
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<tr>
<td>Species correction required</td>
<td>Species correction required – in particular related to material details (species, grain)</td>
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Another comparison (acc. to Forsén, Tarvasinen 2001)

- major differences exist between individual moisture meters
- capacitance meters show much wider (measurement) variation compared to resistance type meters
- correct temperature setting is important for resistance type meters
- correct density setting is essential for capacitance type meters
- sample conditions, i.e., dimensions of sawn timber, mc level and mc gradient are affecting the measurement accuracy
- the choice of the “correct” place (depth, width) where to measure the average moisture content significantly determines the result
- best accuracy of resistance type meters is within 8 % to 20 % mc
- capacitance type meters tend to indicate too low mc values due to low measuring depth and mc gradients
Use of electric moisture meters

Checklist for usage of electric moisture meters
(acc. to recommendations by Forsell, Tanvalen 2001, p. 72)
• Checking operating conditions
  • battery voltage
  • stability of the instrument at different temperatures
  • any checks recommended by the manufacturer
• Calibrating the moisture meter – reference resistances (or resistance meters) or calibration block (capacitance meters)
• check with well-conditioned wood samples – different mc classes, comparing results with results from the oven-dried method
...when performing measurements
• choose correct wood species
• adjust true wood temperature
• measurement target 
• number of measurements (in accordance with an approved standards)

Hygrometrical method

Material equalisation with environment – sorption isotherms
• taking up / detaching water from the inner wood surface (void system in cell walls) = adsorption / desorption
• bond of H2O molecules by electro-chemical and physical forces
• sorption takes only place in the range 0 ≤ EMC ≤ FSP
• driving forces = concentration equalization or partial vapour pressure equalization between humidity in the wood and the environment:
  EMC = f(φ, q), and sorption direction!
• EMC<sub>eq</sub> ≤ EMC<sub>con</sub> ⇒ ΔEMC = hysteresis
• sorption isotherms describe EMC = f(q) at φ = const. and 0 ≤ q ≤ 100 %
• with rising temperature the slope of the isotherms decreases
• ΔEMC decreases with ↑ φ and disappears at approximately φ ≥ 70°C
• FSP decreases by 1 % with Δφ = ±10 K
• sorption isotherms depend on wood species – they are influenced by density, porosity, extractives, reaction wood (change of chemical composition)

Example of a sorption isotherm
• temperature = const.
• first desorption
• adsorption
• hysteresis
• fibre saturation FSP
• EMC = f(φ)
• oscillating sorption
• mean sorption isotherm
Hygrometrical method

Temperature influence on sorption
• \( \vartheta \rightarrow \vartheta \) EMC and \( \vartheta \rightarrow FSP \) at \( \vartheta = \text{const.} \)

Wood and humid air
• sorption isotherms only describe a final condition – the EMC – not the dynamics of moisture equalisation, i.e., the changing rate of the mc!
• the KEYLWERTH Diagram shows the relation between environmental climate (defined by \( \vartheta \) and \( \vartheta \) and EMC) it is derived from measurements with Sitka Spruce (picea sitchensis) and beside the basic grid temperature (= dry bulb temperature) and relative humidity the diagram also shows const. EMC curves and curves of const. wet bulb temperature, to be used for climate measurement by means of a psychrometer (required air flow \( u_r \geq 2 \text{ m/s} \))
• additionally these relations are also available in table form, showing EMC depending on climatic parameters (\( \vartheta \) and \( \vartheta \) and \( \vartheta \) and \( \Delta \vartheta = \vartheta_1 - \vartheta_0 \))
• the indicated EMC might be used for all wood species with sufficient reliability

KEYLWERTH Diagram

Hygrometer

Psychrometer

Technical data
Sensors: resistive thermometer P1000
Dry bulb sensor: 1 or 2 x P1000
Wet bulb sensor: 1 x P1000
Max. permissible current: 3 mA
Protection mode: IP 54
Housing: stainless steel No. 1.4571
Environmental temperature: \(-10 \ldots +100^\circ \text{C} \)
Storing temperature: \(-10 \ldots +100^\circ \text{C} \)
Use psychrom. constant for ice
Hygrometer

Psychrometer

Psychrometer in a dry kiln (equipped with two Pt100 sensors)

Dry bulb thermometer

Wet bulb thermometer

Water tank with wet wick

Equilibrium moisture content

Use of the KEYLWERTH-Diagram

• Intersection of psychrometer temperatures Tdb, Twb (y-axis) and r.h. (x-axis)

• Analogous TWB and r.h. can be derived from TDB and EMC

Dry and wet bulb temperature [° C]

Relative humidity [%]

TDB=E60°C → EMC=E6,1%

TWB=E15°C → EMC=E30%

the usage of the psychrometer requires an airflow minimum of νa ≥ 2 m/s at the wet wick to achieve the adiabatic cooling limit.
Wood Structure

Moisture Content Measurement methods

Direct measurement method
• Oven dry method

Indirect measurement methods
• Conductance m.
• Capacitive m.

Electric moisture meters

Checklist for use of moisture meters
• Hygrometrical m.

EMC & KEYLWERT Diagramm

Thank you for your attention