Impact of thermal treatment on moisture-dependent elasto-plastic behaviour of beech

A. Straže¹, G. Fajdiga¹, S. Pervan², Ž. Gorišek¹

¹ University of Ljubljana
Biotechnical Faculty
Department of Wood Science and Technology
Ljubljana, Slovenia
ales.straze@bf.uni-lj.si

² University of Zagreb
Faculty of Forestry
Zagreb, Croatia
Thermally processing of wood is recognized as eco-friendly technique without the use of chemical additives.

Thermally modified wood is now an established form of modified wood product. It is observed that dimensional stability and natural durability are improved by increasing treatment temperature and processing time. Nevertheless, some mechanical properties such as toughness, strength and stiffness may decrease to an unacceptable level during treatment.
Use of thermally treated (TT) wood for construction applications???

- Outdoors,
- harsh environment (cycling of humidity and temperature)

European market has till now only standardized quality control of innate / natural sawn wood (visual and mechanical CE grading). **Mechanical properties of TT wood in relation to moisture content are less researched.**
Objectives:

- To examine the impact of heat treatment on mechanical properties of wood at compressive loading under various humidity conditions.

Material:

- Innate and industrially heat treated beech wood (*Fagus sylvatica* L.) in unsaturated steam conditions (up to 200 °C; t = 4 h)
- Raw wood specimens: 25 × 80 × 800 mm
Methods

Sampling and conditioning

- Parallel sampling (two of each in L- and T-direction):

Boards: 2000 × 100 × 32 mm; n = 10

(C) Control board sample (L = 1m)

(TT) Thermal-treated board sample (L = 1m)

(L) Longitudinal direction
Oriented bar 1: 600 × 20 × 20 mm

(L) Specimens: 20 × 20 × 20 mm

0 1 2 3 4 5 6 7

(L) Specimens: 20 × 20 × 20 mm

0 1 2 3 4 5 6 7

(T) Transverse direction
Oriented bar 2: 600 × 20 × 20 mm

(T) Specimens: 20 × 20 × 20 mm

0 1 2 3 4 5 6 7

(T) Specimens: 20 × 20 × 20 mm

0 1 2 3 4 5 6 7
- Unsaturated steam atmosphere including pre-drying, heating, cooling and conditioning) (t = 64 h);
  - Heating / Cooling rate: 5 °C/h,
  - Ultimate HT phase: T = 200 °C, t = 4 h.
  - Post “treatment” phase: T = 20 °C, RH = 65%, t = 4 h
Methods

Sampling and conditioning

- Thermostatic conditioning chambers with saturated salt solutions (T = 20 °C).

<table>
<thead>
<tr>
<th>Climate</th>
<th>Medium</th>
<th>RH [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Vacuum drier (50°C / 2 hPa)</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>HCOOK</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>MgCl₂</td>
<td>33</td>
</tr>
<tr>
<td>3</td>
<td>K₂CO₃</td>
<td>44</td>
</tr>
<tr>
<td>4</td>
<td>NaNO₂</td>
<td>65</td>
</tr>
<tr>
<td>5</td>
<td>NaCl</td>
<td>75</td>
</tr>
<tr>
<td>6</td>
<td>ZnSO₄</td>
<td>87</td>
</tr>
<tr>
<td>7</td>
<td>Distilled water</td>
<td>97</td>
</tr>
</tbody>
</table>
Methods

Static mechanical compression test (DIN 52185)

- Longitudinal (L) and transverse to the grain direction (T):

  ![L-direction](image1) ![T-direction](image2)

- Determined mechanical properties:
  - Modulus of elasticity (MOE)
  - Ultimate strength ($\sigma_{\text{max}}$)
  - Proportional limit stress ($\sigma_{\text{PL}}$) “offset yield method at 0.01% plastic strain”
Results: Density / mass loss

- Significant decrease of wood density after thermal treatment.

(Δρ = -9.3%)
**Results: Sorption properties (EMC)**

- Tested equilibrium moisture content states
  - Significant reduction of hygroscopicity of wood after thermal treatment, greater in upper hygroscopic range.
Results: Ultimate strength

- Longitudinal direction:

![Graph showing the relationship between moisture content (MC) and maximum stress (σ_max) for innate and thermal-treated samples in the longitudinal direction. The graph includes regression equations for each condition: y = 84.293e^{0.066x} for innate samples (R^2 = 0.9524) and y = 88.627e^{-0.075x} for thermal-treated samples (R^2 = 0.6887).]

- DRY:
  - Brittle
  - Brittle

- WET:
  - Brittle
  - Brittle

Note: The graph illustrates the innate (○) and thermal-treated (●) samples in different moisture conditions.
Results: Ultimate strength

- Transverse direction:

  ![Graph showing the relationship between moisture content (MC) and ultimate strength (σ_{max}). The graph includes two equations: y = 8.638e^{-0.046x} with R² = 0.4877 and y = 14.6e^{-0.042x} with R² = 0.8379.]

  - **DRY**
    - Ductile
    - Brittle
  
  - **WET**
    - Ductile
    - Brittle

  Innate (○) thermal-treated (●)
Results: Ultimate strength – relative scale

- $\sigma/\sigma_0$ - ratio between strength at single moisture content ($\sigma$) and strength at absolute dry condition ($\sigma_0$)

- L-direction
  - Greater reduction of ultimate strength is present in longitudinal wood direction,
  - no difference between C- and HT-samples.

- T-direction
Results: Ultimate strength – humidity perspective

- **L-direction**
  - Box plots showing compression strength vs. relative humidity for untreated and thermally treated samples.

- **T-direction**
  - Box plots showing compression strength vs. relative humidity for untreated and thermally treated samples.
Results: Modulus of elasticity

- **L-direction**
  - Unchanged stiffness-moisture relation in L-direction,

- **T-direction**
  - \( y = 10.051e^{-0.04x} \)
    - \( R^2 = 0.8801 \)
  - \( y = 10.844e^{-0.044x} \)
    - \( R^2 = 0.6907 \)
  - \( y = 2.3773e^{-0.044x} \)
    - \( R^2 = 0.4223 \)
  - \( y = 2.8188e^{-0.053x} \)
    - \( R^2 = 0.7109 \)
Results: Modulus of elasticity – relative scale

- MOE/MOE₀ - ratio between strength at single moisture content (σ) and strength at absolute dry condition (σ₀)

- **L-direction**

- **T-direction**

- The relative reduction of stiffness with increase of wood moisture content remains unchanged after the thermal treatment.
Results: Modulus of elasticity – humidity perspective

Comparison of stiffness at normal climate (T = 20 °C; RH = 65 %)

- **L-direction**
- **T-direction**

- Apparent (“fictive”) increase of stiffness of wood after thermal treatment.
Results: Proportional limit stress

- $\sigma_{PL}/\sigma_{max}$ - ratio between proportional limit stress ($\sigma_{PL}$) and ultimate strength ($\sigma_{max}$) of single specimen

**L-direction**

**T-direction**
Concluding remarks

- Heat treatment significantly impacts ultimate strength, stiffness and elasto-plastic properties of wood (proportional limit stress).

- The mechanical response of wood in relation to the present moisture content (EMC) remains mostly unchanged after the treatment:
  - Relative change of ultimate strength and modulus of elasticity in relation to the moisture of wood is unchanged,

- The wood structure is more brittle after the thermal treatment (the lost of visco-elastic character was confirmed in transverse wood direction).