Density optimization for the manufacturing of bark-based thermal insulation panels

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Abstract. Buildings in general, consume and lose huge energy amounts through their heating and cooling systems. Thus, effective thermal insulation materials required to endow on energy shaving attains. For this research, bark particles were used as raw materials for the manufacturing of low-density thermal insulation panels. The aim of this work was to determine the optimum density value of these panels in combination with their thermal conductivity and mechanical performance. Three panel densities, i.e. 250 kg/m³, 300 kg/m³ and 350 kg/m³ were used in this study. For each density, specimens for the thermal, physical (water absorption, thickness swelling) and mechanical (static bending, internal bond) assays had been analysed. As proposed by the results, the optimum conditions could be achieved at density levels of 350 kg/m³. All things considered, bark-based particleboards seem to be a very promising feedstock materials for their usage especially as interior thermal insulation panels, in the building sector.

1. Introduction

Buildings in total, are reported to consume 40% of the EU’s total energy demand and produce about 35% of greenhouse emissions. By designing buildings in the concept of ‘sustainable construction’ it is purposed to reduce energy demand for heating consumption of the buildings, in compliance with the three pillars of sustainability, i.e. the ecological, economic and social perspectives [1]. One of the main ways of improving thermal efficiency and decreasing greenhouse gases emissions is the production of insulation panels with low thermal conductivity values [2]. Furthermore, especially in the last decade, low environmental impact thermal insulation panels made of biomasses, also referred as ‘bio-insulations’ have been increasing rapidly due to their availability as renewable, low cost and eco-friendly materials. So far, several agricultural residues and forest wastes including cellulose, reeds, bagasse, palm, hemp, flax, cotton, maize, wheat, rise etc. have being researched as alternative sustainable materials to attain insulation panels [3,4].

Each year, a significant quantity in million tons of bark generated during wood processing is produced globally, emanating as a residual woody biomass in sawmills and wood-based industries [5]. The increasing research and development needs of introducing value added products made of wood waste materials have prompt many research efforts for the usage of bark residues besides burning them as energy fuel, like for example the incorporation of bark into the production of wood-based panels [6]. Wood-based panels are essential and common raw materials suitable for engineering applications in the building construction and furniture industry [7]. Past research efforts have been investigated bark as a feedstock material for the manufacturing of different type of panels such as particleboards, hardboard, medium density fiberboard and oriented strand board [8,9].

There are several factors influencing the thermal conductivity values of wood-based materials in which temperature, moisture and density are considered to be of the most crucial parameters.
conductivity it is accepted to be proportionally increased as a function of temperature, moisture content and density [10]. It is reported in [11] that the thermal conductivity values of wood and wood-based materials, increases linearly with rising density in the range of 200 to 800 kg/m³. Thus, in building sector low density fibreboards or softboards, are usually commercially available as thermal insulation materials. According to EN 316 standard low-density fibreboards are porous panels having a density between 230 and 400 kg/m³ [12].

In addition, it is known that density do have a significant positive influence on the mechanical performance of wood-based panels, since it is acknowledged that the higher the density the stronger are the mechanical properties [13]. Even though the mechanical behaviour is not in first priority and panels having lower mechanical properties can be used as insulating materials in buildings [14], wood panels should withstand a minimum performance during their handling, installation and maintenance as thermal insulation panels. Therefore, the objective of this study was to investigate the optimum low-density conditions of bark-based particleboards combined with their mechanical properties, so to be potentially used as thermal insulation panels.

2. Materials and methods

2.1. Materials
The whole bark samples (inner and outer bark) used in this research were directly collected from the debarking units of a wide diameter range harvested poplar logs stored in a local sawmill at the area of Sopron, Hungary. The commercial UF resin and hardener used in this work was purchased by DUKOL Ostrava s.r.o.

2.2. Bark panels manufacturing
Initially, the various thicknesses bark slices, comprising of inner and outer bark were collected and dried below 20% into a chamber. Consecutively, the inner and outer bark, were cut into small pieces and chipped into particles using a hammer mill equipped with an 8-mm screening holes. The granulated bark particles sized from 0.5 mm to 8 mm fractions were used as raw material for the manufacturing of bark panels. The moisture content of the bark particles was adjusted between 6% to 9% before further processing. A 4% urea formaldehyde (UF) adhesive stirred with a 35% aqueous solution of ammonium sulfate (NH₄)₂SO₄ as catalyst.

Forthwith, the glued mixtures were manually layered and formed in a wooden frame into a mat. Thereafter, the frame was removed, and the mats were pre-pressed by hand to compact the materials without heat transfer. Two Teflon (polytetrafluoroethylene, PTFE) sheets were used on both surfaces of the mat to prevent the produced boards from sticking onto the metal plates during hot pressing process. Bars of 20 mm thickness were inserted between the metal plates before pressing to maintain a uniform thickness for all boards.

Following, the mats were transferred to a single-opening hydraulic hot press machines (Siempelkamp). The pressing temperature was set at 180 °C with a pressing time of 18 seconds per thickness millimetre. The maximum pressure was 2.86 MPa, which was reduced after 120 seconds to 2.00 MPa and after an additional 120 seconds to 1.15 MPa for releasing steam pressure inside the panel. Single-layered particleboards with dimensions of 500 mm x 500 mm x 20 mm³, were weighted to obtain target densities of 250 (C_250), 300 (C_300) and 350 (C_350) kg/m³, respectively.

2.3. Measurements
All the composites boards were kept at 20±2°C and 65±5% relative humidity, until equilibrium moisture content (EMC) was achieved, prior to experimental measurements. All produced particleboards were cut and trimmed into various test specimens.

2.3.1. Physical properties. Bulk density (ρ) was measured on the same samples used for the mechanical tests. The density of each panel was individually measured at current moisture content at time of mechanical bending test (EN 323, 1993). Dimensional stability of the specimens regarding thickness swelling (TS) and water absorption (WA) were calculated according to European standard EN 317 (1993). Sized specimens with 50 mm by 50
mm dimensions were weighed and their thicknesses in the middle of test sample were measured with a level of accuracy of 0.01 g and 0.1 mm, respectively (figure 1a). The specimens were immersed in water at room temperature to a depth of 30 mm and soaked for 2 and 24 h. The results of WA and TS were expressed as a percentage of the original state as follows:

\[
WA(\%) = \frac{\text{wet weight} - \text{dry weight}}{\text{dry weight}} \times 100
\]

and

\[
TS(\%) = \frac{d_2 - d_1}{d_1} \times 100
\]

where wet weight and \(d_2\) is the weight and thickness of the specimens after 2 or 24 h immersion in water, while dry weight and \(d_1\) their initial weight and thickness at equilibrium moisture content, respectively.

2.3.2. Thermal properties. Thermal conductivity was measured across the thickness of the composite board using a heat flow meter using a guarded hot-plate apparatus (figure 1b). The thermal conductivity was calculated at steady state conditions by measuring the heat flux, as described by Fourier’s law, according to the following equation

\[
\lambda = \frac{\Phi_q}{\Delta T} \quad (3)
\]

where \(\lambda\) is the thermal conductivity measured in watts per meter kelvin (W/m·K), \(\Phi_q\) is the heat flux (W/m²), \(\Delta T\) is the temperature difference across the specimen (K) and \(d\) is the thickness of the specimen (m). The tested boards were sandwiched between the hot and cold plate, at the center of both plates within the measuring area, at room temperature. The temperature difference between the hot and a cold plate was set to 10°C by the mean temperature was 10°C. Fifteen thermal conductivity tests were carried out, these being three replicates on each particleboard type with dimensions of 500 mm x 500 mm x 20 mm.

Figure 1. [a] 50 mm x 50 mm specimens of bark panels, [b] thermal conductivity measurement system

2.3.3. Mechanical properties. The bending strength (MOR) and modulus of elasticity (MOE) of obtained bark composite boards were characterized using a universal testing machine Instron 5506 (static three-point bending), in compliance with the appropriate European Standards EN 310 (1993) at a crosshead speed of 8 mm min⁻¹. MOR and MOE were calculated on specimen dimensions of 450 mm x 50 mm x 20 mm³, according to the following equations:

\[
\text{MOR} = \frac{3 \cdot F_{\text{max}} \cdot L}{2 \cdot b \cdot d^2}
\]

and

\[
\text{MOE} = \frac{\Delta F}{\Delta \alpha} \cdot 4 \cdot b \cdot d^3
\]

\[
\text{MOE} = \frac{L^3}{4 \cdot b \cdot d^3}
\]
where $F_{\text{max}}$ is the maximum force at the time of rupture (N), $L$ is the span between supports (mm), $b$ is the width of the specimens (mm), and $d$ is the thickness of the specimens (mm), $\Delta F$ is the load increment and $\Delta \varepsilon$ is the deflection increment rate. Young’s modulus was calculated from the average slope of the stress-strain curves, corresponding to strains between approximately 10% and 40%. The tensile strength perpendicular to the surface (internal bond) was determined by using 50 mm x 50 mm specimens from each panel according to EN 319 (1993), at a speed of 0.04 mm min$^{-1}$. The maximum force ($F_{\text{max}}$) was calculated and internal bond strength (IB) was estimated using the following formula:

\[
IB = \frac{F_{\text{max}}}{b \cdot l}
\]

where $b$ and $l$ are the width and the length of the specimens (mm), respectively.

2.3.4. Statistical analysis. The analysis of variance (ANOVA) was applied using Statistica13 software (TIBCO Software Inc., USA) to statistically examine the influence of density on the properties of bark panels produced in the current study. All data were checked for normality (Shapiro–Wilk test) and homogeneity of variance (Levene’s test), at 5 % significance level. Post hoc tests were conducted with Tukey’s HSD test method.

3. Results and discussion

The overall results on the thermal, physical and mechanical characterizations of bark particleboards are summarized in table 1. Bark particleboards were formatting according to a defined initial weight and target densities, at 20 mm thickness. However, possibly due to inhomogeneities of bark particles during the manual process or their compression during the hot press, the boards with a target density of 350 kg/m$^3$ presented a mean density value of 387.57 kg/m$^3$, slightly raised by 10.73% than the expected. As expected, the thermal conductivity value as well as the static bending properties and internal bond of the experimental panels were significantly increased by raising the density of bark barks from 250 kg/m$^3$ up to 350 kg/m$^3$. The mean thermal conductivity values of C$_{250}$, C$_{300}$ and C$_{350}$ panels were calculated to be 0.059 W/m K, 0.063 W/m K and 0.079 W/m K, respectively. The observed thermal conductivity values were within the range of 0.06 W/m K up to 0.10 W/m K, comparing them to the thermal conductivity of other investigated insulation panels originated from wood or agricultural residues bioresources, some examples of the numerus experimental proposals are given in table 2.

Even though the thermal conductivity value of C$_{250}$ was found to be the lowest, their mechanical properties were extremely low. The proposed C$_{250}$ density boards, were very weak and additionally trimmed during the measurements, therefore these were excluded and considered not suitable for their usage as thermal insulation panels.

As reported in [13] according to European standard EN 622-4:2010 the MOR value of a wood fibre insulation panel, of more than 19 mm thickness and densities ranging from 230 and 400 kg/m$^3$ should be more than 0.8 MPa. In this study, this limit of 0.8 MPa could be overcome only at the C$_{350}$ specimens of the proposed bark particleboards bonded with 8% UF adhesive. Yet in all cases, the IB values were noticeably low and moreover the mean TS% values were surprisingly shown to be significantly low in the varying from 7.27% up to 8.39%.
Table 1 Physical, thermal and mechanical properties of the proposed glass fibre reinforced bark particleboards. Numbers in brackets represent standard deviation of the estimated mean values

| Physical properties | C_350          | C_300          | C_250          |
|---------------------|----------------|----------------|----------------|
| Density (kg/m³)     | 387.57 (± 14.24) | 316.21 (± 10.66) | 259.02 (± 10.84) |
| MC (%)              | 9.73 (± 0.39)  | 10.31 (± 0.41)  | 10.70 (± 0.35)  |
| WA (%) 24 h         | 182.47 (± 25.73) | 195.96 (± 21.28) | 244.10 (± 18.09) |
| TS (%) 24 h         | 8.15 (± 0.99)  | 7.27 (± 1.26)   | 8.39 (± 0.71)   |
| Thermal properties  |                |                |                |
| λ (W/m K)           | 0.079 (± 0.003) | 0.063 (± 0.005) | 0.059 (± 0.002) |
| Mechanical properties|               |                |                |
| MOR (MPa)           | 1.42 (± 0.24)  | 0.42 (± 0.09)   | 0.11 (± 0.04)   |
| MOE (MPa)           |                |                |                |
| IB (N/mm²)          | 0.11 (± 0.01)  | 0.08 (± 0.01)   | -              |

Table 2 Comparative assessment on the experimental thermal conductivity values of wood-related thermal insulation panels

| Materials                     | Parameters (density, thickness, resin etc)                                      | λ (W/m K) | Reference |
|-------------------------------|----------------------------------------------------------------------------------|-----------|-----------|
| Poplar bark particles         | Particle size 0.5-8 mm, 250-350 kg/m³, 20 mm, 8% UF                             | 0.059-0.079 | This work |
| Black locust bark particles   | 200-550 kg/m³, 10-40 mm, particle size (1-8 mm; 8-13mm; 13-45 mm), 10% UF        | ~ 0.065    | [15]      |
| Larch bark particles          | 250-500 kg/m³, particle size 6-10 mm; 20 mm, 5-15% tannin resin                 | 0.069-0.093 | [13]      |
| Poplar and spruce heartwood   | Heat treatment 15 h, 20 mm                                                       | 0.083-0.086 | [16]      |
| Agglomerated cork boards      | commercial boards, 100-400 kg/m³, 10-30 mm thickness, 450 x 450 mm²            | 0.047-0.083 | [17]      |
| Hemp hurds                    | 10-30 mm length, 330 kg/m³, hybrid organic-inorganic binder, 50 mm thickness, dimensions150 x 50 cm² | 0.078      | [18]      |
| Coconut husk and bagasse      | 250-450 kg/m³, 450 mm x 450 mm, thickness 25 mm, binderless, coconut particles length 8-10 mm, bagasse particles length 20-40 mm | 0.046-0.068 | [19]      |
| Wood shavings flakes          | 60-100 kg/m³, 320 x 320 x 50 mm, Douglas fir particles size 13.3 mm x 14.8 mm x 0.21 mm | 0.046      | [20]      |
| Cotton stalk fibers           | binderless, 25 mm thickness, 250-450 kg/m³, 300 x 300 mm mat size               | 0.058-0.081 | [21]      |

4. Conclusion

For this work, the proposed sustainable and renewable bark particleboards were produced to be used as alternative substitutes of petroleum-based, commercial thermal insulation panels. Considering the above mechanical mentioned results, the optimum density is suggested to be in the range of 350 kg/m³, even if these bark boards indicated a relatively large thermal conductivity value of 0.079 W/m K. Further, the observed low thickness swelling values could be a good indicator, since hygroscopic
wood is susceptible to humidity. Potential issues for deeper investigation for the utilization of bark particles as thermal insulation materials could be the assessment of thermal and mechanical properties as a function of moisture content and temperature as well as the adhesive type and content, at 350 kg/m$^3$ or 300 kg/m$^3$ low densities.

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