Substantial Bark Use as Insulation Material

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Abstract

In this study, bark-based insulation boards were made out of pine (*Pinus sylvestris*) bark. Their properties seem to be promising with regard to thermal conductivity, heat storage capacity, and mechanical characteristics. The influences of panel density, resin content, and particle size on the relevant board properties were studied, showing that it is possible to produce comparatively light ($<$500 kg/m^3) bark boards for thermal insulation. In particular, the panels' heat storage capacity is superior to commonly known insulation materials. For this reason bark-based insulation panels could probably be used efficiently for civil engineering purposes and insulation applications in general.

An analysis of the wood market has shown that the production of wood products can only be enhanced if wood imports can be increased or unused wood reserves can be mobilized (Schwarzbauer 2005). With regard to the current mobilizing strategies and the resource availability in Central Europe, both opportunities alone seem to be improbable (Barbu 2011). Options for a long-term successful resource supply could lie within the development of new raw material sources or in an improved efficiency of industrial wood use (Petutschnigg and Katz 2005).

Given the scarce resource supply, sustainable subsistence strategies (Teischinger 2007) call for innovations both in resource efficient technologies and in product development. The global logging harvest used for industrial purposes totals roughly 1.6 billion solid m^3 and represents only 43 percent of total cuts because the majority is directly burned (Barbu 2011). Considering that the average bark content of a tree is approximately 10 percent, use of bark would result in approximately 160 million m^3 of additional raw material (Xing et al. 2007). Even though tree bark is already used in products like bark mulch, absorption materials, raw materials for tannin production, and various fertilizers, there is a call for alternative applications with an increased value added (Naundorf et al. 2004).

Bark is the boundary layer of a tree and protects it from physical and biological exterior attacks. Therefore it has ideal properties, such as a low density, a high concentration of extracts, very good thermal insulation properties, and relatively low flammability (Fengel and Wegener 2003). These characteristics warrant the investigation of bark as an effective insulation material.

A long tradition can be found in the use of bark as raw material in various wood-based panels (e.g., Volz 1973, Nemli and Colakoglu 2005, Kraft 2007, Xing et al. 2007, Yemele et al. 2008). All of those studies show that increased bark content results in poorer mechanical board properties than those of conventional particleboard or fiberboard. A recent study carried out by Gupta et al. (2011) showed that bark panels with a density higher than 800 kg/m^3 can be produced without using additional resin. This investigation also proved that pressing temperature and particle size have a great influence on mechanical and physical board properties. Boards made of finer particles demonstrate better characteristics (e.g., modulus of elasticity [MOE], modulus of rupture [MOR], internal bond [IB], tensile strength [T], thickness swelling [TS], water absorption [WA]) than those made of coarse bark particles.

Naundorf et al. (2004) produced bark pellets that were suitable as blow-in insulation material. Although the thermal properties of wood have been adequately studied (e.g., Suleiman et al. 1999), there are fewer studies focusing on the thermal characteristics of bark. Warnecke (2006)

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produced bark panels bound with natural adhesives with a relatively high thermal conductivity of 0.16 W/(m·K). The thermal conductivity of bark under standard temperatures can be satisfactorily estimated by density and MC. Furthermore, the fact that the anisotropy of bark between the longitudinal and transverse direction is significantly lower than that of wood is advantageous because it means the particle orientation within a board has less influence on its thermal conductivity properties (Martin and Crist 1968). A study focusing on specific heat storage capacity and thermal conductivity of ovendry bark has been carried out by Gupta et al. (2003) in order to gain better understanding of vacuum pyrolysis processes for retrieval of energy and higher refined chemicals. Another early investigation of Martin (1963) showed measurements of the specific heat storage capacity of ovendry bark at a temperature of 25°C. On average it adds up to 1,300 J/(kg·K), which ranges within what has been found by Gupta et al. (2003). Martin (1963) also showed that the specific heat storage capacity of bark can be compared with that of solid wood.

The aim of this research was to produce low-density bark-based panels and to clarify whether bark, especially pine bark (*Pinus sylvestris*), is suitable as an insulation material.

Materials and Methods

Material for the investigation

The bark for the current study was collected in a small Upper Austrian softwood sawmill. According to the sawmill owner, the wood species is 90 percent common pine (*Pinus sylvestris*), 5 percent spruce (*Picea abies*), and 5 percent fir (*Abies alba*).

Sample taking was carried out following the method developed by Paper Wood Austria (2009) for industrial wood chips acceptance. Bark chips were taken from the upper layer of the bark pile at several spots and were withdrawn at an approximate depth of 30 cm to avoid changing effects at the boundary layer. The bark was subsequently dried with a vacuum dryer from an initial MC of 100 percent to a final MC of 5.8 percent.

Bulk density and densification properties of bark

During panel production, particles are resonated and then pressed in a hot press where the particle–resin mixture gets compressed. Therefore a minimum board density is necessary in order to guarantee proper interparticle contact during the pressing process.

For insulation panels where low densities are required in order to achieve low thermal conductivity (Kain et al. 2012), the bulk density of the bark particles has to be known when defining panel density. Moreover bark particles also could be used as a blow-in insulation material, whose thermal conductivity is lower when the bulk density is low.

For investigating the bulk density and the densification properties of bark, the dried material was crushed in a common disk chipper and fractionated with a sieve into three fractions (x_1, x_2, and x_3). The particle size distribution was as follows: 45 mm $> x_1 \geq$ 13 mm, 13 mm $> x_2 \geq$ 8 mm, 8 mm $> x_3 \geq$ 0 mm. The bulk density and the set were determined according to the European standard EN 15103 (Deutsches Institut für Normung [DIN] 2010). Deviating from the standard, a prismatic box with a cross section of 40 by 6 by 40 cm was used to simulate the geometry of a wall instead of a circular bin.

Figure 1.—Bark-based insulation panel (thickness, 20 mm; density, 400 kg/m^3; particle size, 30 mm $> x_4 \geq$ 13 mm).

This box was filled to the upper edge with bark of defined particle size by loose pouring. Afterward the bulk density was determined. Subsequently the box described above was dropped 10 times from a height of 5 cm in a base frame in order to compress the loose bark particles. The density of the densified bark was then calculated, and the compression ratio was ascertained. Six independent measurements were

Table 1.—Experimental design with the factors of density, particle size, and resin content (based on the ovendry weight of bark particles).

Density (kg/m^3)	Particle size (mm)	UF resin content (kg/kg)[a]	No. of specimens
500	30 $> x_4 \geq$ 13	0.12	3
		0.08	3
	13 $> x_5 \geq$ 8	0.12	3
		0.08	3
400	30 $> x_4 \geq$ 13	0.12	3
		0.08	3
	13 $> x_5 \geq$ 8	0.12	—
		0.08	3
350	30 $> x_4 \geq$ 13	0.12	1

[a] UF = urea-formaldehyde.

Table 2.—Bulk density and compression ratio of bark.[a]

Bark fraction (mm)	Bulk density (kg/m^3)	Bulk density densified (kg/m^3)	Compression ratio
$45 > x_1 \geq 13$	168.8 (2.48)	190.5 (2.72)	1.13 (0.011)
$13 > x_2 \geq 8$	182.4 (4.88)	210.0 (4.13)	1.15 (0.017)
$8 > x_3 \geq 0$	212.7 (3.98)	255.3 (5.84)	1.20 (0.019)

[a] Sample size = 6 in each category. Values are means (standard deviations).

Table 3.—Coefficient of correlation (Pearson) between panel density and mechanical board properties.[a]

	CR	MOR	MOE	T	IB	TS	WA
Coefficient of correlation	0.943	0.832	0.610	0.790	0.741	0.329	−0.167
Significance level	0.000	0.000	0.000	0.000	0.000	0.038	0.303
Sample size	40	40	39	74	39	40	40

[a] CR = compressive resistance; MOR = modulus of rupture; MOE = modulus of elasticity; T = tensile strength; IB = internal bond; TS = thickness swelling; WA = water absorption.

Table 4.—P values of the analysis of variance.[a]

Factor	CR	MOR	T	IB	TS	WA	MOE
Explained variance by the model	0.942	0.803	0.768	0.775	0.604	0.949	0.510
Particle size (P)	0.455 (0.016)	0.020 (0.146)	0.514 (0.006)	0.000 (0.312)	0.000 (0.323)	0.000 (0.930)	0.069 (0.094)
Resin content (R)	0.000 (0.443)	0.000 (0.408)	0.000 (0.378)	0.003 (0.236)	0.000 (0.373)	0.000 (0.669)	0.009 (0.184)
Density (D)	0.000 (0.941)	0.000 (0.780)	0.000 (0.675)	0.000 (0.721)	0.001 (0.260)	0.000 (0.382)	0.000 (0.416)
P × R	0.000 (0.381)	0.039 (0.117)	0.734 (0.002)	0.010 (0.180)	0.338 (0.026)	0.661 (0.006)	0.918 (0.000)

[a] Partial ETA^2 values for single factors are provided in parentheses. CR = compressive resistance; MOR = modulus of rupture; T = tensile strength; IB = internal bond; TS = thickness swelling; WA = water absorption; MOE = modulus of elasticity.

carried out per bark fraction. Therefore the effect of particle size on the bulk density of the not densified and densified bark was tested on its statistical significance with an analysis of variance.

Manufacturing of one-layer insulation boards

From the bark material mentioned at the outset (90% pine, 5% spruce, and 5% fir), boards were produced. First, the coarse bark particles were milled in a four-spindle shredder. Within the machine, a 30-mm-mesh sieve was installed to limit the dimensions of the oversized particles after milling. The milled particles were fractionated continuously using hand sieves to obtain two bark fractions: x_4 and x_5. Thus the particle distribution was classified by the following criteria: 30 mm $> x_4 \geq$ 13 mm, 13 mm $> x_5 \geq$ 8 mm. Dust, fines, and particles smaller than 8 mm were not used for the bark-based insulation board production. Afterward the bark particles were resinated with a urea-formaldehyde (UF) glue in a laboratory blender. To conclude the process, bark-based insulation panels (Fig. 1) with a thickness of 20 mm and a target density of 350, 400, and 500 kg/m^3 were produced using a laboratory press (1 by 1 m).

Table 5.—Particle size effect on selected panel properties.[a]

Properties	Particle size: 30 mm $> x_4 \geq$ 13 mm	Particle size: 13 mm $> x_5 \geq$ 8 mm
MOR (N/mm^2)	0.72 (0.34)	0.83 (0.54)
IB (N/mm^2)	0.16 (0.05)	0.12 (0.06)
TS after 2 h (mm/mm)	0.11 (0.03)	0.16 (0.03)
WA after 2 h (kg/kg)	0.34 (0.06)	0.64 (0.09)

[a] Values are means (standard deviations). MOR = modulus of rupture; IB = internal bond; TS = thickness swelling; WA = water absorption.

Experimental design and data analysis

The factorial design used in this investigation is shown in Table 1. The factors chosen were density (350, 400, and 500 kg/m^3), resin content (0.08, 0.12), and particle size (30 mm $> x_4 \geq$ 13 mm, 13 mm $> x_5 \geq$ 8 mm). During panel production, it was found that panels with a density of 400 kg/m^3, resin content of 8 percent, and x_5 particle size showed insufficient strength properties as a result of lacking compression. Therefore no panels with the same density and particle size but only higher resin content were produced. In return a test panel with a density of 350 kg/m^3 and coarser

Table 6.—Resin content effect on panel properties.[a]

Properties	UF resin content (based on the ovendry weight of bark particles): 0.08 kg/kg	0.12 kg/kg
CR (N/mm^2)	1.719 (0.623)	1.958 (0.808)
MOR (N/mm^2)	0.65 (0.35)	0.87 (0.47)
MOE (N/mm^2)	135.54 (78.33)	185.40 (88.42)
T (N/mm^2)	0.48 (0.20)	0.71 (0.23)
IB (N/mm^2)	0.13 (0.06)	0.16 (0.04)
TS after 2 h (mm/mm)	0.15 (0.04)	0.11 (0.03)
WA after 2 h (kg/kg)	0.54 (0.16)	0.37 (0.12)

[a] Values are means (standard deviations). UF = urea-formaldehyde; CR = compressive resistance; MOR = modulus of rupture; MOE = modulus of elasticity; T = tensile strength; IB = internal bond; TS = thickness swelling; WA = water absorption.

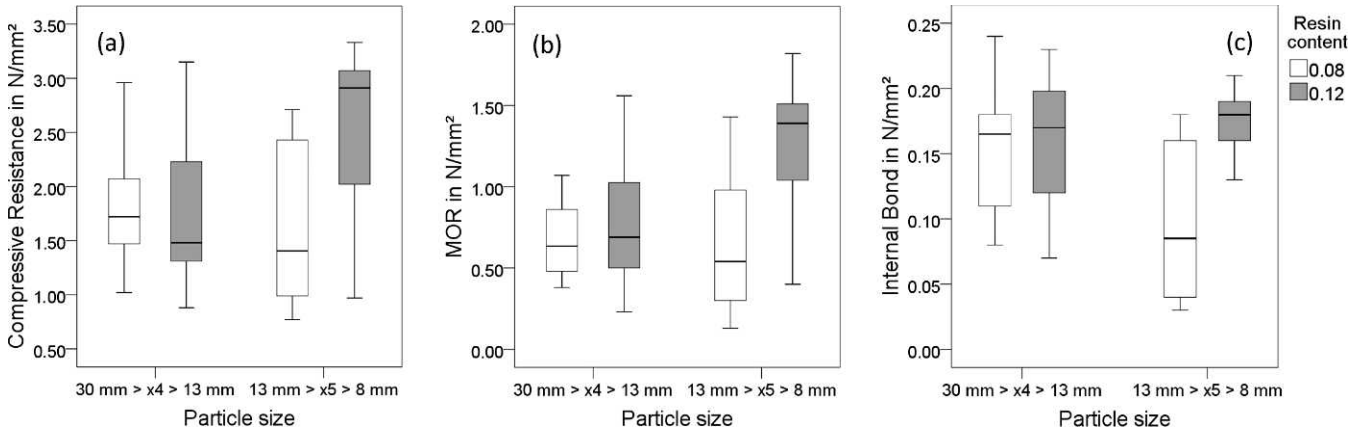

Figure 2.—Box plots showing the effect of interaction between particle size and resin content on (a) compressive resistance, (b) modulus of rupture (MOR), and (c) internal bond.

particles (x_4) with a UF resin content of 12 percent was pressed. This led to eight combinations with three replicates (apart from the last panel) each. In total 22 panels were produced.

The statistical analysis software package SPSS 18 was used for the data processing. An analysis of variance was performed to evaluate the factor influence on the different dependent variables. As the dispersion of panel density is partly high, the panel density was included as a covariate in analysis of variance. Also partial ETA^2 values were calculated, defining the amount of variance that is explained by a factor without the other factor's influence (Backhaus et al. 2011). Finally the results were compared with commercially available insulation boards to evaluate bark panel properties.

Mechanical board properties

All boards were tested for their mechanical properties. The tests were conducted according to the procedure specified in the European standards EN 310, EN 317, EN 319 (European Committee for Standardization [CEN] 1993a, 1993b, 1993c), DIN 52192 (DIN 1979b), and DIN 52188 (DIN 1979a).

After conditioning the panels at 20°C and 65 percent relative air humidity for 1 week, they were cut into samples following EN 326-1 (CEN 1994), after which samples were taken from different positions within one board to randomize density differences due to the production process. The samples were tested for static bending (MOE and MOR), compressive resistance (CR), IB, T, TS, and WA after 2 and 24 hours of immersion in water at 20°C.

Samples used for testing measured 50 by 450 mm for MOR and MOE, 50 by 50 mm for CR, 50 by 200 mm for T, and 50 by 50 mm for IB using a Zwick/Roell Z 250 universal testing machine. Moreover, 50 by 50-mm samples were used for testing TS and WA.

All boards were also evaluated for their physical density.

Measuring the thermal conductivity

The thermal conductivity was determined following the European standard EN 12667 (CEN 2001) with the thermal conductivity measurement device EP500 of Lambda-Measurement Technologies Corporation.

The sample with a given thickness is positioned between the two plates of different temperatures. When the temperature gradient during the sample is stationery, the heat flow q through the sample is constant, and the thermal conductivity can be calculated according to Equation 1. The time t it takes until the heat flow is stationary can be estimated by Equation 2, where a is the thermal diffusivity (Eq. 3; Ashby 2011). Measurements for this investigation were taken at a temperature of the cooling plate of 10°C and a temperature difference to the second plate of 15 K.

The thermal conductivity of bark boards (500 by 500 by 20 mm) was measured. The bark-based insulation panels showed a moisture content (MC) of 12.2 percent on average, with a standard deviation (SD) of 0.6 percent.

The density of the samples varied from 370 to 520 kg/m^3. In order to also gain knowledge about the thermal properties of bark mats of lower density, two measurements on bark bulk material (bulk density, 200 and 250 kg/m^3) with a height of 30 mm were carried out. Bark material from fraction x_5 (13 mm $> x_5 \geq$ 8 mm) with an average MC of 13.4 percent was used for those measurements.

The specific heat capacity for ongoing analysis was used following the data measured by Gupta et al. (2003).

$$q = -\lambda \cdot \frac{dT}{dx} \tag{1}$$

$$t = \frac{w^2}{2 \cdot a} \tag{2}$$

$$a = \frac{\lambda}{\rho \cdot c_p} \tag{3}$$

where

q = heat flow density (W/m^2),
λ = thermal conductivity (W/(m·K)),
T = temperature (K),
x = horizontal position within a wall (m),
t = time (s),
a = thermal diffusivity (m^2/s),
ρ = density (kg/m^3),

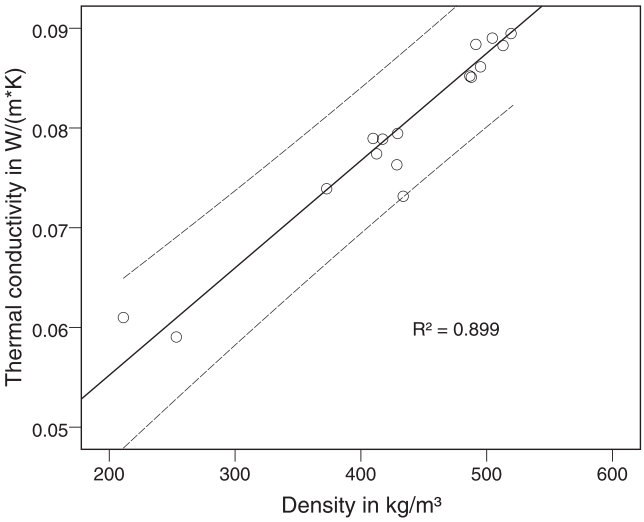

Figure 3.—Linear regression model for the correlation between density and thermal conductivity of bark-based insulation boards and bark loose bulks (with 95% confidence interval for the regression line).

c_p = specific heat capacity (J/(kg·K)), and
w = wall thickness (m).

Results

Densification properties and bulk density of bark

The obtained data for bulk density for different fractionations of the dry bark is presented in Table 2. The influence of the particle size on the bulk density is highly significant ($P < 0.001$).

Owing to agitation, compressed bark material shows an average compression ratio of 1.16. Thus the influence of the particle size on the compression ratio is highly significant ($P < 0.001$), although the differences between the groups are only marginal.

Mechanical board properties

Panel density has a significant influence on mechanical board properties (e.g., Xing et al. 2007 or Gupta et al. 2011), which could also be shown for the low-density bark panels that were investigated. Panel density is highly significantly ($P < 0.001$) positive correlated with CR, MOR, MOE, T, and IB. The positive correlation between panel density and TS after 2 hours of water immersion is significant ($P < 0.05$). Only WA after 2 hours of storage is not significantly influenced by panel density (Table 3).

A two-factorial analysis of variance including the covariate panel density reveals which variables have a significant influence on the investigated mechanical board properties (Table 4). The particle size has a significant ($P < 0.05$) influence on the MOR, which is on average 13 percent lower with coarser particles than with finer ones. IB is highly significantly ($P < 0.001$) affected by particle size where it is 33 percent higher with panels made of coarser particles. Boards made of coarser particles also showed a 31 percent lower TS after 2 hours of water immersion and a 47 percent lower WA (Table 5).

As expected, a higher resin content is at least very significantly ($P < 0.01$) beneficial for all tested panel properties (Table 6). Particle size and resin content show a highly significant interaction influence on the CR (Fig. 2a). Interestingly, a higher resin content only makes sense for the finer particles because 4 percent more resin could not improve the CR with the coarse particles. The same context was observed for the MOR (Fig. 2b). The IB of bark-based insulation boards made from coarse particles is on average 60 percent higher than that of panels with finer particles when only using 8 percent UF resin (Fig. 2c). For panels with a higher resin content (12% UF), the particle size does not have a significant influence on the IB.

Thermal bark properties

For the thermal conductivity measurements of the investigated bark samples, the influence the independent variables resin content (0.08, 0.12), particle size (30 mm $>$ $x_4 \geq 13$ mm and 13 mm $> x_5 \geq 8$ mm), and the covariate density have on the dependent variable thermal conductivity was tested using a two-factorial analysis of variance. The results showed that neither the resin content nor the particle size has a significant influence on the thermal conductivity of the bark samples. The sample density, however, has a highly significant ($P < 0.001$) influence on the thermal conductivity. Following a linear regression analysis was conducted leading to the model in Equation 4 with a coefficient of determination of 0.9. Also, the null hypothesis that no systematic coherence exists can be highly significantly ($P < 0.001$) denied (Fig. 3). It could be shown that for the investigated density range (200 to 550 kg/m^3), the thermal conductivity of a bark layer increases 0.011 W/(m·K) with every 100 kg/m^3 of additional density in the bark layer.

$$\lambda = 1.08 \cdot 10^{-4} \cdot \rho_i + 3.37 \cdot 10^{-2} \quad (4)$$

where

λ = thermal conductivity (W/(m·K)) and
ρ_i = density (kg/m^3).

Interpretation of the results

Traditional investigations focusing on bark panels mainly refer to higher density boards (>500 kg/m^3; e.g., Volz 1973, Yemele et al. 2008, Gupta et al. 2011). Their results that increased bark content is negatively correlated with mechanical board properties could also be confirmed for lightweight bark panels. Nevertheless mechanical strength requirements for insulation boards are lower than those for structural engineered wood products.

Mechanical and physical properties of insulation boards are relevant with respect to their technical applicability. Therefore the IB can be seen as a characteristic describing the adhesion of the single particles when strain is put on orthogonally to panel plane. In terms of IB, the investigated low-density bark-based panels showed relatively good properties compared with other insulation materials (Fig. 4).

Compressive strength is highly affected by panel density (Pfundstein et al. 2007) and is very important with regard to application areas where insulation materials are subjected to compression loads (e.g., floorings). Again the investigated low-density bark-based panels showed a comparatively good performance (Fig. 5).

Schwemmer (2010) defined a minimum T of 0.07 N/mm^2 when investigating insulation materials made of reed mace

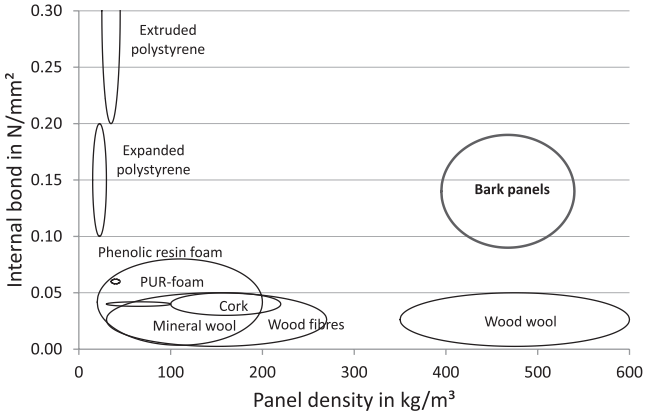

Figure 4.—Internal bond of insulation materials by comparison (data apart from that of bark according to Pfundstein et al. 2007, p. 13).

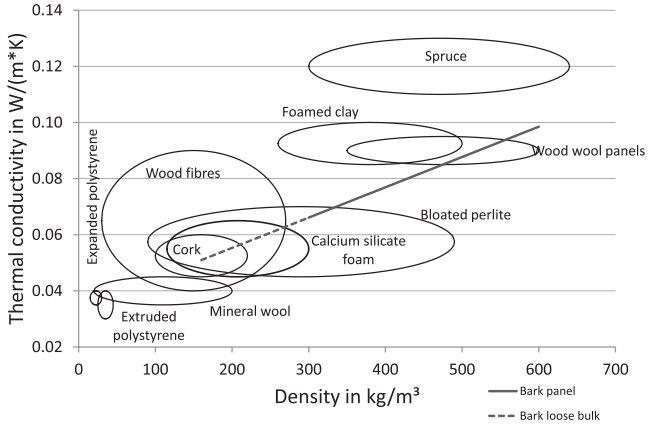

Figure 6.—Thermal conductivity of insulation materials by comparison (data apart from that of bark according to Pfundstein et al. 2007, p. 9).

(*Typha* species). From that point of view, the produced bark-based insulation panels are competitive, having an average T of 0.59 N/mm^2 (SD = 0.24 N/mm^2).

The TS after 24 hours of water storage at 20°C was limited with 15 percent in the investigation of Schwemmer (2010). The bark-based panels of the present study showed on average a TS of 13.3 percent (SD = 4%) after 2 hours and 18.0 percent (SD = 3.8%) after 24 hours of immersion. Therefore, the TS of the investigated panels is relatively high, which should be reduced by wax additives or other resin systems.

The MOR of a standard wood fiber insulation panel with a density between 230 and 400 kg/m^3 and thicker than 19 mm has to be at least 0.8 N/mm^2 according to EN 622-4 (CEN 2010). For the investigated bark-based insulation panels the average MOR was 0.76 N/mm^2 (the lower limit of the 95% confidence interval for the average is 0.63 N/mm^2 and the upper limit is 0.90 N/mm^2).

The results presented above illustrate that bark insulation panels are competitive compared with panels available on the market.

In conclusion, only the TS is relatively high and has to be optimized in further product development.

In order to evaluate the thermal properties of bark mats and bark-based panels, the investigated measurements were compared with those of commercially available insulation products. Therefore insulation material characteristics according to Barbu and Pieper (2008), Pfundstein et al. (2007), and Gammerith (1996) were used.

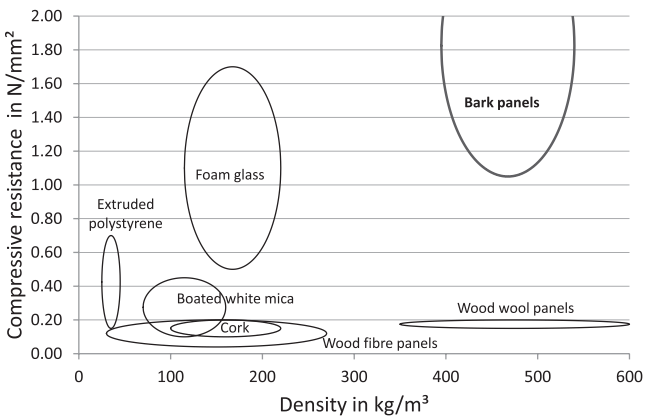

Figure 5.—Compressive resistance of insulation materials by comparison (data apart from that of bark according to Pfundstein et al. 2007, p. 13).

An analysis of the thermal properties shows that bark panels with the same density as spruce (*Picea abies*; 470 kg/m^3 and 15% MC) have an approximately 30 percent lower thermal conductivity at 0.084 W/(m·K) than solid wood, which is comparable to measurements taken by Martin (1963). The thermal conductivity of the bark-based panels is considerably better than that of bark–coal panels produced by Naundorf et al. (2004) and Warnecke (2006) that have a thermal conductivity of 0.18 W/(m·K), although panel density was connotatively higher in those studies.

Based on the experience gained during investigations on bulk density and densification characteristics of bark particles, one can assume that for bark-based panels, at least a density of 250 kg/m^3 will be requested to ensure sufficient contact of particles during the pressing process. Depending on particle size, the bulk density of bark mats varies between 180 and 260 kg/m^3. In the case of a bark mat/layer with a density in that range, one could achieve thermal conductivity properties otherwise common with cork or calcium silicate foam (Fig. 6).

For insulation materials, there are other meaningful parameters in addition to thermal conductivity (Kain et al. 2012), because a low thermal conductivity only minimizes the heat flow density according to Equation 1. If, however, the outside temperature of a house changes, the time t (Eq. 2) until the inner surface temperature of the house changes noticeably should be maximized in order to achieve a comfortable indoor climate. This principle also can be applied with simple passive solar heating, where the building wall is heated up during the day by sunlight, and the heat flow through the wall reaches the inside ideally not before the cool evening hours. This transit time is maximized by not only minimizing the thermal conductivity, λ, but also the thermal diffusivity, a (Eq. 3; Ashby 2011).

Our results as presented in Figure 7 show that the bark-based insulation boards produced do not have a very low thermal conductivity but do have comparatively low thermal diffusivity values and could therefore be well suited for heat storage–optimized insulation materials for buildings.

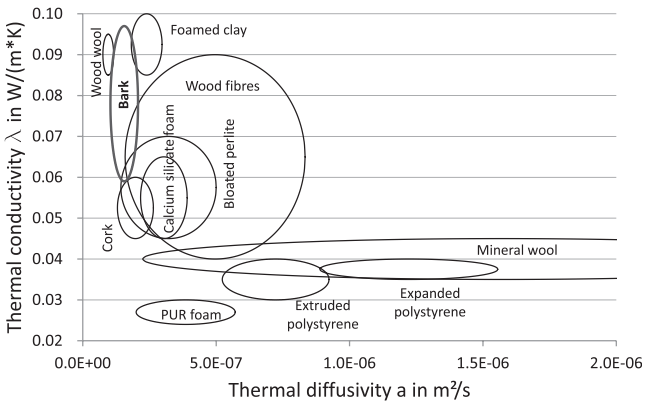

Figure 7.—Thermal conductivity and thermal diffusivity of insulation materials by comparison (data apart from that of bark according to Pfundstein et al. 2007, pp. 8–9).

Conclusions

Bark is available in large quantities and up to now has not been used much for higher value–added products. Because tree bark has interesting characteristics in order to protect a tree's inner life, one can assume that it also could be suitable as an insulation material. Within this study lightweight bark-based insulation panels were produced that are comparable to typical insulation materials on the market with respect to their mechanical properties. Because the density of bark-based panels is significantly higher than that of common insulation materials, their thermal conductivity is relatively high, but still in a range that allows their application as an insulation material. Because of the high specific heat capacity of bark and the relatively high density compared with common insulation materials combined with a good thermal conductivity, the thermal diffusivity of the bark-based panels is excellent compared with typical insulation materials. Resulting buildings equipped with insulation layers made of the studied bark panels would be more consistent with regard to their thermal performance under transient exterior temperatures, which adds to the comfort of interior rooms.

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