Utilization of alternative wood particles for modern thermal insulation products

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Abstract. Thermal insulation materials play a vital role in minimising energy loss in building operation and also affect the amount of greenhouse gas emissions associated with heating and cooling. In this context, it is becoming an increasingly important milestone to find suitable thermal insulation materials that not only meet the technical requirements but also minimise their environmental impact. The trend towards the use of eco-friendly materials for thermal insulation reflects the construction industry's desire to contribute to environmental protection and the transition to more sustainable models of building construction and renovation. For more than 20 years, a number of research teams have been investigating the possibility of replacing synthetically produced materials such as mineral wool and polystyrene foam with natural fibre-based insulation materials. These alternatives include wood as a traditional, easily renewable raw material. This, together with the low energy intensity of processing and manufacturing wood materials, contributes to its low carbon footprint. Compared to traditional synthetic insulation materials, which are often energy intensive to produce, wood is a more environmentally friendly choice. However, with many European countries now facing a potential shortage of higher quality wood, it is necessary to look for alternative sources of wood, including in the field of thermal insulation materials, materials with a lower carbon footprint that can be produced from lower quality wood or from wood waste that would otherwise only have an energy use. The paper is devoted to the study and use of suitable wood waste and secondary raw materials from spruce wood (coarse wood chips, sawdust and wood flour) for the development of modern thermal insulations with the aim of an environmentally friendly and less energy-intensive production process compared to conventional insulants.

1. Introduction

In the construction industry, there is an increasing emphasis on environmental sustainability and reducing environmental burdens. In the context of the new requirements under the Green Deal for Europe to reduce greenhouse gas emissions by 55% (by 2023 compared to 1990 emissions) and the expectation of achieving zero emissions in 2050 [1], new alternative ways to achieve a balanced and environmentally friendly approach to the construction and operation of buildings and the production of building materials must be sought. In the field of building construction, the above requirements are reflected in the new adaptation of the Energy Performance of Buildings Directive [2], the adaptation of which was submitted in December 2023 and approved in April 2024. In the context of the forthcoming adaptations to the requirements for new building construction and the necessary adaptation of existing buildings, a new demand for thermal insulation materials is emerging, without which favourable energy performance of buildings cannot be achieved.

Thermal insulation plays a vital role in minimising energy loss in building operation and also affects the amount of greenhouse gas emissions associated with heating and cooling. In this context, it is becoming an increasingly important milestone to find thermal insulation materials that not only meet technical requirements but also minimise their environmental impact. The drive to use environmentally friendly materials for thermal insulation reflects the building sector's desire to contribute to environmental protection and the transition to more sustainable models of building construction and renovation. Over the past 20 years, a number of research teams have been investigating the possibility of replacing synthetically produced materials such as mineral wool and polystyrene foam with natural fibre-based insulation materials, particularly lignin-cellulose and keratin fibre-based materials [3–7]. Today, there is a manufacturer in virtually every European country that offers alternative insulants based on wood, paper, textiles, sheep wool, flax or hemp. These insulants are offered in a quality that allows them to be incorporated into building structures. These materials are usually marketed in accordance with EAD 040005 00 1201 [8].

2. Thermal insulation materials based on wood and wood fibres

Wood is one of the traditional, easily renewable raw materials. This, together with the low energy intensity of processing and manufacturing wood materials, contributes to its low carbon footprint. Compared to traditional synthetic insulation materials, which often require high energy costs in production, wood is a more environmentally friendly choice. Wood has been used for thermal insulation for a long time and there are wood wool products according to EN 13168 [9], expanded cork products according to EN 13170 [10], wood fibre products according to EN 13171 [11] and loose fill insulation based on wood fibres according to EN 15101-1 and EN 15101-2 [12-13] on the market. Wood is chemically composed of cellulose (about 50 % depending on the wood type), hemicellulose (about 22–28 % depending on the type) and lignin (26–35 % depending on the type). Compared to other natural fibres, wood therefore has a higher content of hemicellulose and especially lignin. It generally has better mechanical properties and a more uniform composition and microstructure compared to e.g. agricultural crops (hemp, flax, etc.) [14].

In terms of CO_2 emissions, the GWP (Global Warming Potential) [15] shows a negative value of -1.29 kg CO_2/kg at the beginning of the A1-A3 phase (according to the LCA Database Sphera - wood with density of 500 kg/m^3). In the case of wood treatment, pulping and the production of wood fibre insulators, there is a strong deterioration of environmental parameters, firstly in terms of the necessary transport of material between the different processors in the different production stages (A2 indicator) - if not carried out in one production plant, and then in terms of CO_2 emissions associated with production in the A3 phase, when the GWP indicator for wood wool materials is already close to 0 or even below 0 (e.g. for wood fibre boards the GWP is around -1.0 kg CO_2/kg, for wood wool boards it is -0.04 kg CO_2/kg). It is therefore evident that any modification of the raw materials and the use of additional components to the wood mass substantially worsens the environmental parameters of the final product. Overall, wood-based insulants (wood wool, fibres and wood particles) have very interesting thermal insulation properties. The coefficient of thermal conductivity can reach 0.036 W/(m·K) for products with lower bulk masses (up to 50 kg/m^3), and gradually increases to 0.05 W/(m·K) for higher bulk masses and greater fibre/particle thicknesses. As with all natural fibre-based thermal insulation materials, the thermal conductivity of wood-based insulants is strongly influenced by the humidity of the environment in which the insulator is incorporated [16]. However, nowadays many European countries are starting to face a potential shortage of higher quality timber, so it is necessary to look for alternative sources of timber also in the field of insulation materials, materials with a lower carbon footprint that can be produced from lower quality timber or from wood waste that would otherwise only have an energy use.

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As mentioned above, wood and wood-based thermal insulators are traditional products that have a long tradition worldwide. However, in recent years, due to pests and drought in central Europe (especially in the Czech Republic), wood resources are diminishing and it can be assumed that wood will soon be scarce and its price will increase. The timber market in the Czech Republic has been quite turbulent for the last few years. In 2020, the price of raw timber started to increase gradually up to a level of around EUR 120/m^3 of 1st quality raw timber (spruce wood) according to the statistics of the Czech Statistical Office [17]. This price subsequently started to fall to around EUR 75/m^3 in 2023. A gradual increase in prices is expected again in 2024. Wood is one of the materials that can be relatively easily recycled and possibly used for energy purposes, and in most cases can be processed into a filler for the widest industrial use. Wood waste is quite strongly represented in the various EU countries, accounting for around 20 % of the total wood consumption in each country [17]. In the field of thermal insulation materials, it represents a relatively interesting raw material source, especially in terms of long-term availability, as its production is less linked to local logging. The research work sought to identify and characterise suitable waste and secondary raw materials that could be used in the most environmentally friendly and energy-efficient way for the production of thermal insulation.

3. Input raw materials and their characterisation and treatment

Three types of raw materials were selected for the research work:

- coarse root chips from root growth, which are produced during the basic processing of raw wood,
- wood shavings from the subsequent operations of calibrating and planing the sawn timber,
- wood particles arising from the sanding of wood (from filter systems).

Figure 1. Photos of coarse wood chips (left), wood shavings (middle), wood flour (right)

The key properties of the feedstock were determined (sieve and microscopic analysis) and then the raw materials were treated in various ways by milling, crushing and sorting to process them into a form suitable for the production of thermal insulation materials for use in the construction industry. The treatment of all raw materials was carried out only in a dry way, with the aim of finding ways to reduce the bulk density and thermal conductivity of the raw materials while using the least energy-intensive processes.

As shown in Figure 1, the coarse wood chips from the root growth contained bark contamination and particles up to 50 mm (length) in size with predominantly linear dimensions, while the wood shavings showed significantly higher purity and particles up to a maximum size of 10 mm with predominantly planar dimensions. For wood flour, the particle size was less than 1 mm.

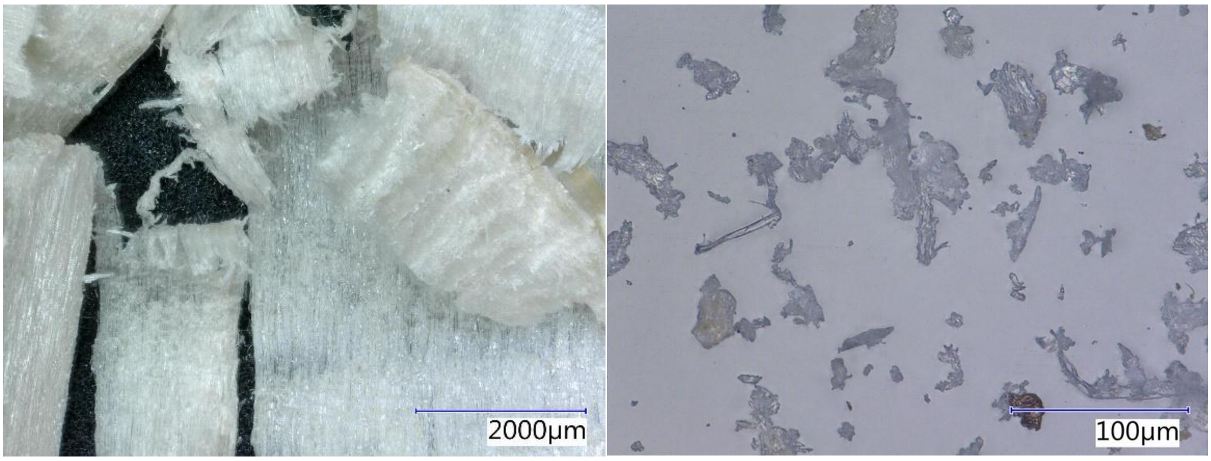

Figure 2. Microscopic photograph of wood shavings particles (left) and wood flour (right)

The loose bulk density was determined on the basic raw materials and the following values in Table 1 were found.

Table 1. Overview of loose bulk densities of raw materials

Raw material	Loose bulk density [kg/m^3]
Wood chips	325
Wood shavings	94
Wood flour	202

As can be seen from the values obtained, the loose bulk density of the wood chips is too high, so the wood chips were ground into two sub-fractions (fine and coarse), whose loose bulk density was reduced to a level by grinding:

- fine wood chips: $\rho_s = 258$ kg/m^3,
- coarse wood chips: $\rho_s = 219$ kg/m^3.

Figure 3. Photos of crushed wood chips (fine wood chips on the left, coarse wood chips on the right)

Sieve analysis was performed on the samples and the results are shown in the graph in Figure 4 below and in the Table 2.

Table 2. Sieve analysis of wood raw materials – measured data

Shive size [mm]	Total passing [%]			
	Chips coarse	Chips fine	Shavings	Wood flour
16	100.00	100.00	100.00	100.00
8	100.00	100.00	96.82	100.00
4	99.98	99.97	65.04	100.00
2	98.80	99.95	44.45	100.00
1	41.03	77.35	21.26	99.00
0.5	18.64	30.16	9.54	96.80
0.25	7.31	11.96	0.98	92.00
0.125	2.77	4.94	0.14	84.50
0.063	0.89	1.51	0.03	69.80
0	0.00	0.00	0.00	0.00

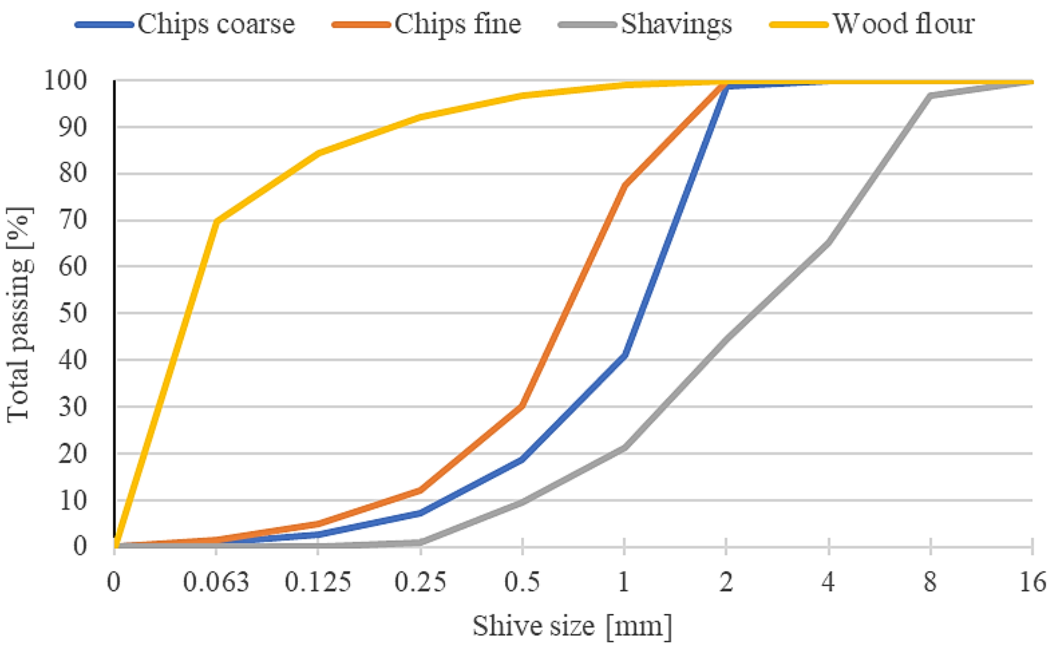

Figure 4. Sieve analysis of wood raw materials

As can be seen from the results obtained, the finest particles were found in wood flour, where the proportion of particles below 0.063 mm was about 70 %. In addition, fine wood chips contained overall about 77 % of particles below 1 mm, coarse wood chips contained about 41 % of particles below 1 mm and shavings contained only a very low proportion of particles below 1 mm (overall only about 21 %). Further work verified the possibility of crushing/grinding the particles (at a crusher speed of 6000 rpm) and their separation into individual fractions. The results were evaluated on the basis of the achieved loose bulk density. The results are presented in the following Table 3.

Table 3. Adjustments of wood shavings (overview of achieved loose bulk densities)

Operation	Conditions	Loose bulk density [kg/m^3]
Milling	10 s	107
Milling	30 s	110
Milling	60 s	156
Separation	Fraction 0–1 mm	152
Separation	Fraction 0–2 mm	115
Separation	Fraction 1–2 mm	100
Separation	Fraction 2–16 mm	78

As can be seen from Table 3, shavings milling is not efficient (compared to woodchip treatment). Grinding results in a demonstrable increase in loose bulk density, which is not desirable from the point of view of insulation properties. Separation of the individual fractions appears to be more efficient and energy saving in this case. It can be seen that the lowest loose bulk density is found in the 2–16 mm fraction, however, the bulk density of the 1–2 mm fraction is also acceptable in terms of bulk density, while the 0–1 mm fraction, which has a maximum bulk density of over 150 kg/m^3, appears to be problematic. Therefore, for further experiments in terms of thermal insulation development, ground wood chips of both fractions were selected, as well as shavings without treatment and shavings of fractions 1–2 mm and 2–16 mm. Subsequently, the usability of the wood meal separately was tested, due to the high fineness of the particles, the portion below 0.063 mm was separated and the possible use of these fine parts for the production of vacuum insulators was verified.

4. Verification of the possibility of using wood particles for the production of conventional thermal insulation

As mentioned above, two fractions of treated wood chips were selected for further work, as well as shavings in untreated form and then sorted fractions of 1–2 mm and 2–16 mm. The samples were conditioned under:

- standard laboratory conditions at +23 °C and 50 % relative humidity,
- under elevated humidity conditions at +23 °C and 80 % relative humidity.

The loose bulk density, moisture content and thermal conductivity were again determined on the samples. The determination of the thermal conductivity coefficient was carried out at steady state according to EN 12667 and ISO 8301 [19, 20] at a mean temperature of +10 °C and a temperature gradient of 10 K. The samples were always packed into the thermal insulation frame in which the measurements were made (the influence of the frame was compensated for in the evaluation results). The results are shown in Table 4 below.

Table 4. Overview of measured thermal insulation properties

Sample / moisture state	Environment: 23 °C/50 % RH			Environment: 23 °C/80 % RH		
	Loose bulk density [kg/m^3]	Moisture [%]	Thermal conductivity [W/(m·K)]	Loose bulk density [kg/m^3]	Moisture [%]	Thermal conductivity [W/(m·K)]
Fine chips	278	9.8	0.0607	261	14.3	0.0669
Coarse chips	246	9.7	0.0598	222	14.4	0.0617
Shavings unmodifies	94	10.4	0.0488	93	14.7	0.0516
Shavings 1–2 mm	126	10.3	0.0494	130	14.6	0.0536
Shavings 2–16 mm	77	10.9	0.0484	77	14.8	0.0517

As can be seen from the results obtained, the sorption moisture contents of the individual samples were comparable because they were representatives of spruce wood (in all cases). In terms of the loose bulk densities, slightly different values were found for some samples, which was due to the different shape of the sample (compared to the llose bulk density determination), but it can be concluded that the bulk densities obtained in the determination of the thermal conductivity coefficient correspond more closely to the real bulk density after incorporation into the building. In terms of the thermal conductivities obtained, it can be seen that the best values are shown by the untreated shavings and the shavings of the 2–16 mm fraction, where the thermal conductivity was found to be in the range of 0.0484–0.0488 W/(m·K) at normal laboratory humidity and 0.0516–0.0517 W/(m·K) at elevated humidity.

5. Verification of the possibility of using wood particles for the production of vacuum insulation

Furthermore, a study was carried out to investigate the possible use of fine particles below 0.063 mm for the production of vacuum insulation panels. The specific surface area was determined using the BET method and it was found that the specific surface area of the raw material is equal to 1.45 m^2/g, which is a relatively high value for a normal filler, but the specific surfaces of materials used for vacuum insulation are usually much higher (smaller particle sizes) [21]. Therefore, a mixture of wood particles and nanosilica Aerosil 200 from Evonic was used to produce the insulators. The ratio of pyrogenic SiO_2 and wood flour was set at 6:4, and 3 % of fine viscose fibres were added to the mixture to achieve the required mechanical properties. In the sample design, the target bulk density was determined to be in the range of 200–300 kg/m^3 and the thickness of the samples was set at 15 mm. The pressing of the samples was carried out in steel moulds at different pressing pressures, gradually increasing the pressing pressure until compactness and the desired mechanical properties of the samples were achieved at a pressure of 750 kPa. Test specimens were made from a mixture of wood flour, nano SiO_2 and viscose fibres, resulting in an average bulk density of 279 kg/m^3.

Figure 5. Photo of moulded sample of wood flour core insulation for vacuum insulators

For the determination of the thermal conductivity coefficient, the FOX200 Vacuum device was used, which allows the determination of thermal conductivity as a function of pressure. The measurements were performed in steady state according to EN 12667 and ISO 8301 [19, 20] at a mean temperature of 10 °C and a temperature gradient of 10 K.

The thermal conductivity was determined at pressure values of 1000; 300; 100; 10; 1; 0.1 and 0.05 mBar.

Table 5. Results of the determination of the thermal conductivity coefficient as a function of pressure

Pressure [mBar]	1000	300	100	10	1	0.1	0.05
Thermal conductivity [W/(m·K)]	0.0301	0.0205	0.0146	0.0088	0.0068	0.0058	0.0055

In addition to the normal mean temperature of 10 °C, the thermal conductivity was determined at various mean temperatures of 20, 30 and 40 °C, both at normal atmospheric pressure and at vacuum (0.05 mBar).

Table 6. Overview of the dependence of the thermal conductivity on temperature at normal pressure and under vacuum

Pressure [mBar]	Thermal conductivity [W/(m·K)]			
	10 °C	20 °C	30 °C	40 °C
1000	0.0301	0.0303	0.0308	0.0312
0.05	0.0055	0.0059	0.0062	0.0064

As can be seen from the results obtained, the samples made from a mixture of wood flour and nanosilica show very good thermal insulation properties and have an interesting potential in terms of possible use for the production of vacuum insulation panels.

6. Discussion of results and conclusion

Within the framework of the conducted research works, different types of secondary raw materials based on wood mass were characterized, which could be used for the production of different types of thermal insulation materials. Currently, there are a number of wood-based insulants on the construction market that have been used for a long time for the insulation of building structures. However, these materials are primarily made from growing wood, which may soon be in short supply in Central Europe, and it is also necessary from a sustainable development perspective to look for similar materials based on alternative raw materials. Three different types of wood materials were analysed in the study. These were rootstock chips, which are coarse, bark-soiled and have no major industrial use. In addition, it was the shavings produced in timber mills during the processing (planing) of timber elements. This raw material also has no major use, mainly because of its diversity, and is often used for energy purposes (pressing of fuel pellets). As a final source of wood pulp, wood flour collected in filter grinding systems for wood processing (e.g. in the furniture industry) was chosen. This material also has no sophisticated industrial use. Different methods of treatment of the raw material, by grinding, crushing and separation into fractions, were tested in the study. Grinding proved to be interesting only in the case of coarse chips, while grinding deteriorated the parameters of the raw material in the case of shavings. The loose bulk density of the feedstock ranged from 94 to 325 kg/m^3. For wood chips, the loose bulk density was reduced to 219–258 kg/m^3 by grinding to different finenesses. For wood shavings, separation into sub-fractions appeared to be more effective, with the lowest bulk density of 77 kg/m^3 for the 2–16 mm fraction. When the thermal insulation properties were determined, it was found that the untreated shavings and the shavings of the 2–16 mm fraction showed the best values. For these samples, the thermal conductivity was found to be in the range of 0.0484–0.0488 W/(m·K) at normal laboratory humidity and 0.0516–0.0517 W/(m·K) at elevated humidity condition. Although these values can be considered higher compared to those of industrially produced insulants, these are insulations that have been made from wood with minimum additional energy-consuming technological processes. These are values that are common for other alternative natural-based insulants (e.g. peat, moss, etc.), as shown for example in a study carried out at the University of Oulu, Finland, published in 2021 [5]. The work carried out also verified the possibility of using fine wood fractions below 63 microns for the production of vacuum insulation panels, where wood could largely substitute nanosilica. Core insulators made using 40 % wood flour were found to exhibit very interesting properties under reduced pressure. These properties are comparable to those of pure SiO_2 based insulants [21]. For the industrial use of this raw material, however, further additional thermal treatments of the wood mass will be necessary to prevent outgassing at reduced pressure and to ensure the durability of the resulting vacuum panels over time; however, even these treatments will be less energy intensive than the production of nano SiO_2, so high potential can be seen in this direction of using the wood mass.

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