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INVESTIGATION OF THERMAL INSULATION PANELS MADE OF WOOD SHAVINGS

Natural insulations made from by-products available in large quantities are growing in importance. In the wood processing industry, among other materials, wood chips and shavings are available in large quantities. The aim of this research was to determine the optimal density of thermal insulation panels made of different wood shavings. Planer and drill shavings of spruce (Picea abies) were used as raw material. The same amount of both types of shavings was compacted. The thermal conductivity of both types of shavings asymptotically approached a value between 0.05 and 0.06 W/mK. After a preliminary experiment, panels were manufactured with densities from 55 to 400 kg/m^3 with urea formaldehyde and with methyl diphenyl diisocyanate glue. The thermal conductivity and the bending strength of the panels increased with increasing density. The bending strength of the panels glued with methyl diphenyl diisocyanate was much higher than for the others with the same densities.

Keywords: natural insulation, wood shavings utilization, urea formaldehyde, methyl diphenyl diisocyanate

Introduction

Due to climate change and the need to conserve natural resources, the energy consumption requirements of buildings have become more stringent, necessitating better thermal insulation for buildings [Gorshkov et al. 2015; Jie et al. 2018]. Nowadays more types of thermal insulation materials are available, but in parallel with the reduction in the energy consumption of buildings, natural-based and waste materials, recyclable and cascade recycled materials and solutions available in large quantities have become more important, and their use

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is expected to increase in the future [Stolarski et al. 2013; Szostak et al. 2013; Tettey et al. 2014; Peñaloza et al. 2016; Dovjak et al. 2017; Sierra-Pérez et al. 2018].

Therefore, natural-based insulation materials are an important research topic today. Researchers have investigated several natural and waste materials, such as rice husks [Buratti et al. 2018], sugar cane, coconut fiber [Panyakaew and Fotios 2008], papyrus [Tangjuank and Kumfu 2011], hemp [Collet et al. 2017], various grasses [Vėjelienė et al. 2011], reed [Asdrubali et al. 2016], jute [Fadhel 2011], pineapple [Tangjuank 2011], oil palm [Manohar 2012], wool [Zach et al. 2012], paper [Russ et al. 2013; Aksogan et al. 2018], bark [Kain et al. 2013; Pásztory and Ronyecz 2013], cork [Limam et al. 2016], as well as feathers, wood ashes, cotton, animal hair [Rébék-Nagy and Pásztory 2014; Ahmed et al. 2019], pine and spruce needles [Muizniece et al. 2015] and straw [Volf et al. 2015; D'Alessandro et al. 2017], olive seeds [Binici and Aksogan 2016], and other wastes [Vasilache et al. 2010; Hadded et al. 2016; El Wazna et al. 2017; Bakatovich et al. 2018] to determine their suitability for insulating houses. Wood chips and sawdust have been used as insulation since the early 1900s. There were also experiments with different fibers, primarily cellulose, in the same century, according to Bozsaky [2010], and today the most common wood-based insulation materials have densities of 30-80 kg/m^3 and thermal conductivity of 0.037–0.067 W/mK, according to two papers [Hurtado et al. 2016; Schiavoni et al. 2016]. The utilization of by-products of birch veneer production is an example presented in the work of Veitmans and Griefelds [2016]. Other types of insulation made of plant fibers have similar thermal conductivity [Schiavoni et al. 2016; Alabdulkarem et al. 2018]. A relatively large amount of energy must be used to manufacture panels from fibers, especially when the fiber particles are less than 1 mm in size. Theoretically, the smaller the particle, the higher the energy demand. Higher energy demand is not a goal in producing environment-friendly insulation materials. Therefore, the question arises of how to utilize by--products from wood-based materials for insulation using the least possible energy.

Wood chips are available in large quantities from the wood processing industry. Their use is diversified: they serve mainly as an energy source, but can also be used to make pulp or to produce various panels [Harkin 1969; Faria et al. 2020; Mirski et al. 2020; Wu et al. 2020; Gößwald et al. 2021]. Insulation is also one of the possible uses.

Porschitz and Schwarz [2000] built a house from finished panels and used slightly compressed planer shavings as thermal insulation. The thermal conductivity of the chips was 0.04 W/mK at approx. 70 kg/m^3 density. Sekino and Kawamura [2004] manufactured insulating panels in different thicknesses with densities between 80 and 120 kg/m^3, using no adhesive during the process. The panels were wrapped in polyethylene film after compression. Using different initial materials with different densities, it was found that a better insulating panel can be made from lower-density wood. Starting from the same initial material, thermal insulation performance deteriorates with compaction. A panel with a density of 45 kg/m^3 had a thermal conductivity of approximately 0.052 W/mK; at 75 kg/m^3 it was approximately 0.06 W/mK. Thermal conductivity was measured using a special particle geometry. Later these types of insulation were carbonized at different temperatures, and their thermal conductivity ranged from 0.044 to 0.06 W/mK [Sekino and Yamaguchi 2010]. Hazrati-Behnagh et al. [2016] made panels with a density of 240 kg/m^3 from planer shavings, which had thermal conductivity between 0.048 and 0.051 W/mK. Insulation was produced with densities between 80 and 150 kg/m^3 using different sizes of chips, which were placed inside panels without adhesive; these had low mechanical strength and thermal conductivity between 0.045 and 0.05 W/mK [Newmann and Salisbury 2015]. Most of these insulating materials were used in bulk form between boards and not in bonded panels, which restricts their use.

Most studies related to wood shavings have used a closed place to be filled with insulating material. No study has been published on the production of stiff insulation panels made of wood shavings. There are two main groups of studies, depending on the additives used with the raw materials. Some investigators do not use adhesives, but merely compress the panels and use the plasticization effect of lignin or filling of closed spaces, or use a blow-in technology, such as filling of a wood frame compartment [Veitmans and Griefelds 2016; Porschitz and Schwarz 2000; Sekino and Kawamura 2004; http://www.tyunnos.co.uk] The other group use natural or organic adhesives [Tangjuank 2011; Hurtado et al. 2016] or uramin (UF) and melamine formaldehyde (MF) [Hazrati-Behnagh et al. 2016]; however, the effect of the adhesive has not been investigated, particular in the case of methylene diphenyl diisocyanate (MDI).

The main objective of this research was to determine the optimal density of stiff thermal insulation panels made of different kinds of wood shavings from a woodworking factory, without any other energy investigation concerning refinement of the raw material. The secondary purpose was to investigate the effect of different adhesives on the thermal conductivity and on the bending strength of panels, which must be handled, machined, transported and stored.

Materials and methods

Drill and planer shavings from spruce (*Picea abies*) were used in the experiments, and the raw material was generated from dried wood (moisture content 8%) by processing with a thickness planer and a drill. The shavings from the planers and drills had average thicknesses of 0.083 mm and 0.167 mm respectively. The shavings were utilized in their original shapes; no additional treatment was performed. The thermal conductivity tests were performed first without adhesives and then after using adhesives as described below. For thermal conductivity measurement a custom-made device was used. The measurement was made by a hot plate method; the temperature difference between the cold and the hot side was 15°C. To ensure parallel heat flow lines, insulation of 20 cm width was used on the sides of the chambers. The measurement started when a steady state was achieved. A steady state was accepted when the fluctuation of the last fifty measurements was under 0.002 W/mK. One measurement was performed every minute, and the average of the last hundred measurements was calculated as the sample result. It is highly important to minimize the uncertainty of measurement of thermal conductivity, as is well explained in the literature [Dominguez-Munoz et al. 2010]. The average of results for samples of the same type was calculated as a sample group result. Three samples were produced from each type of panels, with a size of 500 mm × 500 mm × 20 mm.

Determination of wood shaving thermal conductivity at different compression levels without adhesive

A quantity of 1.5 kg of conditioned (20°C, 35%) shavings was placed into the thermal conductivity measurement apparatus, and their thermal conductivity coefficient was determined at different compression levels. In the first step, the shavings mat were 150 millimeters thick; after the thermal conductivity measurements the shavings were compacted in steps of 10 mm (150 mm, 140 mm, 130 mm …). Planer shavings can be compressed to 60 mm, but drill shavings can be compressed only to 70 mm, because of their higher strength, resulting from the more compact particle geometry. Thermal conductivity was measured for three samples made from planer shavings and three from drill shavings.

Investigation of glued thermal insulation panel made of wood shavings

Only the conditioned planer shavings were used for pressing glued panels using adhesives, because of their better thermal insulation properties and their higher industrial availability. Two types of adhesives were used in the process: urea formaldehyde (UF) and methylene diphenyl diisocyanate (MDI). The viscosities [mPa·s] of the UF and MDI were 500 mPa·s and 176 mPa·s respectively. While the UF has more components and its dry matter content is 68% by weight, MDI is a single liquid component adhesive. Based on the compression and heat conductivity measurements, panels with target densities of 200, 250, 300, 350 and 400 kg/m^3 were manufactured using UF, and panels with target densities of 150, 200, 300 kg/m^3 using MDI. The desired density could be achieved by admeasuring the calculated amount of shavings and adhesives required for the 20 mm × 500 mm × 500 mm panels; the press was able to stop precisely at 20 mm thickness. The difference in density of the samples was less than 2%. A 4% urea–formaldehyde (UF) resin was used; the hardener of the resin was a 35% aqueous solution of ammonium sulfate. A 4% MDI adhesive was also used. Three samples were prepared from five panels of different density glued with UF and three of different density glued with MDI; altogether eight different insulation panels were investigated. MDI expands during bonding, so the impact of the adhesive type and the bonding type was different. While UF forms a physical-mechanical bond, MDI bonds to cellulose chemically. To improve foaming of the MDI adhesive, the low moisture content (8%) shavings were wetted to 12%, assuming that the degree of expansion can affect thermal conductivity. The pressed panels were 20 mm thick. The pressing temperature was 180°C, at a specific pressure of 4.24 MPa. The pressure was reduced in several steps in a laboratory press (Siempelkamp).

After pressing, the panels were conditioned (20°C, 65%) for a week. In the first step, the thermal conductivity was measured in three samples from each type of insulation panels. The size of samples for testing bending strength is significantly smaller than the original 500 mm × 500 mm panel. For this reason, ten samples were used for the bending tests for each type of insulation panels. The bending strength of the panels was examined using an Instron 5566 machine, according to the standard, with 3-point bending [MSZ EN 310].

Scanning electron microscopic (SEM) images were taken to compare the two types of adhesives within the panels. To determine the wetting properties of MDI and UF resins, contact angles (θ) were measured on sessile drops (using a PG-X goniometer) on a wood surface. The volume of the drops was set to 4 µl. Five dynamic measurements were made at randomly selected points, and the contact angle was measured after 15 seconds. The average value of the five tests was calculated.

Results and discussion

Determination of thermal conductivity of wood shavings at different compression levels without adhesive

Thermal conductivity decreased as a function of compression in both drill and planer shavings.

The thermal conductivity of drill shavings was higher than that of planer shavings at all densities, which can be explained by the geometry of the shavings: the thicknesses of the drill and planner shavings were 0.16 mm and 0.08 mm respectively. Figure 1 shows the thermal conductivity of both types of shavings, asymptotically approaching a value between 0.05 and 0.06 W/mK. Compression decreased the air spaces and channels between them, and caused more closed air bubbles to form. This blocked the free movement of air between the shavings and decreased their thermal conductivity. The measurement chamber was not able to compress shavings to more than 155 kg/m^3, although it would have been interesting to compress the shavings more. Presumably further compression would push out more air from the spaces, and the contact surface of the shavings would increase, which would probably increase their thermal conductivity. However, the density of the panel made of planer shavings seems to be very close to the minimum thermal conductivity, at around 150-160 kg/m^3. Further compression would cause an increase in thermal conductivity.

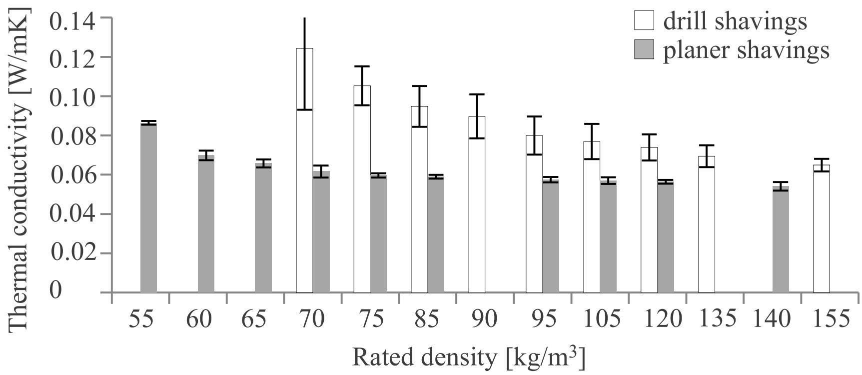

Fig. 1. Thermal conductivity of drill and planar shavings as a function of density without adhesive

Investigation of glued thermal insulation panels made of wood shavings

The lowest density of a glued panel was set to 150 kg/m^3, and the highest to 400 kg/m^3. As expected, the thermal conductivity of the panels deteriorated with increasing density. The reason is that compression increasingly displaced air from the panel, and thermal bridges were formed between flakes in contact, so that the insulation performance deteriorated (Fig. 2). The ideal range is below 200 kg/m^3, although the panel's strength is not then satisfactory (with the amount of adhesive used), and thus it does not meet the initial objectives: a thermal insulation panel which can be machined, transported and stored.

Previous studies have focused mostly on thermal conductivity, and have used insulation mostly in closed wall sections [Porschitz and Schwarz 2000; Sekino and Kawamura 2004; Geving et al. 2015; Schiavoni et al. 2016] without producing stiff panels. This leads to significantly lower density, and consequently also to lower thermal conductivity.

Thermal conductivity increases with increasing density. With higher moisture content for the same density, we found a slight decrease in thermal conductivity (from 0.088 W/mK to 0.086 W/mK) with MDI panels, but the best value was 0.062 W/mK for the 150 kg/m^3 panel (Fig. 2). These panels have lower thermal conductivity than those reported in the literature on wood shavings [Fadhel 2011; Russ et al. 2013; Limam et al. 2016]. The purpose of these panels was not only to reduce thermal conductivity, but also to increase mechanical strength and to find an optimal balance between these two parameters.

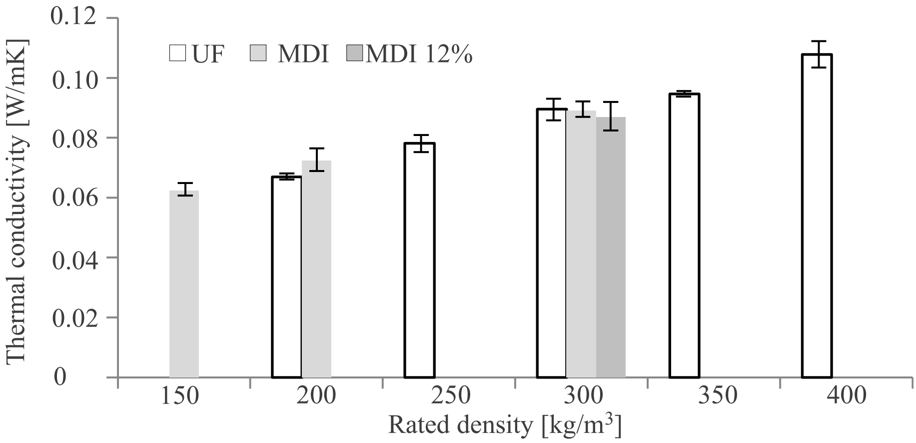

Fig. 2. Thermal conductivity of panels made with UF and MDI adhesives

After measuring thermal conductivity, bending strength was examined. With UF bonded panels, the 200 kg/m^3 rated density panels could not be measured because they were destroyed during the preparation of the samples. With increasing density, the bending strength of the panels increased, and this has a positive influence on the strength of the product. The insulating ability of the panels decreases with increasing density, so the lowest bending strength was measured at 250 kg/m^3 density (0.123 MPa on average), and the highest bending strength was measured at 400 kg/m^3 density (2.068 MPa on average) (Fig. 3).

Faria et al. [2020] used *Eucalyptus grandis* shavings to produce medium-density boards with UF adhesive. The nominal density of the panels was 700 kg/m^3, and the lowest adhesive (UF) content was 6%. Because both the density and the adhesive content were significantly higher for these manufactured panels, their bending strength (6.17 MPa) was higher than that of our panels (2.07 MPa). Gößwald et al. [2021] also produced particleboards from wood shavings, with a target density of 475 kg/m^3 and using 6%, 9% or 12% UF adhesive. The panels with 6% adhesive content had similar bending strength (2.56 MPa) to our panels with 4% UF adhesive and 400 kg/m^3 density (2.068 MPa).

The panels made with MDI adhesive have greater bending strength than those made with UF adhesive. The lower-density panels have lower bending strength than the higher-density ones. A higher moisture content and a better foaming adhesive slightly increased the bending strength (from 2.574 MPa to 2.594 MPa). Papadopoulos [2006] obtained similar results. He compared UF and MDI glued particleboards and found that the panels with MDI adhesive had superior properties, but did not explain the differences. Of course, the mechanical properties of panels can also be influenced by other properties, such as the origin of the wood [Bardak et al. 2019], particle size and particle properties [Łukawski et al. 2019], but in this case the differences can be explained only by the adhesive.

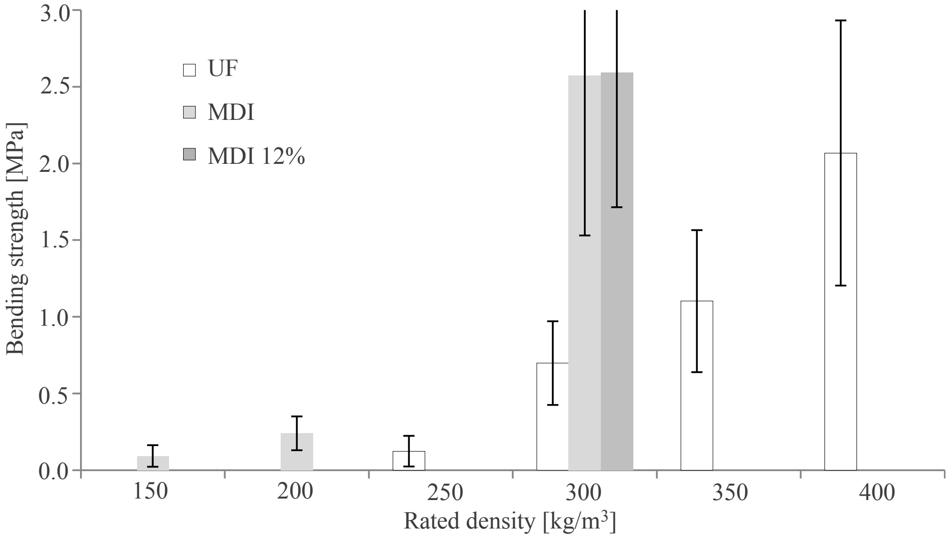

Fig. 3. Bending strength of panels made with UF and MDI adhesives

The good wetting of a wood surface by an adhesive plays a key role in the ability to form inter-facial interactions. Wetting can be achieved if the contact angle between the surface and the adhesive is below 90°. The measured contact angles for MDI and UF adhesives were 35.7° ±2.4° and 84.6° ±3.1°, respectively. As shown in Figure 4, wetting is better with MDI. It can be assumed that the inter-facial interactions are also stronger than with UF. This is in accordance with the observations regarding the differences in their mechanical properties (Table 1).

Table 1. Differences between the two adhesives

UF	MDI
UF adhesive drops on wood sample surface	MDI adhesive drops on wood sample surface
350×	350×

MDI penetrates the cell wall and covers the wood surface more efficiently than UF. The same amount of MDI adhesive covers a larger surface. The SEM pictures show that the UF adhesive film is thinner and more fragile, and cracks

a) b)

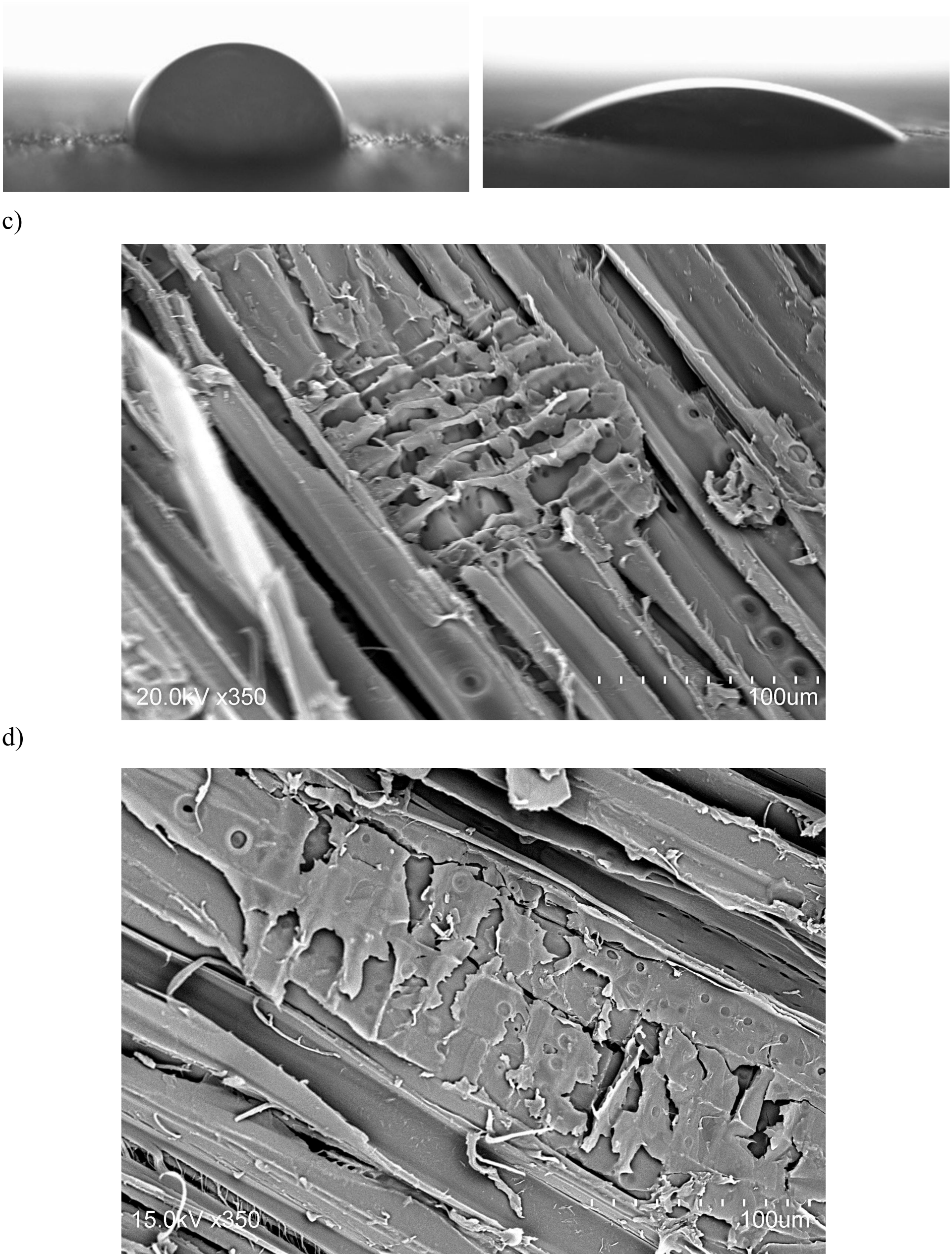

Fig. 4. MDI and UF adhesives on wood sample surfaces: adhesive drops on a wood surface (a) UF and (b) MDI, SEM imgages of adhesive films on a shaving panel fructure surface (c) UF and (d) MDI

are more frequent. Filaments can be frequently found at the edge of the adhesive film. These properties and the chemical nature of the bonding cause better bonding to the wood and produce a higher bending strength.

Conclusion

The thermal conductivity of wood shavings is strongly affected by their bulk density and their geometry. The thinner planer shavings provide significantly better thermal insulation at the same density than the thicker and more massive drill shavings. Thermal conductivity decreased in parallel with compression for both drill and planer shavings, and the thermal conductivity of both shaving types asymptotically approaches a minimum value between 0.05 and 0.06 W/mK, until the bulk density reaches 150 kg/m^3. As the density increases during compression, the difference in thermal conductivity of the planer and drill shavings decreases. Further compression increases thermal conductivity in bonded panels up to 400 kg/m^3. The optimum density for minimum thermal conductivity is around 150 kg/m^3, and the optimum density for mechanical strength is 300-350 kg/m^3. The 300 kg/m^3 MDI panel has about 42% higher thermal conductivity and 27 times higher bending strength than the 150 kg/m^3 panel.

Adhesives play a significant role in determining the bending strength of panels, but they have a negligible effect on their thermal conductivity. The wetting properties of an adhesive greatly affect the size of the bonded surface and thus the strength of the panel. The 300 kg/m^3 MDI panel has 3.68 times higher strength than the UF panels with the same density. An increase in the moisture content of shavings from 8% to 12% has a negligible effect on the strength and the thermal conductivity of MDI panels. It would be interesting to conduct further experiments with highly expandable MDI, increasing the moisture content of the shavings.

The use of planer shavings, a by-product of the woodworking industry, requires only a small amount of energy to produce thermal insulation materials which can be optimized for thermal conductivity and mechanical strength. This cascade utilization of renewable materials is a good opportunity to reduce carbon dioxide emissions.

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