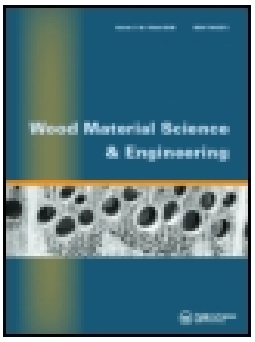

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ORIGINAL ARTICLE

Effect of wood and panel density on the properties of lightweight strand boards

Tien Pham Van, Christian Schöpper, André Klüppel and Carsten Mai

Wood Biology and Wood Products, Georg-August-University, Göttingen, Germany

Abstract

The objective of this study is to evaluate the effect of wood and panel density on the properties of lightweight strand boards (SB). For this purpose, we compared lightweight SBs made of low-density kiri wood (*Paulownia tomentosa*), medium-density pine wood (*Pinus sylvestris*) and high-density beech wood (*Fagus sylvatica*). Single-layer non-oriented SBs were manufactured with target densities of 300 and 400 kg m^{-3}. Cohesion of beech boards was insufficient for further testing. The larger compaction ratio of kiri boards resulted in a steep density profile and mechanical properties, namely modulus of rupture (MOR), modulus of elasticity (MOE) and internal bond (IB), superior to those of pine boards. However, Kiri panels exhibited a higher thickness swelling (TS). MOR of kiri boards was 2.6 and 1.6 times higher than that of pine boards at 300 and 400 kg m^{-3}, respectively, while these ratios were only 1.8 and 1.2 for MOE. We conclude that the effect of wood density on bending properties reduces as panel density increases and that the compaction ratio affects MOR more than MOE, which is mainly determined by panel density. Hence, utilization of low-density kiri wood allows reduction of board density with MOE being the limiting factor.

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KEYWORDS
Bulk density; compaction ratio; kiri wood; *Paulownia tomentosa*; strand board

Introduction

Oriented strand boards (OSB) are wood-based panels designed as a cheaper replacement for plywood. Their structure optimizes the mechanical properties of boards that can be manufactured from low quality (small diameter) logs. The wood elements, strands, are approximately 15–25 mm wide, 75–150 mm long and 0.3–0.7 mm thick. The high aspect ratio (strand length divided by thickness) and horizontal alignment in the flat-pressed boards result in large contact areas between overlapping strands on which adhesive bonds can form. Due to their relatively large size, the surface area of the strands is smaller than the area of elements in particleboards, so that a lower adhesive content is needed for the same amount of adhesive per wood surface area. Additionally, the orientation of the strands in the surface layers increases strength in the respective direction. For these reasons, mechanical properties of OSB are superior to most other wood-based panel products for a given adhesive content and board density (Dinwoodie 2000, p. 232 ff.). Accordingly, OSB is mainly used for load-bearing applications such as subflooring, roof sheathing, wall and ceiling elements as well as for packaging (EPF 2017). These applications require a high strength-to-weight ratio (i.e. specific strength) and, thus, further increasing the specific strength would add value to the product. This is especially true for applications in the transport sector where lightweight allows fuel-saving and easier handling.

In general, there is no proper definition for the term 'lightweight board'. However, it can be stated that lightweight boards exhibit densities of less than 500 kg m^{-3} (Poppensieker and Thömen, 2005). The density of wood-based boards can be reduced in various ways: by using low-density wood species, by densifying the material to a lower degree, by adding light non-wood materials or by employing a sandwich structure with a low-density core (Nilsson *et al*. 2013). For this low-density core various types of lightweight materials are used such as an extremely low-density wood, hollow materials, honeycomb paper, polystyrene foam, polyurethane foam, polycarbonate, polypropylene, ultra-lightweight foam, and wood fibre-based, maize granular (Karlsson and Åström, 1997, Jivkov *et al*., 2012, Shalbafan *et al*., 2013, Burnett and Kharazipour, 2018). The disadvantage of combining wood-based boards with other materials is that these materials are often non-renewable and that mixtures are usually more difficult to recycle. Additionally, sandwich boards allow little flexibility during the manufacture of furnitures because reinforcements are required at the board edges and for joints and fittings.

Utilization of low-density wood species and reduced densification are the other possible approaches to manufacture lightweight boards with acceptable strength properties. Good bonding between the wood particles that make up the board requires a minimum compaction ratio (ratio of board density to wood density). For a given board density, therefore, strength properties are generally expected to increase as the density of the wood raw material decreases (Klauditz 1952). The compaction ratio of particleboards is typically around 150% (Irle and Barbu 2010, p. 7). Zhou (1990) suggested a density of 650 kg m^{-3} for OSB from hybrid poplar (density ca. 400 kg m^{-3}), which corresponds to a similar compaction ratio. However, the industry also produces particleboards and OSB with distinctly lower compaction

CONTACT André Klüppel akluepp@gwdg.de Wood Biology and Wood Products, Burckhardt Institute, Georg-August-University, Büsgensweg 4, 37077 Göttingen, Germany. ☎+49 (0)551 39 33916.

ratio. Chen *et al.* (2010) found that strength properties of aspen OSB increase with board density but this increase gradually lowered as density continued to rise. Properties acceptable for many applications, however, may be achievable at much lower densification ratios (<100%), if high-quality strands are used (Mirski and Dziurka 2015).

The objective of this study is to evaluate the possibility of using low-value and low-density Paulownia wood to produce lightweight OSB. This includes investigating the effect of low compaction ratios. Randomly-oriented strand boards (SB) were used as a model for OSBs to assess the effect of wood density on the properties of lightweight boards. To investigate the effect of wood density on the production of OSB, kiri SBs were compared with SBs made of the medium-density species pine (*Pinus sylvestris*) and the high-density species beech (*Fagus sylvatica*).

Material and methods

Strand production

Strands were produced from kiri, pine and beech logs, with the diameter of the kiri logs ranging from 12 to 20 cm and that of the beech and pine logs ranging from 30 to 35 cm. All logs were 2 m long and were manually debarked before stranding. The strands were manufactured by a knife ring flaker PZUL 8-300 (Pallman Company, Zweibrücken, Germany) at Fraunhofer WKI (Brauschweig, Germany) with a target length of 110 mm, a target thickness of 0.5–1 mm and a target width of 10–50 mm. A single wood stem was firmly held by a hydraulic clamp and moved towards the knife ring. For pine and beech, the feeding speed was 40 mm s^{-1}. For Paulownia, it was reduced to 36 mm s^{-1}, because faster feeding resulted in a high amount of damaged strands. All strands were directly sorted by a sieving shaker into 3 fractions: 10–30 mm, 30–50 mm and bigger than 50 mm. Sieve fractions smaller than 10 mm were discarded as fines. To avoid mould growth, the strands were immediately dried at 70°C to a moisture content of 3% to 5% in a drying oven. Then, strands were stored in plastic bags to keep the moisture content low. For panel manufacturing, the strand fractions were mixed in a ratio of 1:1:2 (10–30 mm:30–50 mm:>50 mm).

Strand characterization

For strand characterization, 100 g of each strand fraction were randomly selected. The strands were placed on a flatbed scanner (Expression 11000XL, Epson, Suwa, Japan) and carefully separated to make sure that they did not overlap. For every fraction, several images were recorded because the scanning area was too small for all strands. A white reference paper of 50×50 mm^2 was scanned with every image. To create a dark background with high contrast to the light strands, the scanner was not closed but it was covered with a carton. Images were processed with the program Image J (Rueden *et al.* 2017): Greyscale images were converted to binary ones by automatic thresholding so that the images were segmented into strands and background (Figure 1). The scale of the image was set on the basis of the reference paper. The area and minimum calliper diameter (Feret's diameter) of each strand were recorded using the software's integrated analysis functions. In this study, minimum Feret diameter served as a measure for the strand width. Assuming a perfectly rectangular shape, strand length was calculated on the basis of area (A) and width (W). In addition, the thickness of 20 randomly chosen strands from each fraction was measured manually with a dial gauge.

To calculate strand density, mass and volume of 20 strands were determined. The volume was determined by the submersion method. Each strand was attached to a sample

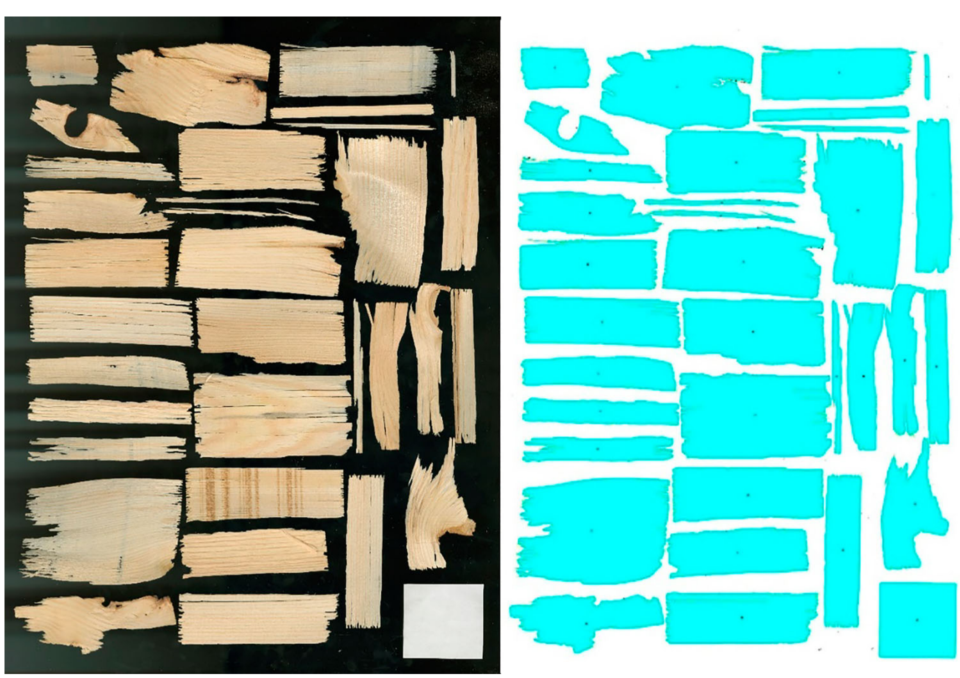

Figure 1. Example for scanned image before (left) and after (right) segmentation.

holder and immersed in a beaker filled with water without contacting the inner walls or the bottom of beaker. Before submersion, the beaker was placed on a scale and the scale was tared to the weight of the beaker (including water) with the immersed sample holder. The weight shown by the scale after immersion of the strand equals the mass of water displaced by the strand. As the density of water is ca. 1 g cm^{-3}, the value is equivalent to the volume of the strand in cm^3.

Determination of mat density

Mat density was determined by using unresinated strands. The mats were formed in the same way as for panel manufacturing using the same mixture of strand fractions and single-strand fractions. The amount of strands used to produce the mat was the same as that needed to produce a board with a density of 300 kg m^{-3}. The height of the mat was recorded for volume calculation (3 times for each fraction and species).

OSB panels manufacturing and testing

The strand fractions were mixed in a ratio of 1:1:2 (10–30 mm:30–50 mm:>50 mm) and directly blended with 5% (m/m based on oven-dry wood) pMDI (polymeric methylene diphenyl diisocyanate, I-Bond PB PM 4350, Huntsman, Everberg, Belgium) in a rotating drum blender at a speed of 30 rounds per minute. After mixing, the strand mat was manually formed in a lab-size forming box of 450 mm × 450 mm without orientation. The moisture content of the mat was adjusted to 10% by spraying water during blending. The mat was pre-pressed and directly placed into a single opening hot-press. A target thickness of 18 mm was established using two iron-distance bars. The boards were pressed at a nominal pressure of 6.3 N mm^{-2} and a temperature of 200°C for 15 s mm^{-1}. Target densities were 300 and 400 kg m^{-3}. After pressing, all boards were conditioned at 20°C and 65% RH for at least 2 weeks to reach the constant mass. Three replicate boards were produced for each factor combination (wood species and board density). The vertical density profile of each board was recorded with an X-ray densitometer (DAX, Fagus-Grecon GmbH & Co. KG, Alfeld, Germany). Bending strength (modulus of rupture, MOR) and modulus of elasticity in bending (MOE) were determined according to EN 310 (1993a; 7 replicates per board, $n = 21$), internal bond strength according to EN 319 (1993c; 5 replicates per board, $n = 15$). Thickness swelling was assessed after 24 h immersion in water at 20°C according to EN 317 (1993b; 5 replicates per board, $n = 15$).

Statistical analysis

Fifth and 95th percentiles of panel properties were calculated by

$$P_\alpha = \mu + t_{n-1,\alpha}\sigma \qquad (1)$$

where P_α is the αth percentile; μ is the sample mean; σ is the sample standard deviation, $t_{n-1,\alpha}$ is the αth percentile of the t-distribution with $n-1$ degrees of freedom; n is the sample size.

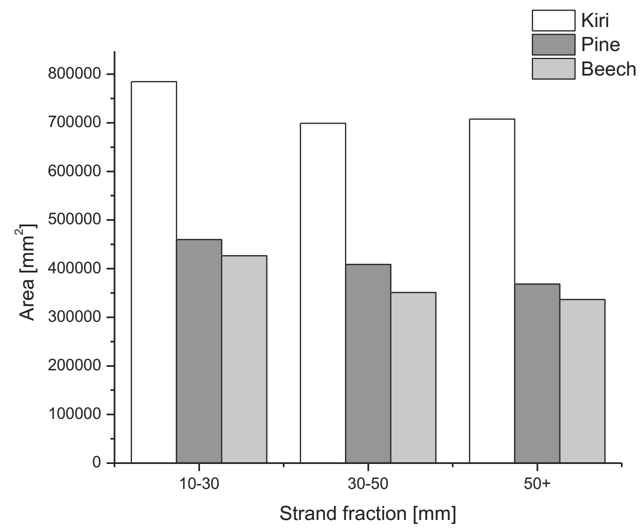

Figure 2. Total area of 100 g of strands for different strand fractions and species.

Results and discussion

Strand geometry and panel structure

The average density of kiri, pine and beech strands were 193, 238, 296 kg m^{-3}; 358, 495, 604 kg m^{-3} and 538, 605, 765 kg m^{-3} (min, mean, max), respectively. Kiri strands (100 g) covered the largest area on the scanner followed by pine and beech strands (Figure 2). The difference between pine and beech was relatively small, but consistent for all sieve fractions, with the area slightly decreasing as the sieve fraction increased (Figure 2). Distributions of strand length and width differed only slightly between wood species (Figure 3). Strands longer than 90 mm covered only a minor proportion of the total area so that most strands were shorter than the target length. Length distribution was very wide with two peaks for the smallest sieve fraction, while it was narrower for the larger fractions. Maximum strand width corresponded to the upper mesh size, but all sieve fractions included strands that were narrower than the lower mesh size. Accordingly, width distribution increased with increasing sieve fraction. Strand thickness varied widely and it seemed to depend on the wood species, with kiri strands being the thickest followed by pine and beech (Figure 4). Also, strands in the smaller sieve fractions appeared to be slightly thinner than those in the larger fractions. The thickness of most strands, however, was within the target range of 0.5–1 mm.

The most important difference between the wood species used in this study is their density. Strand densities determined for kiri and pine are similar to values given in the literature. That of beech is unexpected low but within the range reported by Kollmann (1951). Calculating the wood density based on strand area (of 100 g, Figure 2) and mean thickness (Figure 4) yielded the following values (average of three fractions): 175 kg m^{-3} (kiri), 332 kg m^{-3} (pine) and 448 kg m^{-3} (beech). These values are much lower than those found by the submersion method. Measured thickness values accordingly seemed to be too high. This may be due to surface roughness or deformation of strands. Therefore, thickness values may be used only for comparisons.

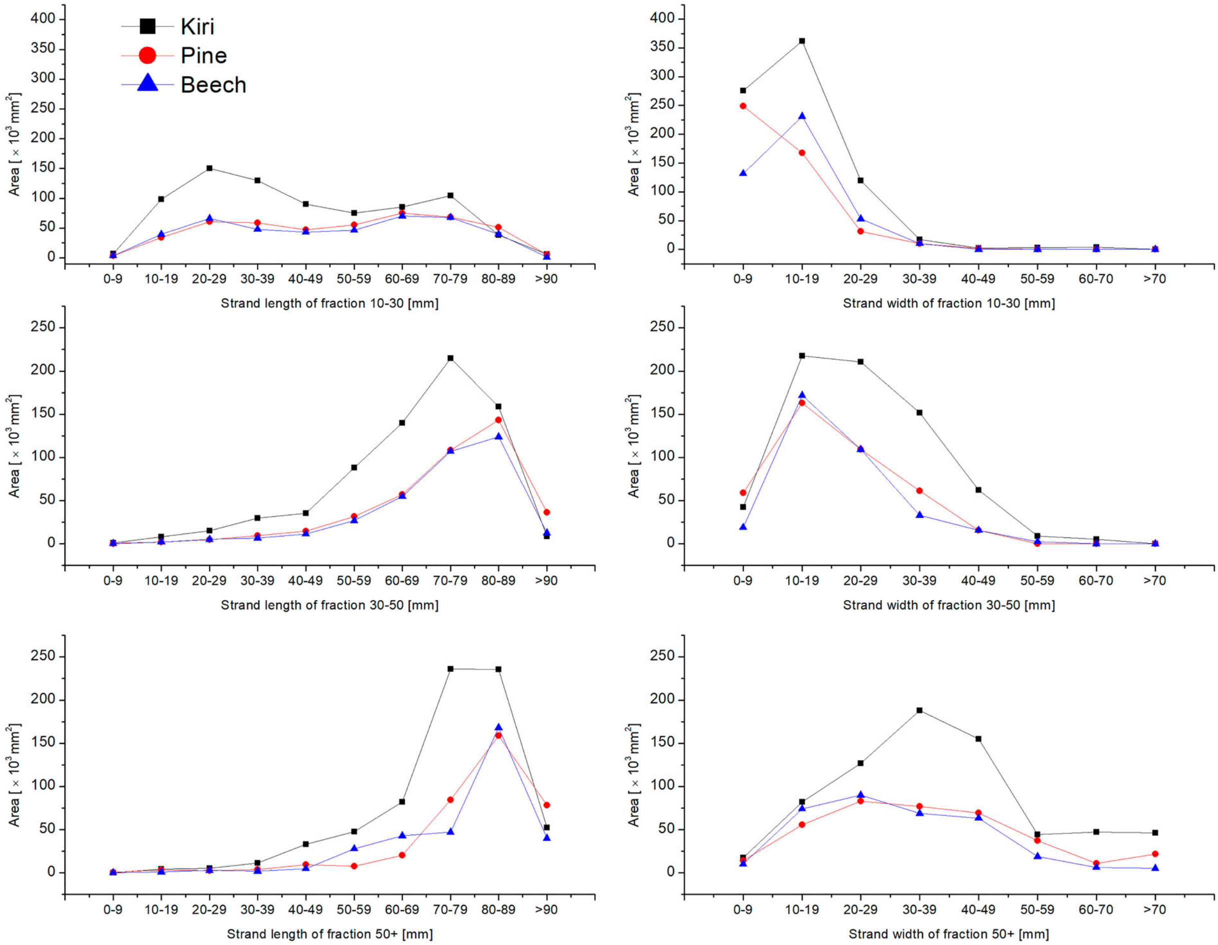

Figure 3. Distribution of strand area according to length and width of strand in each fraction.

The area of a specific mass of strands is affected by both wood density and strand thickness. While wood density determines the overall wood volume, strand thickness affects how this volume is distributed in vertical and horizontal direction. Consequently, a low wood density and thin strands result in a large strand area. Strand thickness is mainly controlled by the projection of the knives in the flaker and the feeding speed (Kruse *et al*. 2000). When logs of different densities are used to produce strands with identical settings, the low-density wood typically yields thicker strands. The reason is that the wood is compressed during the cutting process and expands afterwards. Due to the lower strength, this compression is higher in low-density woods. In the present study, a slower feeding force was used for stranding kiri wood as for pine and beech, which generally results in thinner strands. Still, this adjustment did not completely compensate for the density effect, so that strand thickness increases as wood density decreases. Comparing pine and beech, the effect of strand thickness on the strand area obviously compensated for the effect of wood density. For the strand area of kiri, the low wood density is the determining factor. The decrease of strand area with increasing sieve fraction is also related to strand thickness. The latter increases with sieve fraction, because thick particle is less likely to break into smaller parts during strand generation and handling.

Width and length of strands were very similar for the different species within each sieve fraction. Accordingly, strand shape is assumed not to cause differences in board properties. Target strand length is set by the distance of the scoring knifes in the flaker and usually can be controlled accurately. The reason for the short length of strands in this study probably is that the calculation method underestimates maximum length in fibre direction due to the underlying assumption that strands represent perfect rectangles. In contrast, minimum calliper diameter is assumed to correspond to the widest part of an irregularly shaped strand, so that the modelled strand with the identical area is slightly wider and shorter than the real one. Distribution of strand width is usually broader than that of strand length because it results from a fracture along the grain direction of the wood sheets immediately after cutting due to a bending force. The width distributions of single sieve fractions show that the vibratory screener mainly sorts strands by widths. In doing so, it effectively retains strands wider than the mesh size, but also narrower ones.

Bulk density of kiri strands was lowest followed by that of pine and beech strands, with the latter two being quite similar (Figure 5). It slightly increased with strand size, but the recorded density of the mixture did not obviously depend on a particular sieve fraction. The mixture of beech strands used for panel manufacturing had a bulk density of ca.

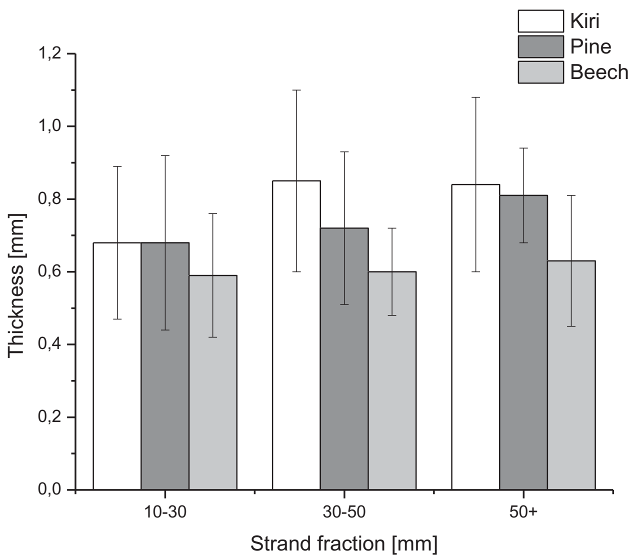

Figure 4. Strand thickness; columns: mean values; error bars: total span; $n = 20$.

100 kg m^{-3}. Accordingly, the mat was densified 3-fold or 4-fold during hot pressing of panels with target densities of 300 and 400 kg m^{-3}, respectively. Nevertheless, the obtained boards were not sufficiently solid for handling and cutting of specimens, so that investigating panel properties was not possible. Pine boards had a more solid structure than beech panels (Figure 6), although the bulk density of the mat was only slightly lower (Figure 5). Compared with kiri panels, pine panels contained more interparticle voids resulting in more porous edges and inhomogeneous panel structure (Figure 6). This was confirmed by the respective density profiles (Figure 7), which showed a jagged, horizontal line for pine panels. In contrast, the density profiles of kiri panels exhibited a smooth line with peaks near the surface.

A strand mat contains wood and voids. Thus, its bulk density depends on the wood density and shape of the strands, because the latter determines the void volume fraction of the mat. In this study, bulk density correlates remarkably close with strand surface area. Beside wood density, thus, strand thickness seems to be the crucial factor that determines mat density. Obviously, a decreasing strand thickness results in a mat with more horizontal layers, which increases the void volume in the mat. As for the strand surface area, the low thickness of beech strands seems to compensate for the lower density of pine resulting in a similar bulk density. In the same way, thicker strands in larger sieve fractions seem to cause the respective increase in mat density. The effect of strand width and length on mat density, the main difference between sieve fractions, seems to be negligible for flat strands. This effect contrasts with the wood furnish materials used for particleboards, the bulk density of which reduces as particle size increases (Schmutzler 1963, Shang *et al*. 1999). Also different from the findings in the present study, the pore structure of wood furnish for particleboards is mainly determined by the smallest fraction, because the smaller particles fill up the spaces between larger particles (Shang *et al*. 1999, Thömen and Klüppel 2008).

Upon densification, the void volume of the mat decreases and strands get closer to each other, because they are rearranged and deformed. As soon as continuous vertical strands columns are formed, wood is compressed. At low compaction ratios, movement and deformation of strands predominate and, thus, compression resistance of the mat is low. As the compaction ratio increases, densification of wood substance occurs and requires much higher forces so that compression resistance progressively increases (Zombori *et al*. 2001, Benthien *et al*. 2018). The present results show that the structure of the finished panel depends on wood density rather than mat density because the former determines the inter-particle void volume fraction: In beech panels, this fraction is so large that there is insufficient contact area between strands for adhesive bonding. For pine panels, the ragged density profile indicates small-scale density variations, i.e. alternation of wood substance and voids. In kiri panels, the strands seem to be in close contact.

Vertical density profiles of wood-based panels typically show peaks near the surfaces with a lower density in the

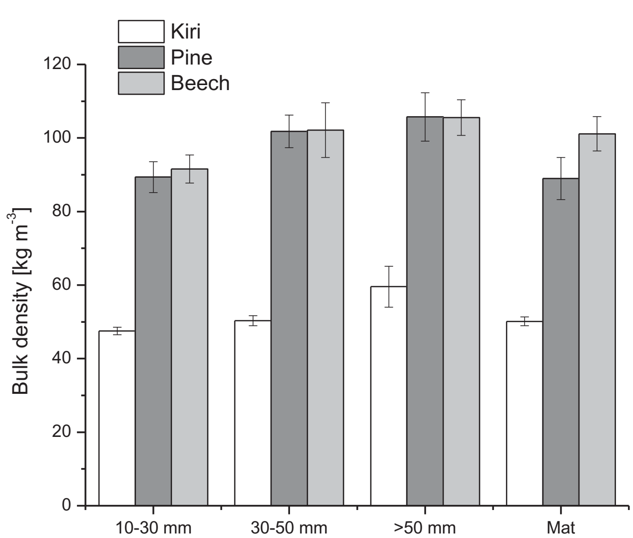

Figure 5. Bulk density of strand mats consisting of different species, sieve fractions and the mixture of fractions used for panel manufacturing; columns: middle value; error bars: from lower to upper value; $n = 3$.

Figure 6. Representatives samples of SBs panels from kiri, pine, beech (top to bottom) with a target density of 300 kg m^{-3} (left side) and 400 kg m^{-3} (right side).

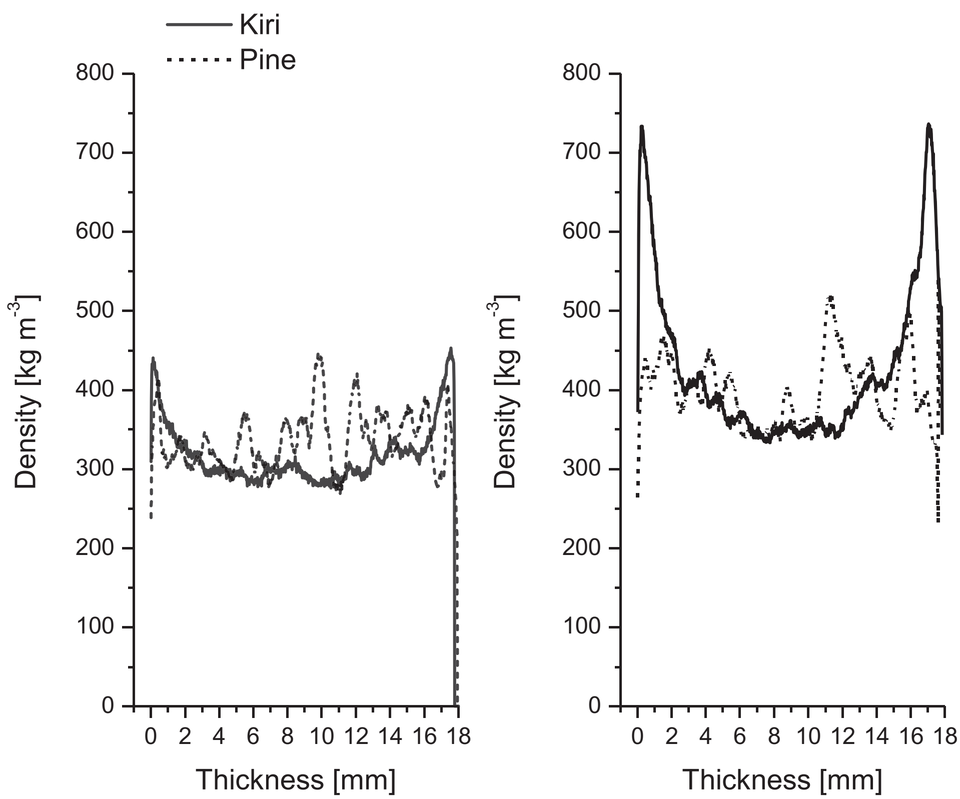

Figure 7. Representative vertical density profiles of pine and kiri boards with a target density of 300 kg m^{-3} (left) and 400 kg m^{-3} (right).

core. This profile is predominantly formed during the closing of the hot press. The stresses applied to each layer are the same and equal the mat pressure. Surface layers, however, heat up first and to a higher temperature than the core resulting in a lower compression modulus and higher densification. The effect of temperature certainly depends on the densification mechanism. It is obviously negligible for the rearrangement of particles, but crucially affects deformation and compression of wood. Furthermore, compression of wood particles is probably more sensitive to temperature changes than deformation, as MOE and compressive strength perpendicular to the grain are the most temperature-sensitive wood properties (Gerhards 1982). This is confirmed by the finding of v. Haas and Frühwald (2000) that the effect of temperature increase as mat density increases. Consequently, we assume that the vertical density profile of kiri panels showed distinct surface peaks because the low wood density required considerable densification of strands during hot pressing. In contrast, densification of the pine mat mainly involved strand rearrangement and deformation. The general finding that the utilization of low-density wood supports the formation of a more pronounced density profile accords with previous studies (Beck *et al*. 2009, Akrami *et al*. 2014). Also, the very narrow surface densities peaks are typical for boards made of low-density wood (Wang and Winistorfer 2000).

Panel properties

Strength values, i.e. MOR, MOE and IB, increased with board density and they were higher for kiri boards than for pine boards (Figures 8 and 9). At a low panel density (300 kg m^{-3}) the difference between kiri and pine panels was larger than at higher panel density (400 kg m^{-3}); for MOR and IB it was larger than for MOE: MOR of kiri boards was 2.6 and 1.6 times higher than that of pine boards at 300 and 400 kg m^{-3}, respectively, while these ratios were only 1.8 and 1.2 for MOE. Especially the internal bond strength of low-density pine panels was remarkably low. Thickness swelling of kiri boards exceeded that of pine boards, while water uptake during the test was similar for both species (Figure 10). While thickness swelling was higher at a high density, percentage of water uptake was higher for low-density boards. IB and TS of kiri boards met the standard requirements at 400 kg m^{-3} (panel thickness: 18–25 mm; EN 300:1997).

Mechanical properties of wood-based panels depend on the strength of individual wood particles and on the adhesive bonds between them. Strength of wood particles generally increases with density, which depends on species (initial density) and densification during hot pressing. However, densification can also damage particles and, thus, decrease their tensile strength (Price 1976, Geimer *et al*. 1985). Bonding strength between the particles is affected by resin area coverage and strand contact area (He *et al*. 2007). For a given mass fraction of resin, the large surface area of low-density wood particles results in low resin area coverage. In contrast, strand area contact increases as wood density reduces because of the more solid board structure described above. Due to the development of a vertical density profile, board density and compaction ratio are not uniform within the board and effects of wood density are not identical for different board properties. While bending properties are

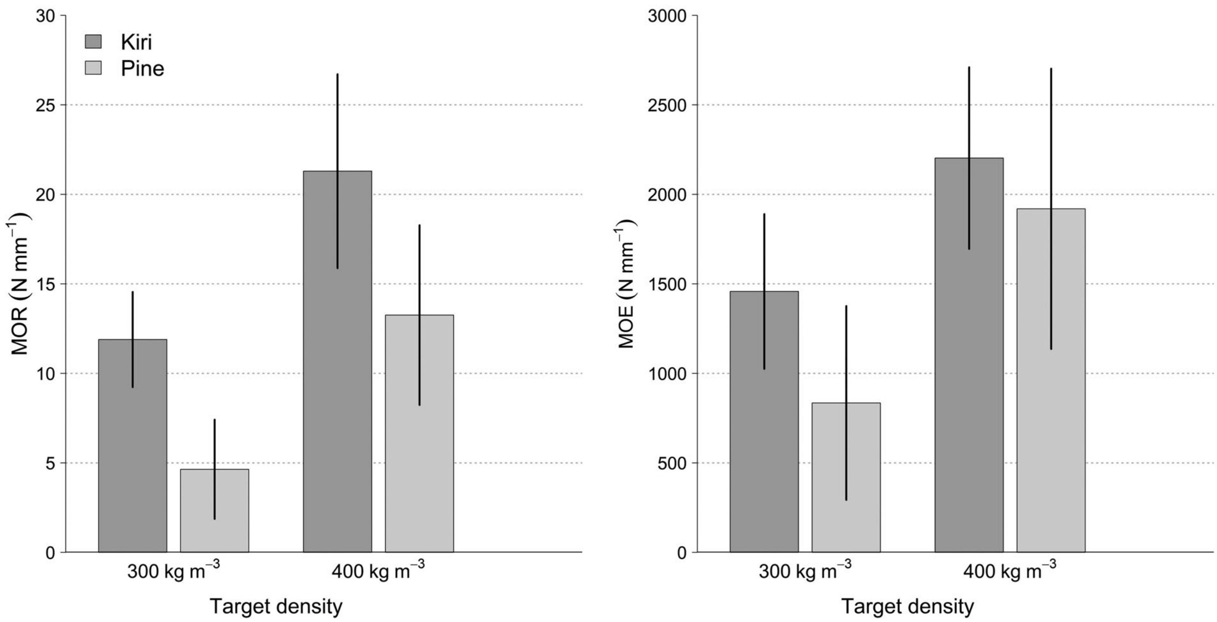

Figure 8. MOR (left) and MOE (right) of strandboards made of kiri and pine; columns: mean values; error bars: 5th to 95th percentile; dashed lines were removed from the figure during revisions.

mainly determined by the surface layers, internal bond strength predominantly depends on the core layer. The steep profile caused by low-density wood species tends to enhance bending properties but to lower internal bond strength (Jin *et al.* 2009).

In the present study, differences between mechanical properties of kiri and pine boards seem to be predominantly caused by the different strand contact area and, thus, inter-particle bonding strength. Accordingly, internal bonding strength, a parameter that serves as a measure of inter-particle adhesion,

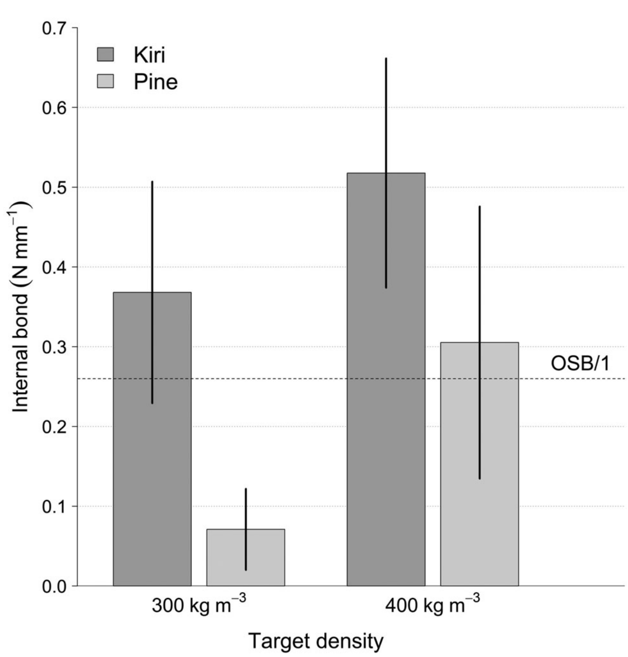

Figure 9. Internal bond strength of kiri and pine strandboards at densities of 300 and 400 kg m^{-3}; columns: mean values, error bars: 5th to 95th percentile; dashed lines: 5th percentile requirements for OSB/1 according to EN 300.

shows the largest differences between the species, although board density of the core layers is similar. Additionally, the fact that the adhesive bonding of beech boards was insufficient for handling confirms this finding as well as several earlier studies (e.g. Klauditz and Stegmann 1958, Zhou 1990). Despite the high surface layer density of kiri boards, bending properties varied less than internal bond according to species. This was especially true for MOE. This result suggests that MOR is mainly determined by adhesive bonding, while MOE is primarily determined by the properties of the individual strands. This finding accords with Hse (1975), who compared black tupelo flakeboards with red maple flakeboards. The cross-grained black tupelo wood exhibited a similar density as the red maple wood but a lower MOR and MOE. While the low MOE of the black tupelo wood was transferred to flakeboards made thereof, the MORs of the boards were similar. The reason might be that the glue joints behave more brittle (higher MOE, lower MOR) than the solid wood, so that elastic deformation occurs mainly in the wood elements of the board, while adhesive bonds might fracture first.

When exposed to water (liquid or vapour), strand boards swell. Thickness swelling is distinctly larger than in-plane swelling. It involves three components: swelling of the strands; partial reversal of densification of strands that were compressed during hot pressing (spring-back); development of inter-particle voids due to breaking of adhesive bonds by internal stresses. The higher the wood density, the more the wood swells. The higher the compaction ratio, the higher are the spring-back and internal stresses, but also the internal bond strength that can take up internal stresses. Overall, the low density, i.e. high compaction ratio, of kiri wood resulted in higher thickness swelling of the boards than those of pine.

Water is taken up by cell walls, intra-particle and inter-particle voids. Therefore, the absolute amount depends on board density rather than board structure. However, a solid structure

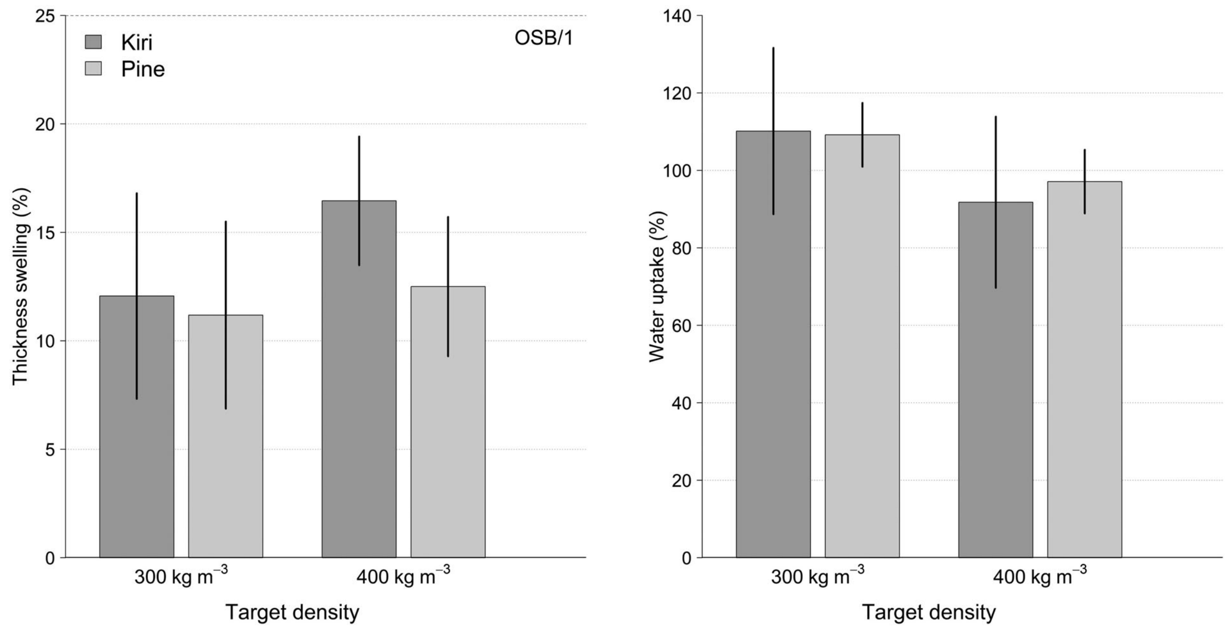

Figure 10. Thickness swelling (left) and water uptake (right) of kiri and pine panels at densities of 300 and 400 kg m^{-3} after 24 h of immersion; columns: mean values; error bars: 5th to 95th percentile; dashed lines: 95th percentile requirements for OSB/1 according to EN 300.

slows down the rate of water uptake. The larger swelling allowed kiri boards to take up more water than pine boards, while their structure caused a slower rate. Present results suggest that both effects compensated for each other.

Conclusions

This study proved the feasibility of producing strandboards from the low-density kiri wood with only minor adjustments to the production process, e.g. the strand generation. Due to the low density of kiri wood, bulk density of the kiri strand mat was much lower than that of pine and beech mats. However, the density of the beech mat was similar to that of the pine mat, because the beech strands were thinner than the pine strands. The fact that it was possible to produce pine boards but beech strands did not form a cohesive board at the target densities, confirms that wood density rather than mat density determines board properties and that increasing mat density by shaping strands has little effect. The lower the wood density, the better the mechanical properties of the boards. Low wood density, however, resulted in higher thickness swelling, because densification of wood strands is reversed during swelling.

Results from this study on randomly oriented strand boards cannot be compared to standard requirements for oriented strand boards, because strand orientation crucially affects board properties. Still, present results suggest that it is possible to meet IB- and TS-requirements for OSB/1 at a board density of 400 kg m^{-3}, corresponding to a compaction ratio of ca. 1.6. Comparison with standard requirements reveals that low-density boards generally exhibit low thickness swelling. In contrast, MOE seems to be generally low for lightweight boards. This is remarkable because the large compaction ratio resulted in a steep vertical density profile, the high surface densities of which generally improve bending properties. Obviously, MOE is primarily determined by the properties of the (densified) wood strands, which correlate with panel density, while MOR and IB mainly depend on inter-particle adhesive bond strength, which correlates with the compaction ratio.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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