FEASIBILITY OF A NEW HYBRID WOOD COMPOSITE COMPRISING WOOD PARTICLES AND STRANDS

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Abstract. Hybrid boards consisting of a strand core and particleboard faces (PSP) with three different shelling ratios were designed using strand sizes from dust to 4.5 mm mesh and normal particleboard face material. Flexural properties, internal bond (IB) strength, screw withdrawal resistance (SWR), hardness, and dimensional properties were measured. The modulus of elasticity of these hybrid boards was 25% greater than that specified by the ANSI standard for M3 industrial particleboard. An increase in modulus of rupture of approximately 50% was recorded for boards containing 60% strands compared with control particleboard without strands. Hybridization also accounted for a decrease in linear expansion compared with particleboard. However, IB strength decreased and SWR values showed no significant change. Therefore, with improved core properties, PSP has the potential to replace M3 particleboard.

Keywords: Particles, strands, hybrid board, oriented strandboard, particleboard, slenderness ratio.

INTRODUCTION

The North American particleboard industry is facing a competitive squeeze from lower cost imports from China and a growing market share from South America and Europe. Between 1999 and 2005, 186 Canadian and American sawmills permanently closed, consequently leading to an ongoing shortage of suitable woody raw materials for the particleboard industry (Spelter and Alderman 2005). For this reason, wood shavings and chips have to be transported long distances to plants resulting in higher wood cost, and the increase in crude oil prices has also led to higher resin cost (Random Lengths 2008). In addition, the panel industry is competing for residual wood material with the pallet and the bioenergy industries. A recent bill by the US Senate giving subsidies to the bioenergy producers has made it more difficult for the panel industry to compete. This has inflated the price of particleboard in the North American market place by 25-30%, making it even less competitive with lower priced

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imports from overseas and substitutes such as medium density fiberboard (MDF).

Currently, 75% of the residential construction in North America uses oriented strandboard (OSB), which is close to market saturation. Because of decreasing log size, log condition (frozen logs), knife speeds, and inefficient technology for drying wood strands, the generation of fine strand material in the OSB industry is inevitable (Spelter and Wang 1996). Depending on the log size, 20-40% of the total strand mass produced is fine material, which is defined as strands that pass through a 3.18-mm square opening (Fakhri et al 2006). However, for panels of higher quality, it is recommended that the total board comprise only 5% fines, although most panels are made up of 15-20% fines (Coil 2005). The rest of the fines are usually used as an energy source. This presents an opportunity to use the excess fine strand material in conjunction with the scarce particles to construct a hybrid wood composite panel.

Wood composite panels with strand surfaces and other core materials have been patented. Rigid expanded foam sandwiched between two strand surfaces was constructed by Day and Hutcheson (1979), whereas Nadezhdin et al (2005) fabricated a three-layer sandwiched panel with the outer layer of wood flakes and a core perforated with chunks of wood chips, paper mill sludge, or recycled paper. However, these panels were intended for structural purposes and they require a two-step process. A stair tread made of four-layer OSB panels was also patented, but this panel uses the normal OSB strands and is also difficult to laminate (Spivey 2001). Other panels such as Combi-Core$^{\text{TM}}$ are made by laminating full particleboard or MDF as surfaces sandwiched with a veneer or plywood core in a two-step process (Columbia Forest Products, Greensboro, NC). Although this lends a smooth surface for thin paper lamination, it consumes resin and wood material as does plywood production. Recent work by Sackey et al (2008) showed that having thicker particles in the core of three-layer particleboard increases the mechanical strength, especially internal bond (IB) strength and screw withdrawal resistance (SWR). This suggests that a hybrid panel with particles that are larger than the coarse particles in particleboard but smaller than OSB strands, eg strand fines, will increase the mechanical properties of conventional boards.

To mitigate the effect of the wood resource shortage, this study aims to maximize the use of the scarce wood particle resource by fabricating a new hybrid wood composite panel consisting of particle furnish on the faces as a substrate for a decorative laminate or veneer with fine wood strands in the core to provide flexural strength. This new panel is denoted as PSP and is shown schematically in Fig 1.

The PSP panel will be a thin, layered panel made in a one-step process with a better strength to weight ratio and less use of wood furnish and resin compared with the two-step Combi-Core$^{\text{TM}}$

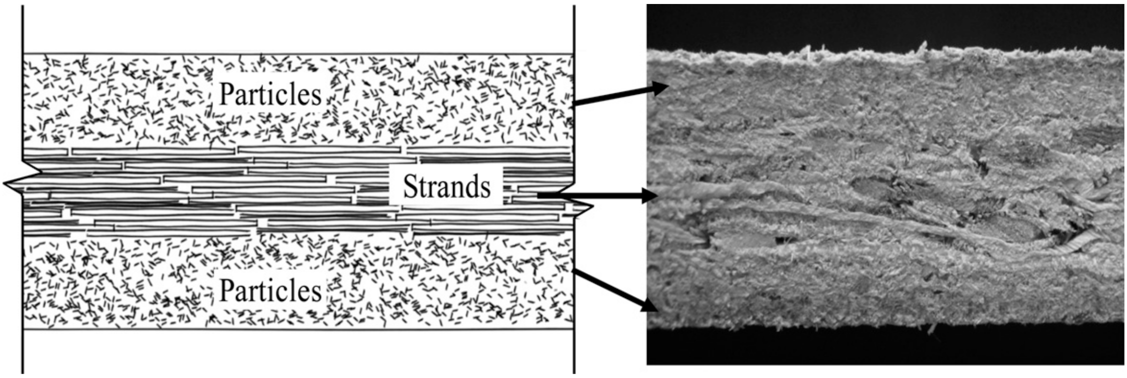

Figure 1. Schematic of PSP board and photograph of the cross-section.

panels. The PSP panel can be used as modular furniture and housing components and to replace high-density M3 and H-grade particleboard panels for interior stair treads and other industrial applications. Owing to the present and future emission standards, this panel will also be made with phenol formaldehyde (PF) resin to comply with no added urea formaldehyde standards. The specific objectives of this study are to 1) fabricate and assess the feasibility of a three-layer particle-strand-particle (PSP) panel and 2) compare the physical and mechanical properties of the PSP panel with those of M3 conventional particleboard.

MATERIALS AND METHODS

Furnish Preparation and Experiment Design

Face and core industrial particleboard furnish (lodgepole pine, *Pinus contorta* var. *latifolia* Engelm.) from a particleboard mill and aspen (*Populus termuloides*) strands from an OSB mill, both in western Canada were used for the study. The aspen industrial strands were screened into four size classes with a mechanical shaker table equipped with square mesh sieves. The sizes were >14.3-mm, 14.3-4.8-mm, 4.8-3.2-mm, and <3.2-mm mesh, the latter considered strand dust. The latter three size classes were thoroughly mixed to form a homogenous strand mix. Three-fifths of the total strand mass passed through the 14.3-mm mesh but not the 4.8-mm mesh, one-fifth passed through the 4.8-mm screen but not the 3.2-mm screen, and one-fifth was strand dust. Table 1 gives the composition of the three different furnish types used for the strand core. Only industrial particleboard furnish was used for the face of the PSP panels.

A completely randomized experimental design was used to determine the feasibility and the effect of the relative mass of particles and strands on panel properties. The factor for this experiment was the mass percentage of the core layer (0, 20, 40, 60%) with three replicates for a total of 12 boards. Analysis of variance was conducted on the results at a 5% significance level. Preliminary work with a mass ratio of 80% strands to 20% particles showed that this ratio was not feasible because a large proportion of the top layer particles moved through the strands, resulting in a rough surface that would be difficult to laminate.

Table 1. Relative mass of particles and strands comprising total board.

Furnish type	Mass percentage (%)			
Strands	0	20	40	60
Fine particles	46	80	60	40
Coarse particles	54	0	0	0
	100	100	100	100

Blending and Mat Formation

PF resin with 60% resin solids was used for blending both face particleboard and core strand furnish. The particle furnish was blended separately with 5% resin content (oven-dry weight [ODW] of furnish) in a Drais particleboard batch blender (Draiswerke GmbH, Mannheim, Germany) equipped with an air-atomizing nozzle. Resin was sprayed on the particles as they were stirred by rotating paddles within the blender cavity. The core strands were blended with 4% resin content (ODW) in a rotary blender also equipped with an air-atomizing nozzle. Each board contained 1.5% wax (ODW). In each batch, sufficient furnish was blended to make three boards. The particle moisture content was 7%, whereas the strand moisture content was 6% before blending. All boards were hand-formed with no intentional strand orientation. A layer of particles was evenly spread over the caul plate followed by a layer of strands for the core layer, and finally the top layer of particles was spread over the surface to make a three-layer PSP panel mat. Mats were then pressed to a target thickness of 15.88 mm and target density of 700 kg/m^3. The press cycle consisted of 30 s closing, 550 s pressing, and 240 s degassing times to avoid delamination. Degassing was extended to 240 s because the 100% strandboard blew with the first two press cycles. All other board types did not blow after the press cycle modifications with the exception of the 100% strandboard. The blow that occurred with the 100% strandboard may have been caused by regions of poor bonding in the core layer. Because the strands were a mixture of fine and smaller strands blended together, the fine strands might have had disproportionately more resin coverage leading to resin starvation of the relatively larger strands. Consequently, the core of the 100% strandboard may not have had enough resin to sufficiently bond the board together. Samples could not be cut from the blown boards. After pressing, each board was cooled to room temperature and then trimmed to 660 × 660 mm and cut as shown in Fig 2.

Vertical density profile of the IB samples was measured prior to gluing with an X-ray densitometer (Model QDP-01X; Quintex Measurement Systems Inc, Knoxville, TN). Sample dimensions and physical and mechanical property testing procedures were done in accordance with ASTM D 1037 (ASTM 2009). Linear expansion (LE) samples were arranged in a conditioning chamber at 20°C and four humidities (50, 65, 75, and 90% RH). The length of samples was measured after they attained equilibrium, ie without further change in weight, and the difference relative to that at 50% RH was the basis for calculation of linear expansion (LE).

RESULTS AND DISCUSSION

Mean Density and Vertical Density Profile

Mean board density ranged 716-747 kg/m^3 at an average 10.7% MC, whereas the basic density ranged 643-676 kg/m^3. In both cases, there was no significant difference between boards with different particle to strand proportions. However, the highest densities were measured from boards with the greatest amount of strands (60%) followed by boards with 40% strands

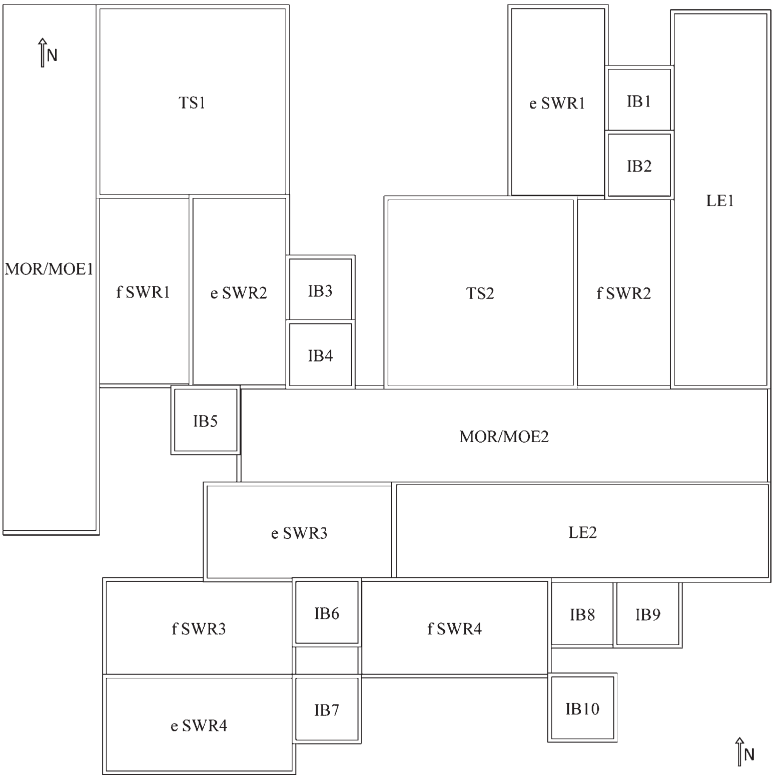

Figure 2. Cutting pattern of the three-layer PSP hybrid board for specimen sampling (10 internal bond [IB], 4-face screw withdrawal resistance [SWR], 4-edge SWR, 2 linear expansion [LE], 2 thickness swell [TS], and 2 MOR/MOE).

(Table 2). The board with the lowest strand-to-particle ratio had consistently lower densities even compared with the control panel with no strand content.

The core density (CD) followed a similar trend to both mean and basic densities; nonetheless, the CDs of boards with 40 and 60% strand content were significantly different from the 20% strand content and control boards (Table 3). As shown in Fig 3, the minimum CD was measured in boards with 20% core strands, whereas the board with 60% strands had the highest CD with corresponding high face densities.

The relative proportion of strands in the board appeared to influence board density. This may be attributed to the fact that strands are more difficult to compact because of their limited ability to rearrange during compression compared with particles (Sackey et al 2008). This resistance also contributes to higher residual stress in the strand core, which causes thickness springback (Post 1961).

Internal Bond Strength and Screw Withdrawal Resistance

Table 2 shows the average values for IB strength and edge and face SWR of all boards. Mean IB strength of all hybrid boards was significantly lower than the control boards and lower than the minimum requirements for M2 and M3 particleboard, which are 0.45 and 0.55 MPa, respectively, in ANSI A208.1 (ANSI 1999). The pattern of mean SWR of all boards made was very similar to that of mean IB strength, which follows the close correlation between edge SWR and IB strength found in a previous study on industrial particleboard (Semple et al 2005).

Table 2. Means of physical and mechanical properties relative to percentage strands in total panel.[a]

	Percentage of strands in board			
Property	0%	20%	40%	60%
MD (kg/m^3)	718 (5.30)	716 (5.38)	731 (7.07)	747 (3.79)
BD (kg/m^3)	647 (5.40)	647 (5.56)	661 (7.21)	676 (3.82)
CD (kg/m^3)	622 (3.95)	606 (4.07)	648 (6.02)	661 (6.17)
IB (MPa)	0.43 (16.65)	0.14 (30.44)	0.24 (21.58)	0.27 (27.80)
Face SWR (N)	766 (13.0)	674 (12.86)	872 (12.93)	767 (19.33)
Edge SWR (N)	629 (18.49)	470 (24.95)	663 (22.47)	623 (30.33)
MOR $\parallel$ (MPa)	11.05 (22.07)	10.74 (10.75)	13.93 (33.81)	16.50 (15.95)
MOR $\perp$ (MPa)	10.68 (10.85)	7.43 (22.62)	10.21 (32.10)	11.40 (17.01)
MOE $\parallel$ (GPa)	2.57 (11.68)	2.48 (14.23)	2.86 (26.67)	3.43 (7.25)
MOE $\perp$ (GPa)	2.45 (11.62)	2.08 (13.12)	2.29 (4.35)	2.60 (5.47)
Hardness (kN)	3.016 (11.71)	3.059 (13.53)	3.373 (11.75)	3.390 (17.77)

[a] MD, mean density; BD, basic density; CD, core density; IB, internal bond; SWR, screw withdrawal resistance. Figures in parentheses indicate coefficient of variation (COV) expressed in percentage.

Table 3. Effects of strand proportions on properties of hybrid boards.[a]

Effect	Mean density	Core density	IB	Face SWR	Edge SWR	MOR	MOE
Board type	$p = 0.172$	$p < 0.001$	$p < 0.001$	$p = 0.016$	$p = 0.007$	$p = 0.054$	$p = 0.046$
mach dir	n.a.	n.a.	n.a.	$p = 0.096$	$p = 0.368$	$p = 0.023$	$p = 0.016$
Effect	LE @65%	LE @75%	LE @90%	TS (2 hrs)	TS (24 hrs)	WA (2 hrs)	WA (24 hrs)
Board type	$p = 0.002$	$p = 0.016$	$p < 0.001$	$p = 0.783$	$p = 0.029$	$p = 0.064$	$p = 0.006$

[a] n.a. = not applicable for that property; mach dir = machine direction.

Note: significant difference was set at the 5% confidence level; $p < 0.001$ = significant at the 0.1% level.

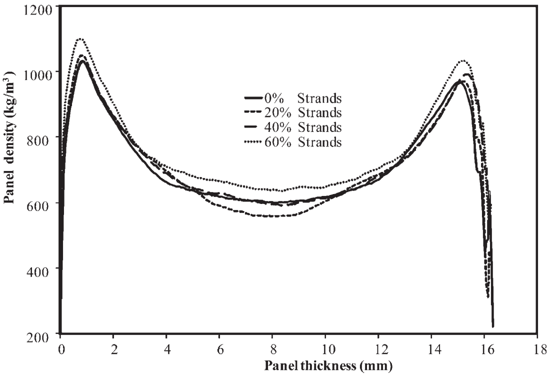

Figure 3. Typical vertical density profiles of board for each strand percentage.

The IB strength of the hybrid boards appeared to increase with CD.

The decrease in both IB strength and SWR may be caused by a weak bonding interface between particles and strands. Particles are more three-dimensional in shape and have variable surface morphologies compared with strands, which are mostly two-dimensional slender elements with tangential and radial surfaces for bonding. When an end-grain particle is bonding with a strand element, more adhesive will be required on the interface to assure sufficient bonding. However, the blending process randomly distributes very little resin on the surfaces, hence numerous end grain and other irregular surfaces are likely to have resin-starved regions. For instance, some of the SWR test specimens failed when pilot holes were drilled, indicating very weak bonds.

Although the hybrid boards had relatively higher densities (ie 40 and 60% strand ratios) than the control, this did not translate into higher core property values (IB and SWR). This signifies that changes in these properties were not caused by density but were strongly influenced by particle/strand ratio or the resin content of the particles and strands. Because the particles are unlikely to be stronger than the strands, resin starvation on the strands is more likely the reason for the lower properties. This could be overcome by increasing the resin content, however, that would also increase material costs.

Flexural Properties and Hardness

Flexural properties (MOR and MOE) of the hybrid boards (Tables 2 and 3) were significantly affected by the proportion of strands in the boards. Both properties had only borderline significance at the 0.05 level. Although particles and strands were not intentionally oriented during mat formation, there was a significant difference in these properties in the machine direction, probably caused by a slight bias toward the parallel direction in hand forming. However, the forming box was square, and one would not expect strands to have a preferential orientation. The flexural values for the two principal directions (parallel and perpendicular to machine direction) were therefore analyzed separately.

Generally, MOR and MOE values increased almost linearly with strand proportion increase in the board with the exception of the control, which contained no strands (Fig 4). This could be partially explained by their densities because the trend was similar to the average and basic densities of the panels. As expected, flexural values of samples taken parallel to machine direction were higher than those sampled perpendicular. The higher the strand proportion in the board, the greater the differences were between the parallel and perpendicular values (36-45% greater). No differences in flexural property values were found between the two directions for the boards consisting of only particles.

The properties of the lowest strand-to-particle ratio boards (20% strands) were consistently lower than the control. Boards with 40 and 60% strand content were 26 and 49% higher than the control for MOR values parallel to the machine direction, whereas for MOE values, they were 11 and 33% higher, respectively. Regarding the flexural properties, there appeared to be a minimum strand-to-particle ratio below which no

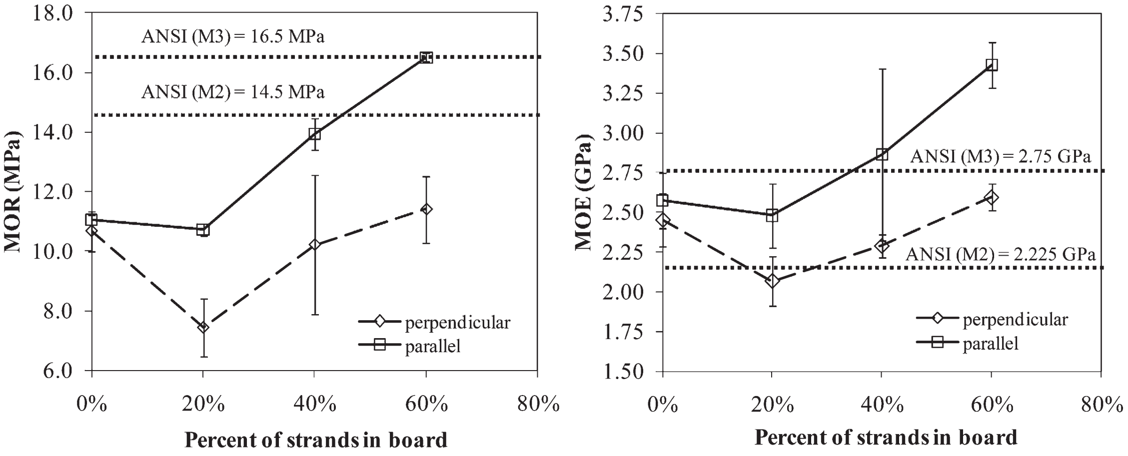

Figure 4. Effect of strand percentage in boards on MOR and MOE of all boards showing error bars for standard error of the mean (SEM).

improvement might be realized. Conversely, increasing strand content to continue to enhance the properties is limited by the thickness of particle face layers. As particle layer thickness is decreased, the particles tend to sink through the core strand mat and the strands then protrude through the particle surface layers.

The MOR parallel to machine direction of the 60% strand PSP exceeded ANSI A208 (ANSI 1999) for M2 particleboard and met the standard for M3 particleboard (16.5 MPa). In addition, for boards with 40 and 60% strand content, MOE perpendicular to machine direction exceeded the ANSI standard for M2 particleboard, whereas in the parallel direction, the MOE for these boards exceeded the standard for M3 particleboard by 4 and 25%, respectively. However, better understanding is needed for bonding behavior at the particle–strand interface, to help clarify the adhesion mechanism at the transition between face particle layer and core strand layers. The knowledge acquired can be used to improve the bonding behavior within the core of the boards. The results in the parallel direction also indicate that MOR can be improved if the strands are intentionally laid with some form of orientation, which may be beneficial for certain applications, eg stair treads. Coefficient of variation was generally high, indicating more variability and irregularity in the board core. This can be attributed to a very irregular core strand surface being bonded to fine surface particles.

Unlike flexural properties, hardness was not affected by direction, because it is more dependent on the integrity of the board surface. Hardness was tested on both board surfaces after conditioning boards in a chamber at 65% RH and 20°C for more than 2 wk. The average hardness values, 3.016-3.390 kN, of all the laboratory-manufactured boards exceeded the ANSI minimum requirements of 2.225 kN for M1-M3 particleboard. Boards containing 40 and 60% strand content were significantly ($p = 0.008$) greater than that of the control by about 12%.

Moisture and Dimensional Properties

Average LE was measured for the three condition ranges, ie 50-65%, 50-75%, and 50-90% (Fig 5a). Average LE ranged from –0.055 to 0.188% for the first, –0.111 to 0.122% for the intermediate, and 0.054 to 0.375% for the final condition, respectively, for all boards. As expected, all board types recorded the highest LE values at 90% RH. Although an increase in humidity was expected to result in more moisture adsorption with a corresponding increase in sample length, increasing humidity 65-75% actually decreased LE. A probable reason was

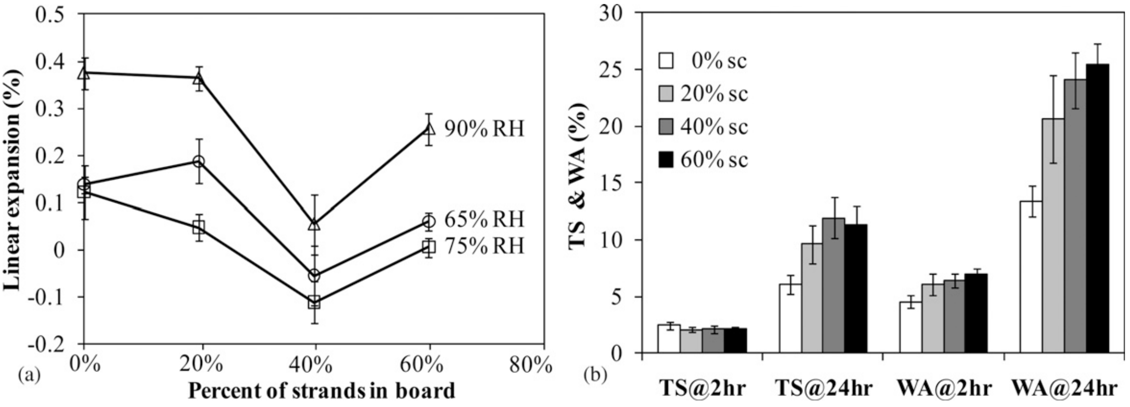

Figure 5. Effect of strand percentage in boards on (a) linear expansion at three humidities and (b) thickness swell (TS) and water absorption (WA) at 2 and 24 h showing error bars for standard error of the mean (SEM). sc, strand content.

that the samples were initially conditioned to 65% RH, redried to 50% RH, and then rewetted to 75% RH. The redrying and rewetting might have led to more surface moisture adsorption and less moisture penetration into the sample core. Because LE is usually a small quantity, the surface moisture adsorption was not enough to cause any recordable elongation but rather a decrease in length between 65 and 75% RH. The LE decrease might also have been caused by sorption hysteresis (Suchsland 1972), where some of the hydroxyls get saturated after drying and therefore are not available for moisture readsorption.

Boards containing 40% strands had significantly lower LE than the rest of the boards. With the exception of the 20% strandboard at 65% RH, boards with 0% strand content had the highest LE values for all conditions, and this result is similar to that of Miyamoto et al (2002). It has been reported that LE decreases with increasing wood element length (Post 1961; Lehmann 1974) but increases with decreasing particle length and increasing particle thickness (Suda et al 1987). These reports support the results of this study, in which boards with shorter and thicker particles recorded higher LE and boards with more slender strands had lower LE. Miyamoto et al (2002), who found that boards with smaller particles had higher LE, attributed the observation to the out-of-plane orientation angle of the smaller particles (Xu and Suchsland 1997). Small particles are also more three-dimensional with varying surface textures compared with strand elements and probably have more open end grain that permit moisture adsorption and penetration. The geometry, surface texture, and orientation of a particle compared with that of strand elements caused more particles to swell in all directions, and the accumulation of this swelling led to higher LE values. Boards made of only particles (0% strands) have more interparticulate pores, which become channels for moisture penetration. In contrast, the strand elements are flatter and have relatively higher slenderness ratios (length-to-thickness ratio) compared with particles, which tend to swell less in the parallel direction and hence contributed very little to LE. As a result, increasing strand content tends to decrease LE with the exception of the 40% strand content boards, which remains an unexplained anomaly.

The 2-h thickness swell (TS) values ranged from a low of 2.06% for the 20% strand content board to a high of 2.42% for the 0% strand content boards. The highest TS value of 11.9% and the lowest of 6.05% were recorded for 40 and 0% strand content boards, respectively, for the 24-h TS measurements. As shown in Fig 5b, TS and water sorption (WA) values showed a contrary trend in LE and increased with increasing strand content, especially for the WA test. The two properties appear to be correlated, confirming observations reported by Lehmann (1972) and Lu and Lam (2001). In both TS and WA tests, there were no significant differences among samples for the 2-h test, but the 0% strand content boards had significantly lower values than all boards with strands when soaked for 24 h. Two-dimensional strands exhibited more differential swelling by swelling far more in the tangential and radial directions than the longitudinal. In addition, strands are more continuous wood elements than particles and hence had higher TS values and adsorbed more moisture. Because the strands were made from aspen, whereas the particles were from lodgepole pine, species may have also contributed to the moisture and dimensional behavior of the boards. Higher density panels are known to have higher TS (Halligan 1970), hence the higher densities of the boards containing strands might have contributed to their greater thickness swelling. Boards containing more strand elements had higher thickness ratios (ratio of initial uncompressed to final compressed mat thickness) and underwent more compression, creating higher compression stresses within those boards. However, the release of compression stresses causes TS (Gatchell et al 1966; Halligan 1970; Kelly 1977; Xu and Winistorfer 1995) when panels are exposed to moisture, leading to higher TS and WA for boards containing strands.

CONCLUSIONS

Within the confines of this study, it can be concluded that constructing a hybrid composite board composed of finer wood strands and wood particles with varying shelling ratio is feasible. The hybrid boards with 60% strand content attained the ANSI standard for M3 industrial particleboard for MOR and MOE was 25% above that specified. The LE of the hybrid boards was also significantly lower than their pure particleboard counterparts. However, core board structural properties such as IB strength and SWR did not meet the standard. The PSP board has the potential to be used as an industrial particleboard and to contribute to the use of fine strands, if the IB and SWR issues are resolved.

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