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Manufacture and properties of *Miscanthus*–wood particle composite boards

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Abstract *Miscanthus sacchariflorus* straw was used as a raw material for the manufacture of *Miscanthus*–wood particle composite board with Douglas-fir particles in ratios of 100/0, 80/20, 60/40, 40/60, 20/80, and 0/100. A commercial phenol–formaldehyde resin was used as a binder at 9 and 11 % for target densities of 0.50 and 0.65 g/cm^3, respectively. The effects of the *Miscanthus*/wood particle ratio on the composite board properties were investigated. In addition, the density profile was also examined to improve the understanding of the composite board manufacturing process. Results indicate that the internal bonding value increased drastically in the board containing up to 50 % wood particles, providing a valuable parameter for subsequent research. The board properties were greatly improved with increasing density and binder addition level.

Keywords *Miscanthus* (*M. sacchariflorus*) straw · Wood particle · Composite board · Density profile

Introduction

Biomass materials have attracted great interest in recent years. *Miscanthus* is one of the perennial grass, considered to be a suitable crop as a sustainable source of biomass for biopower and biofuels because it has some valuable advantages including good yield, high calorific value (20 kJ/kg if dry matter), and well-described material [1]. Of the 17 known species in the *Miscanthus* genus, the most important species are *M. sinensis* and *M. sacchariflorus*, which originate in East Asia including Korea, and *M.* × *giganteus*, which is the inter-specific hybrid of tetraploid *M. sacchariflorus* and diploid *M. sinensis* [2]. Traditionally, in terms of the ratio of energy content to volume, combustion and pyrolysis are efficient methods for controlling the energy efficiency of *Miscanthus* [3]. During *Miscanthus* growth, C4 photosynthesis occurs, which is the primary characteristic enabling this plant to be used in fuel production. In general, few studies have been performed on the use of *Miscanthus* as a source of bioenergy for fuel [4–7].

With the increasing consumption of wood-based materials and scarcity of wood resources, it is inevitable that some substitutions are needed and wood residues should be fully utilized. So far, much research has been devoted to the use of non-wood lignocellulosic materials, such as reeds, wheat, and rice straw, as a partial or complete substitute for wood in the preparation of boards for structural and non-structural panel applications. Low density straw panels have already been suggested for application in thermal and acoustic insulation [8]. Yang et al. [9] using rice straw manufactured insulation board. The composite boards prepared with randomly cut rice straw and wood particles with low specific gravity were found to be suitable as a sound absorbing insulation material. Ajiwe et al. [10] produced ceiling boards from agricultural waste, such as

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rice husks and saw dust. The results confirmed that the board produced was similar to a commercial board. Han et al. [11–14]. conducted a series of studies using reeds and wheat straw as material for preparing particleboard and examined the effect of particle size and board density on the board properties. In addition, silicon coupling agents were used to improve the bonding ability between the reeds and wheat particles and urea–formaldehyde (UF) resin, and mechanism underlying the bonding improvement was investigated. Nikvash et al. [15] used agri-fibers, bagasse, canola, and hemp, as well as industrial wood chips in various proportions ranging from 0 to 100 % to make wood composite panels and suggested that one possible application for those panels is furniture production.

The biochemical composition of *Miscanthus*, as determined classically, is (wt% dry matter) 45 wt% cellulose, 30 wt% hemicellulose, and 21 wt% lignin [6], similar to wood components, which enables *Miscanthus* to serve as an alternative to wood in panels. Therefore, it is necessary to identify alternative applications so that these materials can be fully utilized for the benefit of humankind and the environment. Even though *Miscanthus* currently lack industry utilization for bio-based composite products, given the abundant supply, the potential to utilize this material is great. The objective of this research was to investigate the properties of *Miscanthus*–wood particle composite boards as a function of the ratio of *Miscanthus* particles to wood shavings to produce composite panels with acceptable properties for interior applications.

Materials and methods

Materials

Miscanthus straw, obtained from the National Institute of Crop Science of Korea and industrially produced Douglas-fir wood shavings were used as the raw materials in this study. The *Miscanthus* straw was crushed into small particles and subsequently screened by vibration on a 10-mesh sieve. The Douglas-fir wood shavings were also screened using the same mesh. All the particles used were 100 % those remaining on the 10-mesh sieve, 0.15–0.43 mm thickness, 2.4–3.9 mm width and 19.5–30.3 mm length for *Miscanthus* particles, and 0.08–0.58 mm thickness, 7.2–13.8 mm width, 7.4–11.3 mm length for wood particles. The specific types of particle are presented in Fig. 1. All particles were air-dried to about 6 % moisture content. The binder used to manufacture the board was commercial phenol–formaldehyde (PF) resin (PHENOLITE TD-2207) with a solid content of 67–71 %, a viscosity of 380–530 mP s (25 °C), and a density of 1.205–1.215 g/cm^3 (Kangnam Polytec. Co., Korea). A rotary blender was used for the blending, with the binder being applied under 7–10 kgf/cm^2 pressure using an atomization nozzle.

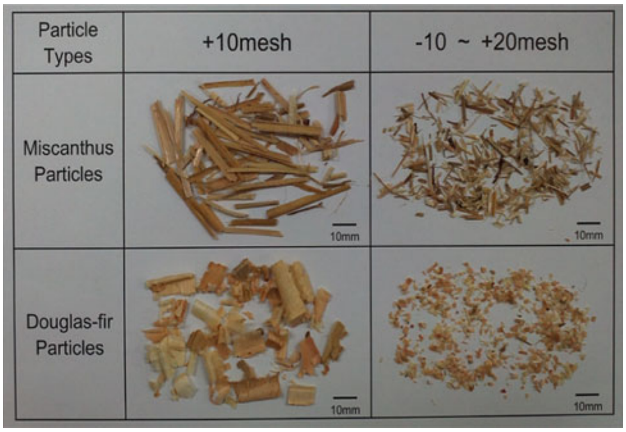

Fig. 1 The particle types of *Miscanthus* and Douglas-fir

Board manufacture

Miscanthus–wood particle composite boards of 35 cm × 35 cm × 1.2 cm were manufactured at target densities of 0.5 and 0.65 g/cm^3. In an attempt to optimize *Miscanthus*/wood particle ratio, the following six ratios were tested: 100/0, 80/20, 60/40, 40/60, 20/80, and 0/100. The resin was sprayed onto the particles in a blender with a resin content of 9 and 11 % based on the dry weight of the particles. The resin-sprayed particles were then hand-formed in a forming box. And 50 s, press closing time, was required for the press plates reaching the target board thickness of 12 mm from a mat height of 70 mm. A three-step hot pressing cycle was employed to hot pressing, first step with pressure of 3.43 MPa (9 min), second step 2.94 MPa (2 min) and third step 1.96 MPa (1 min), respectively. In addition, the platen temperature was fixed at 180 °C. Four replicates of each board were fabricated under the same conditions for a total of 48 boards.

Physical and mechanical properties tests

Prior to testing the physical and mechanical properties, the boards were conditioned at 20 ± 1 °C and 65 ± 5 % relative humidity (RH) until they reached a constant weight. The physical and mechanical tests were carried out in accordance with Korean standard KS F 3104-2006. The internal bonding (IB) and thickness swelling (TS) tests were performed in replicates of eight and four, respectively, at a size of 50 mm × 50 mm × 12 mm. Eight replicates were prepared for the modulus of rupture (MOR) and modulus of elastic (MOE) tests with samples of 220 mm × 50 mm × 12 mm. Prior to the IB test, the density profiles of two samples were determined.

Table 1 Properties of *Miscanthus*–wood particle composite boards

Target specific gravity	Mix ratio (M/W)	MC (%)	TS (%)	MOR (N/mm^2)	MOE (N/mm^2)	IB (N/mm^2)
0.5	100:0	2.68 (0.37)	47.98 (7.28)	3.52 (0.47)	1204.00 (117.51)	0.0163 (0.004)
	80:20	3.17 (0.53)	40.72 (5.29)	3.90 (0.22)	1199.62 (79.40)	0.0167 (0.003)
	60:40	3.00 (0.25)	31.62 (3.13)	4.01 (0.46)	1221.53 (108.69)	0.0218 (0.004)
	40:60	3.30 (0.48)	23.38 (2.57)	3.97 (0.43)	1059.77 (107.99)	0.0221 (0.005)
	20:80	3.90 (0.22)	17.05 (2.85)	4.39 (1.10)	1129.95 (264.49)	0.0280 (0.004)
	0:100	3.65 (0.19)	18.15 (2.68)	4.66 (1.08)	834.58 (327.39)	0.0248 (0.006)
0.65	100:0	4.03 (0.06)	47.93 (0.99)	6.54 (0.30)	1691.53 (139.14)	0.0530 (0.000)
	80:20	3.86 (0.02)	44.39 (0.62)	6.51 (0.35)	1939.40 (50.53)	0.0482 (0.010)
	60:40	3.93 (0.09)	39.05 (3.80)	7.66 (0.87)	2063.24 (255.57)	0.0573 (0.010)
	40:60	3.97 (0.04)	29.64 (0.56)	10.28 (0.65)	2030.49 (115.71)	0.1004 (0.010)
	20:80	3.96 (0.02)	21.79 (2.36)	12.24 (0.22)	2284.51 (90.75)	0.1633 (0.010)
	0:100	3.90 (0.05)	15.00 (1.56)	14.49 (0.78)	2157.87 (193.89)	0.2060 (0.000)

Numbers in parenthesis are standard deviations

Results and discussion

The influence of the *Miscanthus* to wood particle ratio on the properties of the boards

The influence of the *Miscanthus*/wood particle ratio on boards with a density of 0.50 g/cm^3 and 9 % resin content (LB) and on boards with a density of 0.65 g/cm^3 and a resin content of 11 % (HB) was determined; the results are shown in Table 1. In general, the properties of the boards improved as wood particle content increased regardless of the density and resin content. In fact, like rice, wheat, and reed straw described in other studies, those straws have been indentified as a material presenting bonding difficulty [11, 16, 17]. The wax and silica layer results in a low surface polarity, and a subsequently low compatibility between the resin and straw. Meanwhile, the low porosity of the outer layer was responsible for the poor resin penetration and diffusion. Without proper wetting, good bonding cannot be expected. Therefore, incorporating wood particles into the straw material is one of the methods used to improve the bonding quality of the straw board.

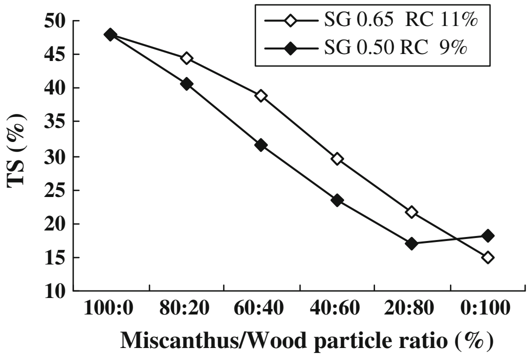

Fig. 2 Influence of *Miscanthus*/wood ratio on TS

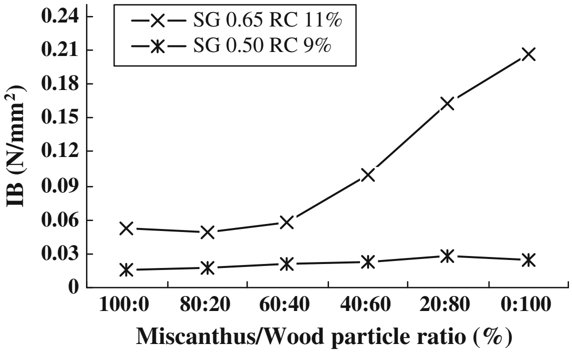

Fig. 3 Influence of *Miscanthus*/wood ratio on IB

In the case of the MOR and IB, when the wood particle content increased from 20 to 80 %, despite poor values, the IB value increased by 67.7 % for the LB board and more than 3 times for the HB board (from 0.048 to 0.163 N/mm^2). In addition, the MOR increased from 6.51 to 12.24 N/mm^2 for the HB board. From Figs. 2, 3, 4, and 5, it is evident that more obvious improvements were achieved with an increasing wood particle proportion for HB boards, whereas only a slight change was observed for LB boards. Furthermore, the IB and MOR values were markedly improved when the *Miscanthus*/wood particle ratios were below 60/40, which was consistent with what was reported in other studies [9, 15, 16]. The significant improvement might be attributed to the increased bonding contact area between the resin and particles with the increasing content of wood particles, which have better wettability. A considerable reduction in TS was observed with increasing wood particle content. It is considered that an increase in both the IB strength and wood particle proportion might reduce water penetration. As for MOE, it is largely influenced by the particle shape factor

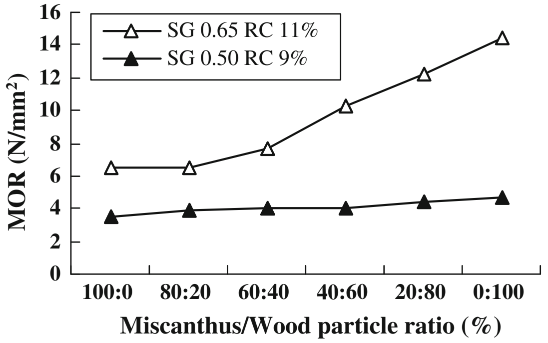

Fig. 4 Influence of *Miscanthus*/wood ratio on MOR

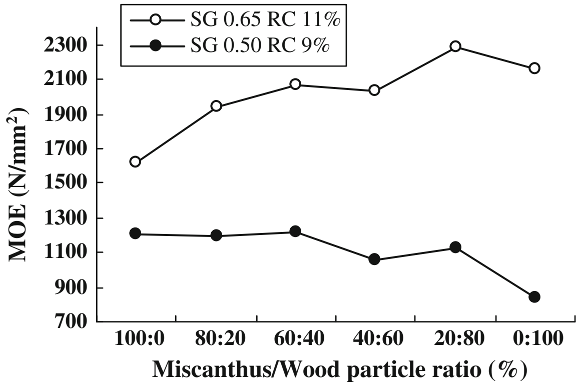

Fig. 5 Influence of *Miscanthus*/wood ratio on MOE

(length/width ratio). From Fig. 1 it can be observed that length/width ratio of +10-mesh *Miscanthus* particles is higher than that of wood particles which are short along the grain direction. Consequently despite of increased bonding strength with increasing wood particles, the MOE decreased drastically when the board was totally made by wood particles (Fig. 5), especially for the LB board. In the case of HB boards, increasing wood particles proportions contributed to increased MOE, however, no obvious effect for LB boards. In contrast, the MOR increased with increasing wood particle content in the HB board, and this was probably due to improved bonding.

The influence of density and resin content on the properties of boards

As stated above, when the *Miscanthus*/wood particle ratio was below 60/40, the board properties were enhanced significantly. Therefore, the 40/60 ratio was used to compare the properties of boards with different densities and resin content. The TS after immersion in water for 24 h tended to increase with increasing density. Even though increasing resin content indeed enhanced the bonding strength in certain degree which was confirmed by increased IB value, higher density could cause greater spring-back of the compacted particles. The increased inter-particle bonding strength is relatively week to offset this spring-back, resulting in TS value of HB board is greater than that of LB board. A similar trend was observed for the IB, MOR, and MOE, all of which increased drastically with increasing density and resin content. These changing properties were caused by an increase in the surface contact between the resin and particles, leading to improved bonding quality.

Table 2 Vertical density distributions of boards

Target density (g/cm^3)	Mix ratio (M/W)	Average density (g/cm^3)	Peak density (g/cm^3)	Core density (g/cm^3)	Core/ave density ratio (%)
0.5	100:0	0.52	0.662	0.445	87.5
	80:20	0.537	0.664	0.475	88.6
	60:40	0.502	0.590	0.437	87.1
	40:60	0.506	0.596	0.439	86.8
	20:80	0.489	0.574	0.416	85.1
	0:100	0.516	0.613	0.454	88.0
0.65	100:0	0.676	0.795	0.610	90.3
	80:20	0.646	0.771	0.585	90.5
	60:40	0.657	0.768	0.596	90.7
	40:60	0.647	0.741	0.568	90.5
	20:80	0.663	0.794	0.609	92.0
	0:100	0.638	0.787	0.580	90.9

In this study the core density is the minimum density of the central region of the total board thickness

Vertical density profile

Table 2 shows the face and core densities from the vertical profile data for all boards. In general, the core/average densities, around 85 and 90 % for boards with densities of 0.65 and 0.50 g/cm^3, were slightly higher than that of a conventional wood particle board with a reference value of 67 %. This is probably due to the homogeneous structure of the composite board. Meanwhile, according to Dai et al. [18], the slighter the density variation, the better the permeability. Therefore, the data indicate that during the hot pressing process, the mat had good permeability, which resulted in increased consolidation, faster heat transformation to the core, and thus more rapid curing of the resin. It is reported that permeability is linked to the existence of voids between mat elements [18–20]. *Miscanthus* particles are quite different from wood particles in terms of their geometric shapes and size distributions, as opposed to the wood particles (Fig. 1). Consequently, when the *Miscanthus* and wood particles were mixed together, more voids formed between them.

In general, the core/average density ratio of the LB boards was lower than that of the HB boards. Specifically, the HB board made with a ratio of 20/80 (*Miscanthus*/wood) had a

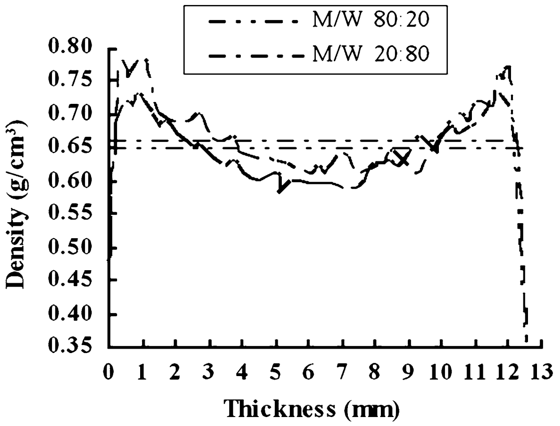

Fig. 6 Density profile of *Miscanthus*–wood-based board with 0.65 g/cm^3 target density

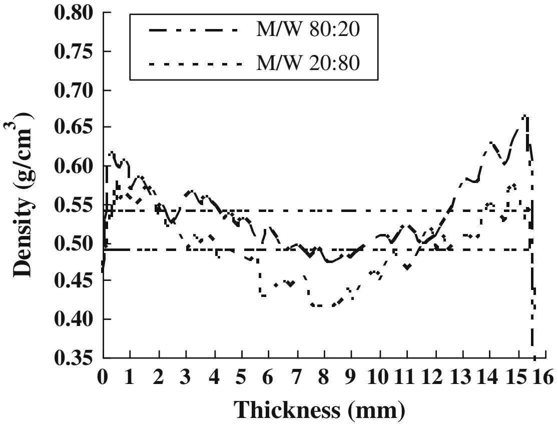

Fig. 7 Density profile of *Miscanthus*–wood-based board with 0.50 g/cm^3 target density

higher core/average ratio, which was strongly correlated with a better IB value of a board made under the same conditions. The density profile distribution of that board, as well as the board with a ratio of 80/20 (*Miscanthus*/wood) is shown in Fig. 6. For comparison, the density profiles of the LB boards with 20/80 and 80/20 ratios are graphed in Fig. 7. Increasing density and resin content was expected to result in better mat consolidation. With the same final thickness, the greater the compaction ratio and the thickness ratio, the more uniform the mat [21].

Conclusions

The *Miscanthus*/wood particle ratio was found to have a significant influence on the improvement of board properties, particularly for boards with a density of 0.65 g/cm^3 and 11 % resin content. In a whole, increasing wood particles proportion contributed to increased MOE for HB boards but no obvious effect for LB boards. When the *Miscanthus*/wood particle ratio was below 60/40, the enhancements were more obvious despite HB board experienced more spring-back, resulting in higher TS. Taking making full use of *Miscanthus* into consideration, approximately 50/50 of *Miscanthus*/wood ratio, further investigation for better mechanical properties is necessary. Current composite board properties are not satisfactory and must be improved. The vertical density profiles study shows that during hot pressing the mats were well densified, which is related to the good permeability of the composite boards.

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