Wood Science and Technology 34 (2000) 355–365

Straw-wood composites bonded with various adhesive systems

A. H. Grigoriou

Abstract In order to study the feasibility of utilizing wheat straw as an alternative raw material for panels, experimental one-layer particleboards were produced by mixing straw with industrial wood particles in various proportions (100:0, 75:25, 50:50, 25:75, 0:100). Three different adhesive systems were used for blending the raw materials: a UF resin (E_2 grade), a PMDI resin and various UF:PMDI combinations (10:0, 8:2, 7:3, 6:4, 5:5). The evaluation of the mechanical and hygroscopic properties of panels showed the following results: Partial replacement of wood particles from straw in panels bonded with pure UF resin resulted in deterioration of all properties except linear swelling. Partial or whole substitution of wood by straw in PMDI bonded panels, improved the bending strength and all hygroscopic properties of the panels but reduced the internal bond (dry and wet) and screw holding strength, although to a much smaller degree compared to UF bonded panels. The properties of panels bonded with various UF:PMDI combinations and comprising 50% wood and 50% straw were considerably improved by increasing the PMDI content. In terms of the properties, pure straw panels or panels made of certain wood/straw mixtures, if bonded with PMDI resin or the appropriate UF:PMDI combination, can be used for specific applications where high quality panels are required according to the specifications of the related standards.

Introduction

Worldwide, economic growth and development have generated unprecedented needs for converted forest products such as pulp and paper, composite boards, plywood and lumber. Furthermore, the diminished supply of larger dimension timbers have created high pricing. Through these changes the industry is forced to identify alternative lignocellulosic sources and make improvements in traditional production methods.

Received 11 February 1998

A. H. Grigoriou
School of Forestry and Natural Environment,
Laboratory of Forest Products, Aristotelian University,
54006 Thessaloniki, Greece

The skilled technical assistance of Mr. Georgios Ntalos (Ph. D. Candidate) and Mr. Costantinos Grigoriadis (Technician) is gratefully acknowledged by the author. The author also wish to express gratitude to Bayer AG, Geschäftsbereich Polyurethane, Leverkusen, Germany for courtesy of supplying the polymeric diisocyanate.

Lignocellulosics from field crop residues like cereal straw, flax straw, stalks from corn, cotton and sorghum, bagasse and grass represent a potentially valuable source of fibre which could be used either as a supplement to, or as a direct substitute for wood in the manufacture of forest products, e.g. particleboard, fiberboard or pulp for paper-based products. Approximately 2.5 billion mt of these agricultural residues are annually produced worldwide. Factors that consistently hamper increased use of agro-based residues in pulps and composites are economics and problems and costs associated with the seasonability, the collection, the transportation and storage of the raw material.

However, in those countries where there are little or no wood resources left, or where due to regulations the use of wood is restricted, alternate sources like agricultural residues are needed if there is to be a natural fiber industry in those countries (Youngquist et al. 1993; Rowell et al. 1997).

Cereal straw as an annually-renewable fiber is one of the most important agricultural residue because it is available in abundant volumes in many regions of the world; the worldwide production of cereal straw is estimated at 1.5 billion mt annually (Rowell et al. 1997). In EC about 140 million tons of cereal straw per year are produced of which just a small part (2–3%) is processed in the industry. Because of environmental restrictions, straw may not be burned anymore in many EC-countries. Therefore, new applications have to be found besides the traditional forage and bedding for animals (Dam et al. 1994).

In the search for alternative fibers replacing natural wood, the use of straw as potential fiber for composites and particularly for particleboards has been gaining increasing research interest during the last twenty years (Rexen 1975; Hesch 1979; Heller 1980; White and Ansell 1983; Tröger and Pinke 1988; Thole and Weiss 1992; Zucaro and Reen 1995; Möller and Böttcher 1995; Sauter 1996; Dalen and Sharma 1996; Russell 1996; Hague 1997). In terms of process, straw fiber offers advantages such as the ability to be processed with less costly chipping and drying equipment. On the other hand, greater press capacity may be needed to accommodate the longer press times required for adequate steam dissipation (Hesch 1979; Spelter 1996). The waxy coating on the epidermis of straw stem causes problems in bonding this material with conventional urea formaldehyde (UF) binders. As derived from previous works, the polymeric isocyanate binder (PMDI) is the most effective binder in the manufacture of straw composites (Heller 1980; Tröger and Pinke 1988; Zucaro and Reen 1995; Dalen and Shorma 1996; Sauter 1996; Hague 1997). Rexen (1975) achieved acceptable bond quality in straw boards by using a modified UF resin. Apart from UF and PMDI, other binders like polyester (White and Ansell 1983) and gypsum (Thole and Weiss 1992) have been used for various types of straw composites. A natural light composite product consisting of a core made from straw stems, parallelly glued with glutin foam and wooden faces from veneer, has been developed by Möller and Böttcher (1995) as alternative to synthetic and aluminium products. In spite of the fact that straw has always been inexpensive, at present there is only one plant in the USA which produces particleboard from straw (Dalen and Shorma 1996) and another is under construction in Canada (Porter 1997). This is attributed to the fact that the appropriate PMDI binder for straw is expensive and has created a big price gap with wood particleboard which uses the less expensive UF resin; now as the cost of wood is continually increasing, the gap tends to close. It is also important to note that straw composite plants could offer new employment opportunities in agricultural areas.

The objective of this research, which is the subject of this paper, is to determine whether wheat straw could be substituted for virgin wood at significant levels in developing high-quality panels using as binders a UF resin, a PMDI and various UF:PMDI combinations.

Materials and methods

Wheat straw particles were produced from baled straw stems with approximately 10% moisture content using a hammermill with an 8 mm round hole screen. After hammermilling, the particle furnish was screened by an Allgaier (type 600/3) screening machine through meshes with 3 mm and 1.5 mm apertures to remove oversize and undersize particles. The fraction retained on the 3 mm aperture mesh was rehammermilled and mixed back into the furnish.

The wood particles for the various wood/straw blends were typical middle layer particles supplied by a local particleboard plant. From the obtained wood particles (~7% m.c.) the fraction retained between the 5 mm and 1.5 mm meshes was chosen for panel production. The wood particles were made up of approximately 75% mixed poplar and pine species and 25% veneer trims.

For comparative reasons, the following characteristics of straw and industrial wood particles were determined: fractional composition, dimensions (length, width and thickness), bulk density and ash content. Screen analysis was conducted by an Endecotts (type EFL) screening machine. The determination of ash content was performed in accordance with the ASTM-D 1037/95 standard. For the determination of the compaction ratio, the nominal density of the board (0.650 g/cm^3) was divided by the bulk density of the particles.

A commercial E_2 grade UF resin and a PMDI of PU1520A20L type obtained from Bayern, A.G. (Germany) were used as binders for the various wood/straw mixtures. Furthermore, some boards were produced by blending furnishes with both UF and PMDI in various proportions in an attempt to evaluate the fortifying effect of PMDI on UF bond quality and to lower the cost of boards made with pure PMDI. In the latter case, the UF resin was sprayed onto the particles before the spraying of PMDI. The two successive operations were carried out in the same rotating drum blender. All blendings of furnishes were performed at low rpm in order to avoid straw particles breakage. With the exception of one PMDI bonded board type made from pure wood in which 0.7% wax (solids based on oven dried particles) was added, no water-repelling agent was applied to the other board types tested.

Three experimental one-layer particleboards of 12 mm thickness were manufactured for each parameter (totally 45 boards). Table 1 presents all parameters and the production conditions of the boards. In order to avoid delamination or springback of UF bonded boards, pressing times were gradually increased with increasing straw percentage in boards (Table 1).

The following properties of boards were evaluated in accordance with specifications of appropriate European (EN) and American (ASTM) standards: static bending (EN 310/1993), internal bond (EN 319/1993), internal bond wet strength after 2 hours boiling (EN 1087–1, V100 test), internal bond wet strength after wet cycling (EN 321, V313 test), thickness swelling after 24 h immersion in water (EN 317), thickness swelling after wet cycling (EN 321). Screw holding strength was determined according to ASTM-D1037/95 standard by using screws with $d = 3.5$ mm, $l = 45$ mm and a hole diameter of 2.5 mm. In addition, the permanent springback of specimens used for thickness swelling (24 h) was measured after their reconditioning in laboratory conditions. The linear swelling

Table 1. Types of one layer experimental particleboards and their manufacture conditions

Nr.	Raw material	Adhesive system	Glue solids (%)	Pressing time (min)	Temperature (°C)	Nominal density (g/cm^3)
1	100% wood	UF	8	4	180	0.650
2	75% wood:25% straw	UF	10	$4^1/_2$	180	0.650
3	50% wood:50% straw	UF	10	5	180	0.650
4	25% wood:75% straw	UF	10	$5^1/_2$	180	0.650
5	100% wood	PMDI	8	$5^1/_2$	180	0.650
6*	100% wood	PMDI	8	$5^1/_2$	180	0.650
7	75% wood:25% straw	PMDI	8	$5^1/_2$	180	0.650
8	50% wood:50% straw	PMDI	8	$5^1/_2$	180	0.650
9	25% wood:75% straw	PMDI	8	$4^1/_2$	180	0.650
10	100% straw	PMDI	8	$4^1/_2$	180	0.650
11	50% wood:50% straw	UF	10	$4^1/_2$	180	0.700
12	50% wood:50% straw	UF:PMDI	8:2	$4^1/_2$	180	0.700
13	50% wood:50% straw	UF:PMDI	7:3	$4^1/_2$	180	0.700
14	50% wood:50% straw	UF:PMDI	6:4	$4^1/_2$	180	0.700
15	50% wood:50% straw	UF:PMDI	5:5	$4^1/_2$	180	0.700

* 0.7% wax on oven dry mass of particles

test after 24 h immersion in water was performed using specimens of 20 mm by 120 mm.

Results and discussion

Characteristics of wood and straw particles

Table 2 presents the fraction analysis of straw particles in comparison to industrial wood particles. Straw particles have a higher content of the fractions >4 mm and >1 < 2 mm but lower of the fraction >2 < 4 than wood particles. As can be seen from Table 3, which shows the dimensions of raw materials for both fractions >4 mm and >2 < 4 mm, straw particles are longer but thinner and smaller in width than wood particles. Thus, length to thickness (slenderness) and length to width ratios of straw particles are considerably higher than the corresponding values of wood particles. Similar observations about the slender configuration of straw particles have been mentioned in previous works (Rexen 1975; Hesch 1979; Sauter 1996). As shown in Table 4, the bulk density of straw particles is much lower (about one third) than that of wood particles; therefore straw-made panels have a considerably higher compaction ratio in comparison to wood made panels. Straw ash content was found to be extremely high (6.40%) when compared to that of industrial wood particles (0.54%), probably as a result of the high percentage of straw in silica (Youngquist et al. 1993; Sauter 1996).

Table 2. Fractional composition (%) per weight of straw and industrial wood particles*

Screen mesh width (mm)	Industrial wood particles	Straw particles
>4	15.4	34.9
>2 < 4	52.9	24.6
>1 < 2	28.1	36.5
<1	3.6	4.0

* Mean values of five fraction analyses

Table 3. Dimensions of wood and straw particles and the corresponding values of their length:thickness and length:width ratios*

	Fraction >4 mm		Fraction >2 < 4 mm	
	Wood particles	Straw particles	Wood particles	Straw particles
Length (mm)	22.9 (6.134)	28.4 (8.002)	15.3 (5.916)	19.4 (7.986)
Width (mm)	4.0 (0.952)	1.6 (0.589)	2.4 (0.636)	1.5 (0.583)
Thickness (mm)	1.7 (0.783)	0.37 (0.174)	1.1 (0.385)	0.33 (0.103)
Length:Thickness	19.9 (5.671)	129.7 (18.321)	17.7 (4.935)	87.4 (14.737)
Length:Width	7.0 (3.233)	21.4 (5.824)	7.1 (2.510)	13.9 (4.207)

* Mean values from 200 measurements. In parentheses, standard deviations

Table 4. Bulk density and compaction ratio of straw and industrial wood particles

	Bulk density* (g/cm^3)	Compaction ratio
Industrial wood particles	0.124 (0.0067)	5.3
Straw particles	0.044 (0.0019)	14.8

* Mean values of eight tests. In parentheses, standard deviations

Properties of UF resin boards

The properties of UF bonded particleboards comprising various amounts of wood/straw particles are presented in Table 5. At 100% straw level experimental panels delaminated, thus they are not included in Table 5.

Although panels made from wood/straw mixtures contained a higher solids resin content (10%) than control panels made of wood (8%), almost all their properties deteriorated as the straw level increased. From the wood/straw combinations tested, only the one with 25% straw content met the minimum standard requirements for board use in interior fitments in dry conditions (EN 312-3).

Among the tested properties the most negatively affected one was the internal bond. Considering that internal bond strongly correlates to adhesive bond strength, it became obvious that very limited cross-linking was achieved between UF resin and straw particles. Apparently, the wax and silicate coating of straw obstructs the development of strong bonds with UF resin.

The relatively lower degree of bending strength deterioration of wood/straw panels can be attributed to the higher length to thickness ratio of straw compared to wood particles. This finding is in agreement with the results of Heller (1980) but in contrast with those of Sauter (1996) who found that bending strength of wood/straw panels remained the same or improved in comparison to the values of pure wood panels.

Despite the fact that straw contains higher amounts of hydrophobic substances (wax and silicate) than wood (Rexen 1975; Youngquist et al. 1993; Sauter 1996), panels containing straw in amounts of 50% or higher showed inferior performance in thickness swelling, springback and water absorption than pure wood panels, probably as a result of the inferior bond quality of straw with UF resin. These results are in line with those quoted by previous researchers (Zucaro and Reen 1995; Sauter 1996). As far as linear swelling is concerned, no substantial differences were obtained between wood panels and panels made of various wood/straw mixtures. According to previous investigations (Turner 1954;

Table 5. Properties of experimental UF particleboards made from various wood/straw mixtures

Properties*	Wood:Straw (%) (Glue solids)			
	100:0 (8%)	75:25 (10%)	50:50 (10%)	25:75 (10%)
Density (g/cm^3)	0.659 (0.015)	0.667 (0.011)	0.647 (0.026)	0.638 (0.018)
Bending strength (MOR)(N/mm^2)	18.88 (1.56)	16.88 (1.03)	13.80 (0.92)	11.58 (0.89)
Internal bond strength (N/mm^2)	0.99 (0.073)	0.41 (0.044)	0.16 (0.025)	0.070 (0.013)
Screw holding strength, ⊥, (N)	1058 (152.8)	904 (132.6)	789 (100.9)	641 (57.2)
Thickness swelling (24 h) (%)	23.9 (1.81)	23.3 (1.60)	27.5 (3.13)	31.3 (1.71)
Springback (%)	16.9 (1.67)	16.5 (1.65)	21.2 (1.94)	24.3 (1.33)
Water absorption (24 h) (%)	67.9 (3.16)	65.0 (3.20)	71.8 (5.49)	79.1 (4.88)
Linear swelling (24 h) (%)	0.45 (0.049)	0.42 (0.034)	0.43 (0.059)	0.43 (0.048)
Moisture content (%)	7.6 (0.10)	7.8 (0.15)	7.6 (0.21)	7.5 (0.12)

* Mean values of twenty specimens for each property with the exception of bending strength (fifteen specimens). In parentheses, standard deviations

Brumbaugh 1960; Lehmann 1974) the straw particles, being longer and thinner than wood, should have contributed to a decreased linear swelling; that this is not the case is due to the ineffective bonding of straw with UF resin.

PMDI bonded boards

The experimental results of wood/straw panels bonded with PMDI are shown in the Tables 6 and 7. By increasing the straw level, the following changes in panel properties have occurred compared to control panels made from wood alone:

a) Improvement of bending strength, as a result of the greater length to thickness ratio and compaction ratio of straw in comparison to wood particles; panels containing 100% straw gave bending strength values almost 100% greater than wood panels (Table 6).
b) Decrease of internal bond dry and wet strengths (V100 and V313) and screw holding strength (Table 6). The adverse influence of straw on internal bond (dry) and screw holding strength has also been quoted by other workers (Tröger and Plinke 1988; Hague 1997). Apparently, the wax and silica coating of straw negatively affects the bonding strength when using PMDI resin, but to a much smaller degree than with UF resin (compare Tables 5 and 6).

A possible explanation of the improved adhesion strength of PMDI resin in contrast to UF-resin is that PMDI penetrates more deeply into the wax and silicate film of straw; this explanation is based on the findings of Roll et al. (1990) and Marcinko et al. (1995) who observed that PMDI compared to other thermosetting resins penetrates into wood much more deeply.

c) Improvement of thickness swelling (24 h), thickness swelling after wet cycling test, linear swelling and water absorption; concerning the above properties the rate of improvement (reduction) of pure straw panels in comparison to those of pure wood was 163%, 57%, 82% and 40% respectively. With exception of the

Table 6. Mechanical properties of PMDI bonded particleboards made from various wood/straw mixtures

Properties*	Wood:Straw (%) (Glue solids)					
	100:0 (8%)	100:0** (8%)	75:25 (8%)	50:50 (8%)	25:75 (8%)	0:100 (8%)
Density (g/cm^3)	0.666 (0.021)	0.666 (0.017)	0.654 (0.022)	0.656 (0.024)	0.657 (0.025)	0.650 (0.020)
Bending strength (MOR) (N/mm^2)	22.06 (2.36)	20.72 (1.60)	23.19 (1.42)	29.28 (2.07)	32.66 (3.03)	40.38 (1.79)
Internal bond strength (N/mm^2)	1.61 (0.087)	1.57 (0.101)	1.28 (0.075)	1.07 (0.079)	0.88 (0.010)	0.85 (0.065)
Internal bond wet strength (2 h boiling, V100) (N/mm^2)	0.38 (0.016)	0.36 (0.035)	0.30 (0.026)	0.26 (0.021)	0.25 (0.023)	0.24 (0.022)
Internal bond wet strength (cycling test, V313) (N/mm^2)	0.55 (0.046)	0.54 (0.070)	0.45 (0.037)	0.42 (0.057)	0.38 (0.026)	0.36 (0.027)
Screw holding strength, ⊥ (N)	1510 (132.3)	1490 (108.9)	1222 (164.5)	1168 (169.9)	1088 (67.7)	1008 (97.6)
Moisture Content (%)	7.3 (0.15)	7.1 (0.03)	7.3 (0.10)	7.4 (0.12)	7.3 (0.10)	7.4 (0.12)

* Mean values of twenty specimens for each property with the exception of bending strength (fifteen specimens). In parentheses, standard deviations
** Addition of 0.7% wax

thickness swelling (24 h) value which remained higher, wood panels achieved similar to pure straw panels hygroscopic properties only after the addition of 0.7% wax (Table 7).

As far as thickness swelling (24 h) is concerned, the findings of this work are in contrast with those of Tröger and Plinke (1988) and Hague (1997) who reported poorer thickness swelling properties for panels comprising various amounts of straw.

All PMDI bonded board types shown in Table 6 met the requirements of the European standard (EN 312-6) concerning heavy duty load-bearing particleboards in dry conditions. Only pure straw panels and pure wood panels containing 0.7% wax fully satisfied the requirements of EN 312-5 standard for load-bearing particleboards in humid conditions; panels with wood/straw mixtures of 50:50 and 25:75 fulfilled this standard with the exception of thickness swelling after wet cycling test; pure wood panels without wax failed to satisfy the above mentioned standard because of excesive thickness swelling (after 24 h and after wet cycling test). With the exception of the thickness swelling after the wet cycling test, only the board type comprising 50% wood and 50% straw met the requirements of EN 312-7 standard for heavy duty load-bearing boards in humid conditions; pure wood panels containing 0.7% wax failed to fulfill this standard only regarding the bending strength value.

Among the board types tested, only the one consisting of 100% straw fully satisfied the requirements of EN 622-5 standard for load-bearing medium density fiberboards (MDF) in dry conditions. Furthermore, the requirements of EN 622-5

Table 7. Hygroscopic properties of PMDI bonded particleboards made from various wood/straw mixtures

Properties*	Wood:Straw (%) (Glue solids)					
	100:0 (8%)	100:0** (8%)	75:25 (8%)	50:50 (8%)	25:75 (8%)	0:100 (8%)
Thickness swelling (24 h) (%)	15.0 (1.41)	8.4 (0.65)	11.8 (1.19)	9.7 (1.44)	8.4 (1.12)	5.7 (0.74)
Water absorption (24 h) (%)	51.2 (4.93)	26.3 (1.78)	42.3 (3.23)	39.3 (2.65)	37.4 (2.57)	36.7 (2.24)
Thickness swelling (after wet cycling test), (%)	14.2 (1.20)	9.7 (1.34)	14.3 (1.19)	14.3 (1.13)	12.1 (1.41)	9.0 (1.45)
Springback (%)	10.2 (1.18)	5.7 (0.84)	8.8 (0.98)	8.4 (1.26)	6.7 (0.97)	5.6 (1.08)
Linear swelling (%)	0.44 (0.059)	0.25 (0.029)	0.39 (0.063)	0.29 (0.032)	0.25 (0.032)	0.24 (0.036)

* Mean values of twenty specimens for each property with the exception of bending strength (fifteen specimens). In parentheses, standard deviations
** Addition of 0.7% wax

standard concerning general use of MDF in humid conditions were met only by panels with wood/straw mixtures of 50:50, 25:75 and 0:100.

Panels made of 50, 75 and 100% straw complied with the requirements of EN 300 standard for heavy duty load-bearing oriented strand boards (OSB) in humid conditions; pure wood panels and panels with 25% straw failed to satisfy this standard because of the low bending strength values. It should be pointed out that straw-made panels have some advantages over traditional OSB panels: firstly they have approximately similar bending strength values in all plain directions of the board and, secondly, they have a superior surface smoothness.

Boards bonded with various UF:PMDI combinations

Table 8 shows the properties of wood/straw-made boards in proportion of 50:50 glued with various UF:PMDI combinations. The results revealed that the addition of PMDI to UF resin improved significantly both dry and wet strength V313 and swelling properties. Apparently, the addition of PMDI enhances the cross-linking reactions of UF resin in the combined system UF:PMDI contributing to final strength and water resistance. Similar findings concerning the reinforcing effect of PMDI on UF bonded particleboard were quoted from Deppe (1977) and Wittmann (1983).

The improvement of board bonded with a UF:PMDI mixture of 8:2 in comparison to pure UF resin (10%) bonded board for bending strength, internal bond and thickness swelling was 43%, 128% and 107%, respectively. Concerning internal bond wet strength (V100) none of the UF:PMDI combinations satisfied the minimum requirements of EN312-5 standard, whilst all of them met the requirements of this standard for internal bond wet strength (V313). All UF:PMDI glue formulations tried, met the requirements of EN 312-6 standard for heavy duty load-bearing boards in dry conditions. It is important to notice that when the PMDI amount in an adhesive system was 3% or higher, the panels complied with the requirements of EN312-5 standard regarding thickness swelling without wax adding. Furthermore, UF:PMDI glue formulations containing PMDI in amounts of 2% or higher met the requirements of EN 300 standard for load-bearing OSB in dry conditions.

Conclusions

Partial replacement of wood by straw in UF resin bonded panels deteriorates dramatically their basic properties.

Partial or whole substitution of wood by straw in panels bonded with PMDI resin improves significantly the bending strength and the hygroscopic properties but affects adversely the internal bond (dry and wet) and the screw holding strength of the panels, although to a much smaller degree compared to UF bonded panels.

UF:PMDI glue combinations improve significantly the properties of panels made of wood/straw mixtures of 50:50 compared to those bonded with pure UF resin.

Judging from their properties, some panel types made of pure straw or certain wood/straw mixtures if bonded with PMDI or the appropriate UF:PMDI combination can compete with wood made particleboards, MDF and OSB in certain applications, as they satisfy the requirements of the related European standards (EN). Pure straw panels are characterised by improved bending strength values as a result of the great slenderness and compaction ratio of the straw, hence they are particularly suitable for application demanding high flexure properties.

Table 8. Properties of panels made of wood/straw mixtures in proportion of 50:50 and bonded with various UF:PMDI combinations

Properties*	UF 10%	UF:PMDI 8:2	UF:PMDI 7:3	UF:PMDI 6:4	UF:PMDI 5:5
Density (g/cm^3)	0.700 (0.021)	0.698 (0.016)	0.693 (0.017)	0.693 (0.009)	0.689 (0.028)
Bending strength (MOR) (N/mm^2)	18.54 (1.48)	26.39 (2.17)	28.47 (2.01)	29.10 (1.35)	30.99 (1.53)
Internal bond strength (N/mm^2)	0.29 (0.030)	0.66 (0.047)	0.72 (0.040)	0.80 (0.061)	0.87 (0.081)
Internal bond wet strength (cycling test, V313) (N/mm^2)	–	0.25 (0.026)	0.30 (0.025)	0.35 (0.032)	0.41 (0.019)
Screw holding strength, ⊥, (N)	852 (93.6)	940 (124.6)	1018 (81.5)	1041 (81.8)	1083 (132.5)
Thickness swelling (24 h), (%)	23.4 (1.62)	11.5 (1.24)	9.6 (1.27)	9.2 (0.81)	8.7 (0.75)
Water absorption (24 h), (%)	62.7 (2.92)	41.4 (2.96)	38.0 (2.15)	36.4 (2.55)	35.3 (2.63)
Thickness swelling (after wet cycling test), (%)	–	25.5 (1.84)	18.3 (2.62)	16.9 (1.41)	13.9 (1.26)
Springback (%)	17.2 (1.56)	9.9 (1.18)	7.1 (1.30)	6.9 (0.75)	6.3 (1.03)
Moisture content (%)	7.6 (0.12)	7.7 (0.15)	7.6 (0.09)	7.1 (0.10)	7.0 (0.19)

* Mean values of twenty specimens for each property with the exception of bending strength (fifteen specimens). In parentheses, standard deviations

References

Brumbaugh JI (1960) Effect of flake dimensions on properties of particleboard. Forest Prod J 10: 243–246

Dalen H, Shorma T (1996) The manufacture of particleboard from wheat straw. In: Proceedings of the 30th Washington State University international particleboard/ composite materials symposium, Pullman, Washington, pp. 191–196

Dam v. JEG, Shannon WB (1994) Increased application of domestically produced plant fibres in textiles, pulp and paper production, and composite materials. European commission, Agro-Industrial Research Division, pp. 74–75

Deppe H-J (1977) Technische Fortschritte bei der Isocyanatverleimung von Holzspanplatten. Holz Roh- Werkstoff 35: 295–299

Hague JRB (1997) Biomass as feed-stocks for the forest products industry. Aspects of Appl Biol 49: 455–464

Heller W (1980) Die Herstellung von Spanplatten aus unkonventionellen Rohstoffen. Holz Roh- Werkstoff 38: 393–396

Hesch R (1979) Stroh als Rohstoff für Platten. Holz-Zbl. Nr. 3, pp. 22 and Nr. 13, pp. 196

Lehmann WF (1974) Properties of structural particleboards. Forest Prod J 24: 19–26

Marcinko JJ, Phanopoulos C, Newman WH, Sander MA (1995) The Nature of MDI/Wood bond. In: Proceedings of the 29th Washington State University international particleboard/ composite materials symposium. Pullman, Washington, pp. 175–183

Möller F, Böttcher P (1995) Naturstoffsandwich: ein leichter Werkstoff aus nachwachsenden Rohstoffen. Holz-Zbl. Nr. 34: 573, 576

Porter K (1997) Industry's largest show gets even bigger this year. Wood Techn Nr. 7/8: 27–28

Rexen F (1975) Stroh als Rohstoffmaterial für Spanplatten. Holz-Zentralbl. 101, Nr. 34: 471–472

Roll H, Tröger F, Wegener G, Grosser D, Frühwald A (1990) Untersuchung zur PMDI-Verteilung in Spangemischen und Spanplatten. Holz Roh- Werkstoff 48: 405–408

Rowell RM, Young RA, Rowell JK (1997) Paper and Composites from Agro-Based Resources. CRC Lewis Publishers, Boca Raton New York Tokyo

Russel WC (1996) The straw resource: A new fiber basket? In: Proceedings of the 30th Washington State University international particleboard/composite materials symposium, Pullman, Washington, pp. 183–190

Sauter SL (1996) Developing composites from wheat straw. In: Proceedings of the 30th Washington State University international particleboard/composite materials symposium, Pullman, Washington, pp. 197–214

Spelter H (1996) Capacity, production, and Manufacture of wood-based panels in the United States and Canada. General technical report FPL-GTR-90, Madison, WI: U.S. Department of Agriculture, Forest Service. Forest Products Laboratory, p 17

Thole V, Weiss D (1992) Eignung von Einjahrespflanzen als Zuschlagstoffe für Gipsspanplatten. Holz Roh- Werkstoff 50: 241–252

Tröger F, Pinke G (1988) Beitrag zur Herstellung PMDI-verleimter Spanplatten mit verschiedenen Strohanteilen. Holz Roh- Werkstoff 46: 389–395

Turner HD (1954) Effect of particle size and shape on strength and dimensional stability of resin bonded wood-particle panels. Forest Prod J 4: 210–222

White NM, Ansell MP (1983) Straw-reinforced polyester composites. Journ Mat Sci 18: 1549–1556

Wittmann O (1983) Herstellung von Spanplatten mit verstärkten Aminoplast-Leimharzen. Holz Roh- Werkstoff 41: 431–435

Youngquist JA, Spelter H, English BE, Chow S (1993) Agricultural fibers in composition panels. In: Proceedings of the 27th Washington State University international particleboard/composite materials symposium. Pullman, Washington, pp. 133–152

Zucaro J, Reen R (1995) The second forest: filling the wood source gap while creating the environmental performance board of the 21st century. In: Proceedings of the 29th Washington State University international particleboard/composite materials symposium. Pullman, Washington, pp. 225–230