Carbohydrate Polymers 120 (2015) 15–21

Contents lists available at ScienceDirect

Carbohydrate Polymers

journal homepage: www.elsevier.com/locate/carbpol

Suitability of sorghum stalk fibers for production of particleboard

Abolghasem Khazaeian[a], Alireza Ashori[b,*], Mostafa Yahyavi Dizaj[a]

[a] Department of Wood Engineering and Technology, Gorgan University of Agricultural Sciences and Natural Resources (GUASNR), Gorgan, Iran
[b] Department of Chemical Technologies, Iranian Research Organization for Science and Technology (IROST), Tehran, Iran

ARTICLE INFO

Article history:
Received 23 September 2014
Received in revised form
27 November 2014
Accepted 2 December 2014
Available online 10 December 2014

Keywords:
Sorghum
Particleboard
Resin content
Physical properties
Mechanical properties

ABSTRACT

The aim of this study was to investigate the suitability of sorghum (*Sorghum bicolor*) stalk (SS) as a promising raw material for particleboard manufacturing. The SS particles and industrial hardwood particles in various proportions were used as the raw materials for the surface and core layers of the three-layer particleboards. Commercial urea formaldehyde (UF) adhesive was used as a binder. Morphological and chemical characteristics of the SS were evaluated. Effects of five variable parameters on the physical (thickness swelling (TS), water absorption (WA)), and mechanical (modulus of rupture (MOR), modulus of elasticity (MOE), internal bond (IB)) properties of the particleboards were determined. Other parameters such as type of resin (UF), hardener content (1%), type of hardener (NH_4Cl), press closing time (5 mm/s), board density (0.70 g/cm^3), and press pressure (30 kg/m^2) were held constant. Fractional factorial was used to find the optimum condition for the studied variable parameters. The morphological results showed that SS had comparable fiber length with softwoods and fiber width and wall thickness values greater than the hardwood of common forest species. They had higher hot-water solubility values, lignin and ash contents than those of the other woody materials. The experimental results showed that increasing of SS particles usage in the surface layer significantly affects the board properties. Containing 50 wt% SS particles in the surface, the MOE and MOR values exceed the minimum requirements of the European norms (EN) standards, for general purposes. All of the particleboards produced from SS had IB higher than the EN standard requirement. The presence of SS in the particleboards resulted in higher WA and TS values. All the mechanical properties of the boards decreased when the press temperature was increased from 160 to 180 °C. Finally, it can be stated that SS has enough potential as a supplement fibrous material, in combination with industrial hardwood particles, for particleboard manufacturing and indoor applications.

1. Introduction

Recently, increasing environmental awareness, growing global waste problem, depletion of fossil fuels, and the increasingly higher price of crude oil have together created a groundswell of interest in renewable resources (Dos Santos, Battistelle, Bezerra, & Varum, 2014). In addition, deforestation and over-harvesting have created environmental issues, while increasing demand for forest resources in various applications has led to the shortages of wood supply in the most developing countries like Iran (Azizi, Tabarsa, & Ashori, 2011). Thus, there is a need to look for innovative ways of using non-traditional forest resources such as non-woods, agro residues and wood wastes, to substitute wood raw material for wood-based industries (Abdul Khalil, Issam, Ahmad Shakri, Suriani, & Awang, 2007). Agro residues and wood wastes are potentially usable in different ways. According to the end uses, agro residues could be sorted, processed and provided as raw materials for manufacture of pulp, fiberboard and particleboard (Ashori, 2006). Manufacturing of value added panel products may be the most efficient use of such waste materials.

Particleboard has become one of the most popular wood-based composite materials for decorating materials because of its low density, good thermal insulation, sound absorption, and wonderful machining properties. The primary lignocellulosic material used in the particleboard industry is wood (Yang, Fei, Wu, Peng, & Yu, 2014). However, the manufacture of particleboard is the most common way to reuse waste materials (Akgul & Camlibel, 2008). Research has been carried out on a wide variety of non-wood plant fibers and agro residues from many different regions of the world: wheat–cereal straws (Cheng, Sun, & Karr, 2004; Sain & Panthapulakkal, 2006), rice straw (Zhang & Hu, 2014), tobacco (Ntalos & Grigoriou, 2002), bagasse (Widyorini, Xu, Umemura, &

* Corresponding author. Tel.: +98 21 56275192; fax: +98 21 56275191.
E-mail address: ashori@irost.ir (A. Ashori).

http://dx.doi.org/10.1016/j.carbpol.2014.12.001
0144-8617/

Table 1
Various blending formulations and their mass ratios of the boards produced.

Board type	Particle size (mesh)	SS content (wt%)	Press time (min)	Press temp. (°C)	UF content (wt%)
L1	20	10	6	160	8
L2	20	10	6	180	12
L3	20	10	10	160	8
L4	20	10	10	180	12
L5	20	50	6	160	8
L6	20	50	6	180	12
L7	20	50	10	160	8
L8	20	50	10	180	12
H1	40	10	6	160	8
H2	40	10	6	180	12
H3	40	10	10	160	8
H4	40	10	10	180	12
H5	40	50	6	160	8
H6	40	50	6	180	12
H7	40	50	10	160	8
H8	40	50	10	180	12

Kawai, 2005), rapeseed straw (Mazhari Mousavi, Hosseini, Resalati, Mahdavi, & Rasooly Garmaroody, 2013), sunflower stalks (Nemli, 2003), kenaf (Kalaycıoglu & Nemli, 2006), bamboo (Sudin & Swamy, 2006), oil palm (Abdul Khalil et al., 2007) and cotton carpel (Alma, Kalaycıoğlub, Bektas, & Tutus, 2005).

The main goal of the current study is to confirm the feasibility of applying sorghum stalks as alternative raw material for particleboard industry, which, to our knowledge, has not been thoroughly investigated before. The objectives of study are; (a) to investigate the chemical and fiber morphology of sorghum stalks, (b) to prepare 3-layer particleboards made from mixture of sorghum stalk (SS) and industrial hardwood particles, bonded with urea–formaldehyde resin and, (c) to study the effect of some variable parameters on the physical and mechanical properties of particleboard samples. This reuse would provide a solution to the wood shortage, especially in countries with insufficient forest resources.

2. Methods

2.1. Materials

Two different types of fibrous materials were used in this study: sorghum (*Sorghum bicolor*) stalks and the mixture of industrial hardwood. The sorghum stalks were collected from an experimental field in the Gorgan-Kordkoy road in Iran, directly after crop harvest. The industrial hardwoods were obtained from forests in the northern part of Iran. Leaves, branches and piths were removed and then sorghum stalks were gently scrubbed in tab water. After air-drying, the stalks and industrial hardwoods were separately chipped using a laboratory-scale Drum-Chipper. The chips were then reduced into smaller pieces using a laboratory-scale Ring-Flaker. Particles were oven-dried at 80 °C for 10 h to a moisture content of less than 4% and then stored in plastic bags for future use.

Urea–formaldehyde (UF) adhesive with a solid content of 67%, density of 1.265 g/cm^3, viscosity of 61 cp, gelation time of 45 s, and pH of 7.5 was applied. As a hardener, ammonium chloride (NH_4Cl) solution (solid content: 20%) was added to the adhesive.

2.2. Chemical compositions

The chemical compositions of sorghum stalks were determined following the standards outlined in the TAPPI test methods and the other published procedures where indicated. Alpha-cellulose was determined following the procedure of T 203 cm-99. Acid-insoluble (Klason) lignin content was determined by hydrolyzing the carbohydrates with 72% sulfuric acid as per T 222 om-02. The procedure for the hot-water solubility was determined by T 207 cm-99. To determine ash content, the procedure outlined in T 211 om-93 was followed.

2.3. Fiber morphology determination

The samples for fiber measurements were obtained from the middle sections of the stalks. As per the modified Franklin method (Sheshmani, Ashori, & Farhani, 2012), pieces of samples were placed in test tubes containing an equal amount of glacial acetic acid and 35% hydrogen peroxide. For this study, one hundred (100) undamaged/unbroken fibers were measured in terms of their length (L), fiber width (d), lumen diameter (l) and cell wall thickness (w), directly from the magnified image.

2.4. Lab production of boards

Three-layer particleboards were produced using sorghum stalk for face layers and industrial hardwood particles for core layer. The whole experimental plan is shown in Table 1, where the blending formulations are summarized. As seen, five variable parameters are: particle size (20, 30 and 40 mesh), sorghum stalk content (10, 30 and 50%), UF content (8, 10 and 12%), pressing time (6, 8 and 10 min), and press temperature (160, 170 and 180 °C). Other parameters such as hardener content (1 wt%), press closing rate (5 mm/s), press pressure (35 kg/cm^2), board thickness (10 mm), and target density (0.70 g/cm^3) were held constant.

Dried particles for the face and core layers were separately blended with UF adhesive in a rotating drum-type mixer fitted with a pneumatic spray gun. The resinated particles were placed in a molding box with dimensions of 30 cm × 30 cm and manually formed. The press cycle consisted of two phases. First, in order to reduce the mat height and to densify it, the randomly oriented mats were cold pressed at a load of approximately 30 kg/m^2 for 4 min. In the second phase, the boards were pressed using a hydraulic hot press (OTT, Germany). Stop bars were used in the press to allow the same board thickness to be achieved for all the test runs. No wax or any other hydrophobic substance was applied for manufacturing of the boards.

2.5. Testing methods

After hot pressing, boards were stacked for 24 h in order to be completely cured and then trimmed and cut into various test specimens. All specimens were conditioned at a temperature of 25 ± 2 °C, and 65 ± 5% relative humidity in a conditioning chamber for at least

Table 2
Experimental parameters with their levels.

High value	Low value	Variable
40	20	Particle size, mesh
50	10	SS content, wt%
12	8	UF content, wt%
10	6	Press time, min
180	160	Press temp., °C

2 weeks until they reached equilibrium. All tests were carried out in accordance with DIN 68763 standard. The tests performed on the specimens were: internal bond strength perpendicular to the plane of the board (IB), modulus of rupture (MOR), modulus of elasticity (MOE), water absorption (WA) and thickness swelling (TS).

For each measurement and particleboard type, six specimens were tested. Rectangular 250 mm × 50 mm pieces were used to determine three-point bending measurement of MOR and MOE. Specimens of 50 mm × 50 mm were used for IB measurement. Mechanical properties were determined using a Universal Testing Machine (Schenck Trebel) with crosshead speed at 5 mm/min for three-point bending (MOR and MOE) measurement and 1.5 mm/min for IB measurement. To determine water absorption and thickness swelling properties, boards were cut into 50 mm × 50 mm and fully immersed in distilled water at 25 ± 2 °C for 2 h and 24 h.

2.6. Data analysis

For the above-mentioned property experiments, data analysis was conducted using Minitab (version 16). Fractional factorial experimental design was done considering five process and material variables with their two levels and the center point in planning experiments (Table 2). The effects of variable parameters on the properties of particleboards were evaluated by analysis of variance (ANOVA).

3. Results and discussion

3.1. Chemical and morphological characteristics

The purpose of this part of the study was to provide basic information with respect to the chemical components of sorghum stalks (Table 3). The chemical components are important in determining how the material will perform in the final products as well as in their production. In this investigation α-cellulose content was determined to be 45.9%. It is expected that high α-cellulose content exhibits a number of properties that fulfill the requirements of a good raw material such as high tensile strength, suppleness, hydrophilicity and ability to absorb additives (Villar, Revilla, Gómez, Carbajo, & Simón, 2009). Klason (acid-insoluble) lignin content was found to be 17.2. As can be seen from Table 3, hot-water solubles are considerably higher than those in hard and softwoods. The amount of ash was determined to be 6.6%. Although the ash content of sorghum stalk is low in comparison to most non-woods (for example, rice straw can have ash level as high as 20%), they are still rather high compared to the conventional woods (most of these materials have ash contents below 1%) (Abdul Khalil et al., 2007).

Table 3
Chemical compositions and fiber dimensions of the used sorghum stalks and some agro-waste materials.

Property	Sorghum	Bagasse[a]	Rice straw[a]
Chemical			
α-cellulose, %	45.9	40.5	46.6
Lignin, %	17.2	27.7	20.9
Hot-water solubility, %	5.7	6.5	8.4
Ash, %	6.6	4.8	10.0
Morphological			
Fiber length, mm	1.8	0.87	1.17
Fiber width, μm	13.8	22.2	8.6
Wall thickness, μm	2.9	5.4	2.3
Lumen width, μm	7.9	12.1	4.0

[a] Ashori, Hamzeh, and Amani (2011).

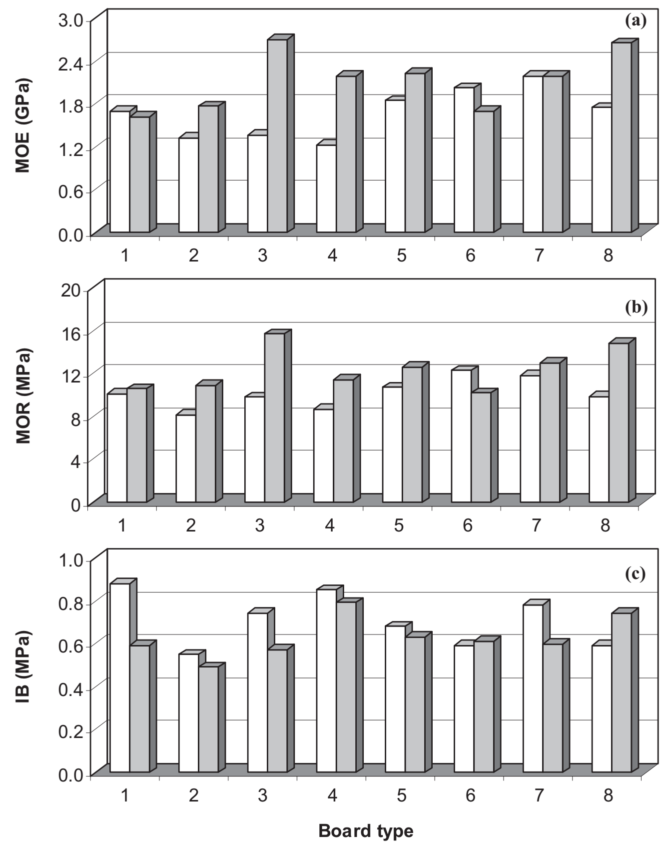

Fig. 1. Comparison of (a) MOE, (b) MOR, and (c) IB of particleboards. (□ low level, ■ high level variable parameters)

The fiber dimensions are presented in Table 3. The average length of sorghum fibers (1.8 mm) is in the range of softwoods and bamboo but higher than hardwoods. The mean fiber width and lumen width of fibers was greater than hardwoods.

3.2. Mechanical properties

In general, statistical analyses showed that the mechanical properties of the experimental boards were significantly influenced by the variable parameters. The average values of MOE, MOR, and IB of experimental boards are presented in Fig. 1. Based on European norms (EN) standard, 1.6 GPa is the minimum requirement for the MOE of particleboards for general uses and furniture manufacturing (EN 312-3, 1996). On the other hand, the minimum requirements for the MOR are 11.5 (EN 312-2, 1996) and 13 MPa (EN 312-3, 1996) for general purpose and interior fitments (including furniture), respectively. The range of data in the MOE was from 1.2 to 2.7 GPa (Fig. 1a). Most types of boards met the minimum MOE requirement of the EN standards for general uses. Except for board types L6 and L7, all other boards, which were made with low values of variable parameters, had lower MOR than the general purpose requirements. However, most boards with high values of variable parameters met the minimum MOR requirement of the EN standards for general uses (Fig. 1b). Internal bond data ranged

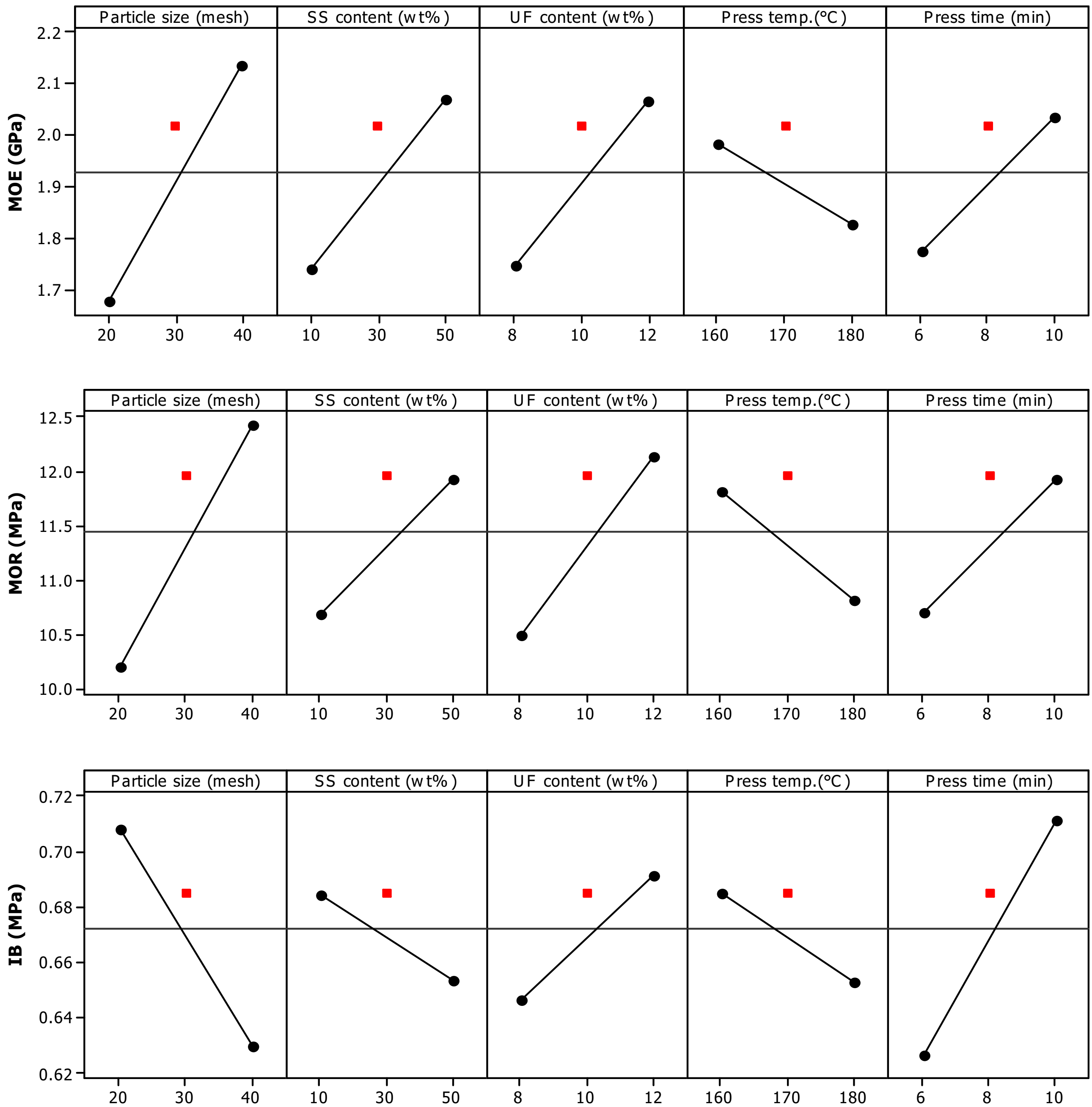

Fig. 2. Effects of each variable parameter on the mechanical properties. (■ low and high values, ■ center point).

from 0.5 to 0.88 MPa. The minimum requirements of internal bond strength in the EN standards are 0.24 MPa for general purpose (EN 312-2, 1996), 0.35 MPa for interior fitments (EN 312-3, 1996), and 0.50 MPa for heavy-duty load bearing boards (EN 312-4, 1996). As can be derived from Fig. 1c, all of the produced boards exceeded the EN requirements.

Multifactor analysis of variance on the effects of variable parameters on the static bending, modulus of elasticity and internal bond of the particleboards are shown in Fig. 2 and Table 4. Except press temperature, other parameters had positive effects on the MOE of particleboards. Based on statistical analysis, these effects were significant at 95% or 99% confidence levels (Table 2). In agreement with previous research (Nourbakhsh & Ashori, 2008), the internal bonding strength of the particleboards decreased with increasing particle size, sorghum stalk content and press temperature (Fig. 2). However, internal bonding values for boards with different amounts of variable parameters did not differ significantly (Table 4). Except interaction of particle size and press time (A × E), the interaction between the other main variables was not significant for MOE, MOR, and IB based on the ANOVA analysis. In addition, the results showed that all boards made with 180 °C press temperature had the lowest values among the other types of specimens. In other words, all mechanical properties of the boards were decreased when the press temperature was increased from 160 to 180 °C, which clearly shows that thermal stress occurred in the core section of the mat. In addition, boards made with sorghum stalk content of 50 wt% had the lowest values among the other types of specimens. MOE, MOR, and IB strength values of the specimens increased with increasing resin content and most board types showed statistically significant differences.

Table 4
Analysis of variances on the effects of variable parameters and their interactions.

Source	MOE		MOR		IB		WA 2-h		WA 24-h		TS 2-h		TS 24-h	
	F	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
A	57.35	0.000**	13.30	0.011*	2.94	0.137	2.85	0.142	39.02	0.001**	9.32	0.022*	13.19	0.011*
B	29.87	0.002**	4.16	0.087	0.45	0.526	0.25	0.635	3.72	0.102	4.08	0.090	20.09	0.004**
C	27.87	0.002**	7.38	0.035*	0.96	0.364	57.45	0.000**	408.26	0.000**	6.55	0.043*	30.93	0.001**
D	6.77	0.041*	2.68	0.153	0.50	0.508	1.44	0.275	20.20	0.004**	0.46	0.522	3.26	0.121
E	18.81	0.005**	4.04	0.091	3.43	0.113	0.50	0.505	0.02	0.901	1.16	0.323	0.00	0.949
A × B	12.64	0.012*	1.51	0.265	2.27	0.183	17.77	0.006**	43.78	0.001**	0.09	0.773	3.76	0.100
A × C	2.83	0.143	0.87	0.386	3.93	0.095	0.31	0.595	13.75	0.010**	0.18	0.689	6.90	0.039*
A × E	34.09	0.001**	5.89	0.051	0.10	0.765	9.60	0.021*	45.66	0.001**	0.34	0.584	1.60	0.253
B × D	1.31	0.296	1.60	0.253	0.03	0.878	3.75	0.101	13.46	0.010**	0.08	0.793	0.00	0.975
B × E	0.08	0.788	0.18	0.683	0.50	0.505	1.85	0.223	48.94	0.000**	1.45	0.273	10.67	0.017*
C × D	5.59	0.056	0.03	0.866	0.08	0.787	1.52	0.263	6.27	0.046*	1.88	0.220	0.08	0.792
D × E	0.03	0.876	0.47	0.518	5.03	0.066	4.66	0.074	27.99	0.002**	0.63	0.457	6.20	0.047*

Note: A = particle size; B = SS content; C = resin content; D = press temperature; E = press time; *F* = *F* value; ns = not significant.
* Significant difference at the 5% level ($p \leq 0.05\%$).
** Significant difference at the 1% level ($p \leq 0.01\%$).

3.3. Physical properties

Water sensitivity is an important criterion for many practical applications of particleboard products. The poor resistance of the fibers to water absorption can have undesirable effects on the mechanical properties and the dimensional stability of the boards. Therefore, it is important to study in detail the water absorption behavior. Fig. 3a shows the percentages of the water uptake for the particleboards at different periods of immersion, which vary depending upon the testing conditions. The range of data in the water absorption was from 42.5 to 99.9% for 2-h immersion and from 62.3 to 115% for 24-h. This is well-known that lignocellulosic fiber is highly hydrophilic because it contains an abundance of hydroxyl groups. Additionally, large numbers of porous tubular structures present in fiber, accelerates the penetration of water by the so-called capillary action. On the other hand, it is also clear that water uptake of all boards increased with increase of immersion time. As time goes on, water can penetrate the inter-phase and also the loose cellular cellulose network structure of cellulosic materials, resulting in high water uptake. In general, most of the boards compressed at 160 °C had higher water absorption values in comparison to the boards compressed at 180 °C. This indicates that lesser amount of resin within mat at 160 °C had been cured than those of boards at 180 °C. The possible reason is that steam within a particle near the surface is transferred to the core of mat at higher temperature, and this could accelerate the curing of an adhesive (Yang et al., 2014).

To improve the water resistance, three different methods could be considered based on current practices in the particleboard manufacturing industry. The first method is to add wax (0.5–1%) to

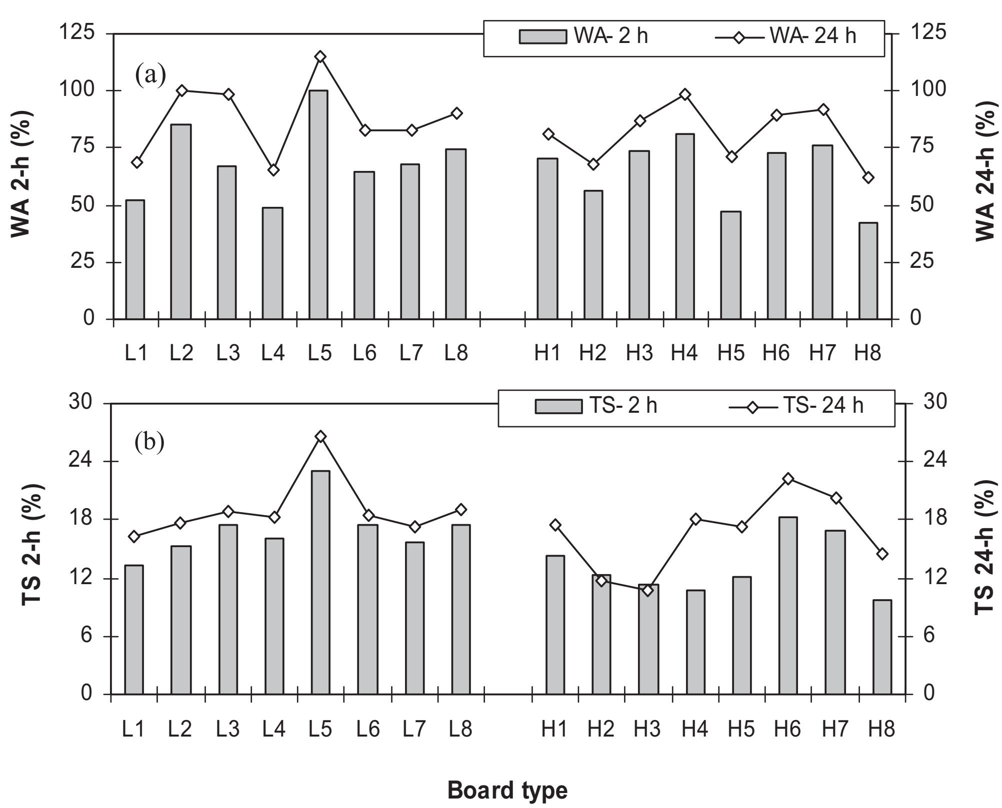

Fig. 3. Comparison of water absorption and thickness swelling of particleboards.

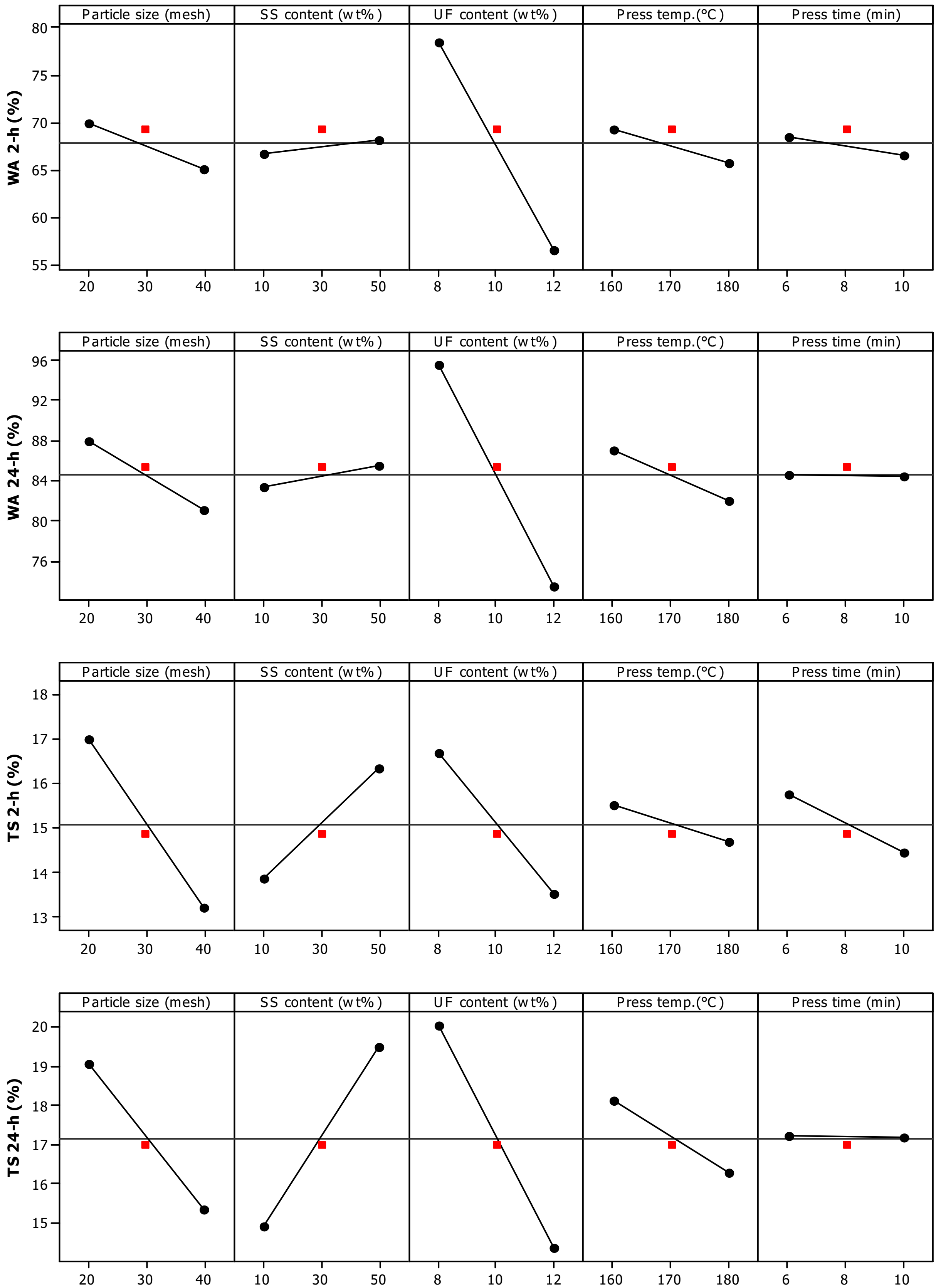

Fig. 4. Effects of each variable parameter on the physical properties. (■ low and high values, ■ center point)

the mixture of adhesive and particles during the manufacturing process. The second method is to decrease "springback" effect by reducing the density of the particleboards. If reducing particleboard density is not desirable for certain applications, adding wax should be used even though the mechanical properties may be lowered to some degree. The third method is to acetylate the particles (Zheng, Pan, Zhang, Jenkins, & Blunk, 2006).

As mentioned, the poor absorption resistance of the cellulosic material is mainly due to the presence of polar groups, which attract water molecules through hydrogen bonding. In addition, any pores or voids that are present after fabrication will help accommodate some of the swelling of the added wood fiber. This phenomenon leads to a moisture build-up in the fiber cell wall (fiber swelling) and also in the fiber–adhesive interface. This is responsible for the changes in the dimension of particleboards, particularly in the thickness and the linear expansion due to reversible and irreversible swelling of the boards. The results are shown in Fig. 3b, which demonstrate the influences of variable parameters on the thickness swelling of experimental boards. It is interesting to note that the 2-h and 24-h thickness swelling follows a trend similar to the water absorption behavior. Average thickness swelling of the specimens ranged from 9.8 to 23% and 10.8 to 26.7% for 2- and 24-h immersion, respectively. Based on EN standards, particleboard should have a maximum thickness swelling value of 8% for 2-h immersion. In addition, the maximum thickness swelling for 24-h requirement EN 317 (1993) is 15%. Board type L5 gave the highest thickness swelling of 23% and 26.7% after soaking for 2- and 24-h, respectively (Fig. 3b). In general, boards did not satisfy the thickness swelling requirement for general uses. As a consequence, the boards require additional treatments such as the coating of particleboard surfaces with melamine-impregnated papers or laminates or high press temperature usage to become a more stable product (Nemli, 2002). However, the thickness swelling value (9.8 and 14.6% for 2- and 24-h immersion, respectively) of the particleboard type H8 was very close to the required level of thickness swelling of boards for general uses. According to the statistical results, all physical properties of the boards were increased when the sorghum stalk content was increased from 10 to 50 wt%. Although particle size, resin content and press time had negative effect on increasing water absorption and thickness swelling, but their effects were not significant (Fig. 4 and Table 4).

4. Conclusions

Based on the results of this study the following conclusions can be drawn.

- Chemical and morphological properties of sorghum stalk showed that it is comparable with soft and hardwoods.
- The MOR, MOE and IB strength of the samples met EN 312-2 and EN 312-3 requirements for general purpose and furniture manufacturing.
- In general, both water absorption and thickness swelling of particleboards considerably increased with increasing the soaking time from 2 h to 24 h.
- The thickness swelling of the boards was relatively high, ranging from 10.8 to 26.7% for 24-h immersion. Since no hydrophobic substance was used during the board manufacturing, low dimensional stability of the boards can be related to this fact.
- Increasing of press time, resin content and particle size positively affected all mechanical and physical properties of the boards. This may be due to interference in the curing of urea formaldehyde adhesive, reduced wet ability of the particle surface or limitation of diffusion and/or spreading of the adhesive within the particles and over the particle surface.
- The above results suggest that it is completely feasible to manufacture acceptable or high quality particleboard using sorghum stalk.
- Based on the findings of this study, it can be stated that sorghum stalk has potential as a supplement fibrous material, in combination with wood particles, for particleboard manufacturing.

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