Effects of Core Layer Fiber Size and Face-to-core Layer Ratio on the Properties of Three-layered Fiberboard

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The objective of this study was to transfer benefits of three-layered particleboards to medium density fiberboard (MDF) manufacture by using coarse fibers and, thus use less energy and lower-cost fibers as core layer material. In the first phase of this study, the effect of wood fiber size in the core layer on the properties of MDF was investigated. In the second phase, the effect of surface to core layer ratio (30/70, 40/60, 50/50, 60/40, and 70/30) on the properties of the MDF was investigated. The surface layers of the panels consisted of fine fibers. The wood fibers were produced using a thermo-mechanical refining process. The length and thickness of the fibers considerably increased with increasing defibrator discs distance. The 24-h TS values of the MDF specimens decreased from 36.8 to 34.2% as the fiber length in the core layer was increased from 4.3 to 11.5 mm. However, further increases in the fiber length increased TS values. Similarly, the bending strength, bending modulus, and internal bond strength increased with increasing fiber length (up to 11.5 mm) and thickness (up to 0.73 mm). The bending properties of the MDF specimens improved with increasing surface layer ratio, while the internal bond strength decreased.

Keywords: Fiberboard; Wood fiber; Technological properties; Wood-based composite; Adhesive

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INTRODUCTION

Medium density fiberboard (MDF) is the world's second most common wood-based panel in the furniture industry, after particleboard (FAO 2016). In conventional particleboard manufacture, surface layers consist of fine particles; the core layer consists of coarse particles. However, in conventional MDF production there is only one mat forming process, such that the surface and core layers consist of the same mixture of wood fibers (Ayrilmis 2007). In the furniture industry, the surfaces of MDF should be smooth and stable for direct painting or laminating (Ayrilmis and Winandy 2009; Jarusombuti *et al*. 2010). By contrast, the core layer can be formed with coarse fibers when the MDF panel is faced with decorative laminate or melamine paper. The fiber size in the core layer does not directly affect the suface quality of the MDF when the panel is overlaid with melamine paper or other decorative laminates. However, the core layer should be made from the fine fibers when the MDF panel is profiled by panel processing machines such as profile wrapping machines.

In this study, the mat forming line employed for MDF production was based on the mat forming line that is conventionally used for three-layer particleboard. Similar to particleboard, MDF can be made in three-layers, in which face layers consist of fine fibers and the core layer consists of coarse fibers. Different sizes of wood fibers can be produced by changing defibrator discs distance, which is a strategy that can be used in the core layer of MDF. The fiber production capacity of the defibrator can be increased by increasing the distance between the defibrator discs. This improves energy savings in the defibrator.

The objective of this study was to transfer benefits of three-layered particleboards to dry-process MDF manufacture by using coarse fibers and, thus, less energy and less cost-intensive fibers as core layer material. In this study, the face layers of the MDF panels were prepared from commercial size wood fibers, while the core layer was prepared from the coarse fibers. This was because three-layer MDF panels having fine fibers in the surface layers have better surface appearance than three-layer particleboard (Hiziroglu *et al.* 2004).

Although there is extensive literature pertaining to MDF, there has been very limited research on the three-layer MDF. Sliseris *et al.* (2017) proposed an efficient virtual design method based on micro–macro simulations to optimize MDF. They reported that it was possible to simulate MDF with oriented fibers and 3-layer MDF by using a calibrated model. In other work, machinability of three layer MDF panels made of wood fibers with different dimensions was investigated (Czarniak *et al.* 2014). However, physical and mechanical properties of three-layer MDF panels have not been investigated yet. In the first phase of the study, the defibrator discs distance between the defibrator discs was gradually increased from 0.4 to 1.2 mm to obtain different sizes of the wood fibers in the core layer while it was kept at 0.4 mm for the wood fibers in the surface layer. The optimum coarse fiber size was determined based on the technological properties of the MDF panels produced with five different coarse fibers. In the second phase of the study, the surface layer to core layer ratio of the MDF panels produced with optimum size of the coarse fibers was varied from 30/70 to 70/30, and the technological properties of the MDF panels were compared.

EXPERIMENTAL

Wood Fibers

Wood chips from two different tree species (*Pinus sylvestris* L. and *Fagus orientalis* Lipsky) were produced using a thermo-mechanical refining process (defibrator from Pallmann Maschinenfabrik GmbH & Co. KG, Zweibrücken, Germany) at the Kastamonu Integrated Wood Company in Gebze, Turkey. The steaming parameters in the digester were 170 °C, 8 bar, and 4 min. With these steaming parameters, the defibrator discs distance was gradually increased from 0.4 mm to 1.2 mm to produce different sizes of coarse wood fibers in the core layer while it was kept as 0.4 mm for fine wood fibers in the surface layers. The coarse wood fibers in the core layer were produced from beech wood chips, while the fine wood fibers in the surface layers were produced from pine wood chips. Increased distance between the defibrator discs resulted in a higher proportion of larger fibres and fibre bundles (shives). The size and shape of the fibers used in the core layer and surface layers are shown in Fig. 1.

Prior to MDF production, the wet fibers obtained from each defibratar discs distance were transported in plastic bags to the Faculty of Forestry, Istanbul University. The wet wood fibers were then immediately dried in a laboratory dryer until they reached 2 to 3% based on the oven-dry weight of wood fibers.. A hundred fibers were randomly obtained from each classified group, and their length and thickness were measured using a Brinell microscope. The average length and thickness of the coarse fibers are presented in Figs. 2 and 3.

A B

Fig. 1. A: Coarse beech wood fibers used in the core layer of MDF (1.2 mm defibrator discs distance). **B:** Fine pine wood fibers used in the face layers of MDF (0.4 mm defibrator discs distance)

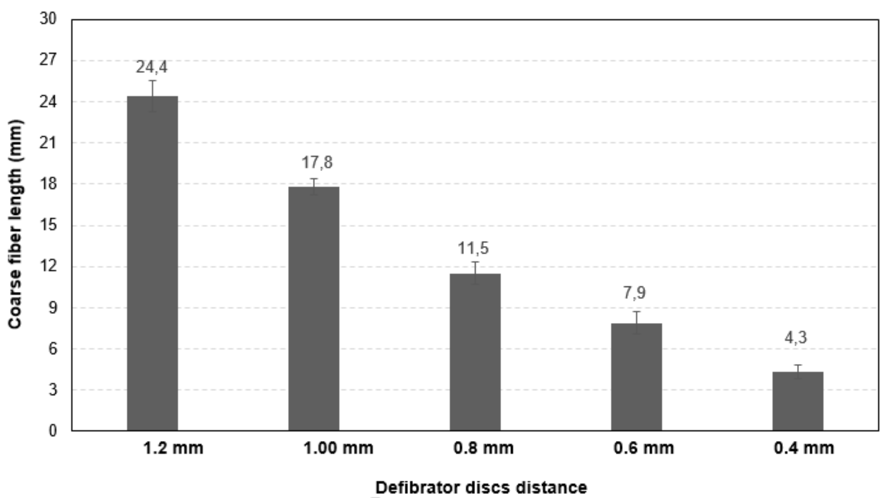

Fig. 2. Variations in the length of coarse wood fibers (beech) in the core layer of the MDF

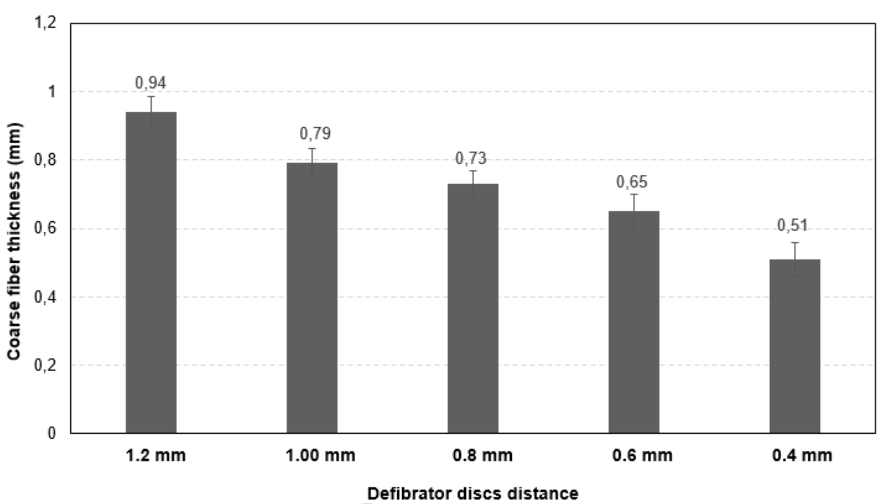

Fig. 3. Variations in the thickness of coarse wood fibers (beech) in the core layer of the MDF

Adhesive

A commercial liquid E1 grade urea-formaldehyde (UF) adhesive with 50 wt.% solid content was supplied by Kastamonu Integrated Wood Company, Gebze, Turkey. Ammonium chloride (NH_4Cl) solution with 20 wt.% solid content was used as a hardener for the UF adhesive.

Production of Three-Layer MDF Panels

Three-layer MDF panels were prepared from a central layer (core) and two outer layers (faces), and manufactured under laboratory conditions, using standardized procedures that simulated industrial production (Fig. 4). Both surfaces of all the MDF panels were prepared from fine pine wood fiber, while the core of all the MDF panels was prepared from different sizes of coarse beech wood fibers. As a hardener, 1 wt.% ammonium sulfate based on the solid content of the adhesive was added into the UF adhesive.

The surface and core fibers were separately placed into a drum blender. To obtain a homogenized mixture, the 10 wt.% UF adhesive, based on the oven dry weight of the wood fiber, was applied using an air-atomized metered spray system for 5 min. The surface and core fibers of the three-layer boards were separately weighed then distributed evenly by hand into a 400 mm forming box. A second plate was laid on the top, and both were covered with siliconized paper to prevent adherence between the panel and plates. After cold pre-pressing, the mats were transferred to the hot press, operated in plate position control mode. The hot pressing temperature, press pressure, and total press time were 190 °C, 3.5 N/mm^2 and 480 s, respectively.

Fig. 4. Production of three-layer MDF panels at the laboratory

The target MDF thickness and density were 10 mm and 700 kg/m^3, respectively. Three replicate MDF panels were produced from each fiber type (Table 1). Prior to sample cutting, the panels were allowed to cool, and the edges were trimmed. Test specimens were conditioned in a climatic chamber at 20 °C and 65% relative humidity (RH) for 2 weeks before testing. Based on the findings of MDF specimens of Phase 1, the optimum fiber size (Type C) was used in the production of MDF specimens in Phase 2.

Table 1. Experimental Design

Phase	MDF Type	Defibator Discs Distance (mm)	Coarse Fiber Length (mm)	Coarse Fiber Thickness (mm)	Face Layer Ratio (%)	Core Layer Ratio (%)	Adhesive Content in Face Layer (wt.%)	Adhesive Content in Core Layer (wt.%)
Phase 1: Effect of fiber size in core layer of MDF	A	0.4	4.3 (0.5)*	0.51 (0.03)	50	50	10.5	10.5
	B	0.6	7.9 (0.8)	0.65 (0.04)	50	50	10.5	10.5
	C	0.8	11.5 (0.8)	0.73 (0.04)	50	50	10.5	10.5
	D	1.0	17.8 (0.6)	0.79 (0.03)	50	50	10.5	10.5
	E	1.2	24.4 (1.1)	0.94 (0.05)	50	50	10.5	10.5
Phase 2: Effect of surface/core layer ratio	F	0.8	11.5 (0.8)	0.73 (0.04)	30	70	10.5	10.5
	G	0.8	11.5 (0.8)	0.73 (0.04)	40	60	10.5	10.5
	H	0.8	11.5 (0.8)	0.73 (0.04)	50	50	10.5	10.5
	I	0.8	11.5 (0.8)	0.73 (0.04)	60	40	10.5	10.5
	J	0.8	11.5 (0.8)	0.73 (0.04)	70	30	10.5	10.5

* The values in the parentheses are standard deviations.

Determination of Physical and Mechanical Properties

The physical and mechanical properties of the MDF panels were determined according to European Standards (EN). The one-day thickness swelling test was performed on the 15 MDF specimens with dimensions of 50 mm × 50 mm × 10 mm according to the EN 317 standard (1993). The linear and thickness variations of the 15 MDF specimens in changing relative humidity (between 85% and 35% RH at 20 ± 2 °C) were determined in conformance with the EN 318 standard (2002). The increases in length and thickness were monitored from 65 to 85% relative humidity in adsorption using a digital caliper, while the decreases were monitored from 65 to 30% relative humidity in desorption. The bending strength and bending modulus of the 12 MDF specimens with dimensions of 250 mm × 50 mm × 10 mm (the average of 6 parallel and 6 perpendicular to the MDF surface) were tested according to the EN 310 standard (1993). The internal bond (IB) strength was determined on the 10 MDF specimens with dimensions of 50 mm × 50 mm × 10 mm according to EN 319 (1993). The densities of the 15 MDF specimens with dimensions of 50 mm × 50 mm × 10 mm were measured according to EN 319 (1993).

Statistical Analysis

The effect of fiber size and surface/core layer ratio on the technological properties of the MDF panels was evaluated using analysis of variance (ANOVA; $p < 0.05$). Significant differences among the mean values of MDF types were determined using Duncan's multiple range test.

RESULTS AND DISCUSSION

Physical Properties

The physical properties of the MDF panels are presented in Table 2. The average densities of the MDF panels were 694 kg/m^3 and 701 kg/m^3. The thickness swelling of the MDF specimens was significantly increased by the increased surface layer ratio. As the core layer ratio was decreased from 70 to 30%, one-day thickness swelling of the MDF specimens increased from 29.2 to 46.7%. The thickness swelling of the MDF specimens was also affected by the increased length and thickness of the fibers used in the core layer. As the thickness and length of the coarse fibers increased from 0.51 to 0.73 mm and 4.30 to 11.5 mm, respectively, the thickness swelling values of the MDF specimens decreased from 36.8 to 34.2%. However, this decrease was not significant. Further increase in the length (24.4 mm) and thickness (0.94 mm) of the fibers increased the thickness swelling values (39.6%) of the MDF specimens. The thickness swelling values of all the MDF specimens were found to be higher than the maximum requirement (15%) for MDF panels used in dry conditions per the EN 622-5 standard (2009). This could be due to the fact that no hydrophobic chemicals, such as paraffin, were used in the production of the MDF panels. Statistical analysis found significant differences ($p < 0.05$) between some group averages for physical properties. The significant differences between groups determined using Duncan's multiple comparison tests are presented in Table 2.

Table 2. Select Physical Properties of Three-Layer MDF Panels

MDF Code	Density (kg/m^3)	Thickness Swelling (24 h) (%)	Dimensional Changes in Changing Relative Humidity at 20 °C			
			Relative Humidity (65 to 30% at 20°C)		Relative Humidity (65 to 85% at 20 °C)	
			$LC_{65\ to\ 30}$ (%)	$TSh_{65\ to\ 30}$ (%)	$LE_{65\ to\ 85}$ (%)	$TS_{65\ to\ 85}$ (%)
A	698 (13)	36.8 (2.6) ab	0.18 (0.02) ad	2.88 (0.4) a	0.16 (0.02) a	2.80 (0.4) ae
B	701 (22)	35.6 (2.2) ab	0.16 (0.02) ad	2.73 (0.3) ae	0.15 (0.01) a	2.64 (0.3) ab
C	696 (21)	34.2 (1.8) bf	0.15 (0.01) a	2.36 (0.2) be	0.14 (0.02) ad	2.25 (0.2) bd
D	700 (20)	37.7 (2.3) ad	0.17 (0.03) ad	3.05 (0.5) a	0.17 (0.03) a	2.89 (0.4) ac
E	696 (18)	39.6 (2.3) ad	0.19 (0.02) cd	3.15 (0.5) ac	0.18 (0.03) ac	3.10 (0.3) cef
F	694 (18)	29.2 (1.7) c	0.11 (0.01) b	1.96 (0.1) d	0.10 (0.01) bd	1.91 (0.2) d
G	699 (15)	31.8 (2.6) cf	0.12 (0.02) b	2.15 (0.3) bd	0.11 (0.01) bd	2.12 (0.1) d
H	696 (21)	34.2 (1.8) bf	0.15 (0.01) a	2.36 (0.2) be	0.14 (0.02) ad	2.25 (0.2) bd
I	695 (24)	40.6 (3.4) d	0.18 (0.01) ad	3.14 (0.3) ac	0.16 (0.01) a	3.10 (0.3) cef
J	698 (13)	46.7 (2.9) g	0.22 (0.03) c	3.47 (0.2) c	0.21 (0.02) c	3.39 (0.4) f

LC: linear contraction. TSh: thickness shrinkage. LE: linear expansion. TS: thickness swelling. Groups with same letters in column indicate that there is no statistical difference ($p < 0.05$) between the specimens according to Duncan's multiply range test.

The dimensional stability of the MDF specimens in changing relative humidity conditions was affected by the surface/core layer ratio. The increase in surface layer ratio significantly increased the linear expansion and thickness swelling of the specimens (Table 2). As the relative humidity in the conditioning room decreased from 65 to 30%, the linear contraction (LC) of the MDF specimens increased from 0.11 to 0.22% as a function of decreasing core layer ratio (70 to 30%). Thickness shrinkage (TSh) increased from 1.96 to 3.47% as the core layer ratio decreased from 70 to 30% (Table 2). A similar trend was observed for linear expansion (LE) and thickness swelling (TS) of the MDF specimens as the relative humidity increased from 65 to 85%. The highest dimensional stability was found in the specimens having the highest core layer ratio (70%), while the lowest dimensional stability was found in the specimens having 70 wt% surface layer ratio. The lower dimensional stability of MDF specimens with a higher core layer ratio is explained by lower adhesive content for the surface area of short fibers, compared to longer fibers with the same adhesive content.

The dimensional stability of the MDF specimens improved with increasing fiber size until it reached 0.73 mm in thickness and 11.5 mm in length. For example, as the thickness of the coarse fibers increased from 0.51 mm to 0.73 mm and length increased from 4.30 mm to 11.5 mm, the linear contraction and thickness shrinkage of the MDF type C specimens at 65 to 30% relative humidity decreased from 0.18 to 0.15% and 2.88 to 2.36%, respectively. A similar trend was observed for the linear expansion and thickness swelling values. However, further increase in fiber size negatively influenced the dimensional stability of the MDF specimens. The ANSI A.208.2 (2002) standard was used in this case for comparison of linear expansion property since there is no established maximum performance requirement for MDF in European standards. According to the ANSI A.208.2 standard, linear expansion of fiberboards performed between 50 and 80% relative humidity must have a maximum value of 0.33%.

The primary explanation for greater thickness swelling of the MDF panels having higher surface layer ratio could be due to residual stresses created within the fiber mat during hot pressing (Ayrilmis 2007; Rindler *et al*. 2017). The release of the compression generated in the MDF panel during hot pressing could become more effective as the amount of the surface layers increased. Furthermore, spring-back-swelling forces are responsible for partial failures of bonds between fibers, which results in greater thickness swelling (Geimer and Kwon 1999; Ayrilmis *et al*. 2009). When MDF panels make contact with water, the wood swells and some of the residual stress is released, causing an increase in the thickness of the panel.

Mechanical Properties

The mechanical properties of the MDF specimens are shown in Table 3. The bending strength of the MDF specimens significantly improved as the surface layer ratio increased. Significant differences ($p < 0.05$) between select group averages are presented in Table 3. The bending strength increased from 14.82 to 18.88 N/mm^2 as the surface layer ratio was increased from 30 to 70%. A similar result was observed for the bending modulus values. As the surface layer ratio was increased from 30 to 70%, the bending modulus values of the specimens increased from 1913.8 to 2278.4 N/mm^2. Increasing surface layer ratio positively affected the bending properties. This was due to face layers made of fine fibers having a greater compaction ratio, and consequently, better bending properties than the core layers (Wilczyński and Kociszewski 2012). It is well known that MDF has a specific vertical density profile (VDP), in which the outside layers have higher density than core layer (Maloney 1993). Surface/core layer ratio affects the VDP of the wood-based panels (Rofii *et al.* 2013). The higher density in the surface layers results in correspondingly higher bending strength. In particular, compression stress in the top surface and tension stress in the bottom surface affect the bending properties of the wood-based composites, as well as other materials. This explains why the MDF specimens with higher surface layer ratio had higher bending strength and bending modulus than the specimens with lower surface ratio.

Table 3. Some Mechanical Properties of Three-Layer MDF Panels

MDF Code	Bending Strength (N/mm^2)	Modulus of Elasiticty in Bending (N/mm^2)	Internal Bond Strength (N/mm^2)
A	15.18 (1.02) a	1884.6 (125.6) a	0.49 (0.06) a
B	15.90 (1.14) ab	1969.0 (131.5) ab	0.52 (0.05) ac
C	17.25 (1.09) bc	2149.4 (134.7) bc	0.56 (0.06) ab
D	14.54 (1.24) a	1802.3 (125.9) a	0.61 (0.07) b
E	13.75 (1.18) a	1745.9 (99.4) a	0.58 (0.05) bc
F	14.82 (1.01) a	1913.8 (105.7) ab	0.53 (0.07) ac
G	15.57 (1.14) ab	2044.3 (86.9) bc	0.55 (0.05) ab
H	17.25 (1.09) bc	2149.4 (134.7) bc	0.56 (0.06) ab
I	18.42 (0.85) c	2200.7 (110.4) bc	0.58 (0.06) bc
J	18.88 (1.28) c	2278.4 (105.9) c	0.60 (0.08) b

Groups with the same letters in column indicate that there is no statistical difference ($p < 0.05$) between the specimens according to Duncan's multiple range test.

The bending properties of the MDF specimens increased with increasing slenderness ratio of the fiber until reaching 0.73 mm in thickness and 11.5 mm in length. A high aspect ratio is desirable for better panel properties in any wood composite products (Maloney 1993; Ayrilmis 2002). In a previous study, Stark and Rowlands (2003) reported that aspect ratio, rather than particle size, has the greatest effect on strength and stiffness of the panel. However, further increment in the fiber length and thickness decreased bending strength and modulus of the specimens.

The internal bond strength of the MDF specimens increased with increasing coarse fiber length (up to 17.8 mm) and thickness (up to 0.79 mm) (Table 3). At the same adhesive content, surface area of the fibers increased as fiber size decreased. More adhesive is required to sufficiently bond the fibers as the fiber size decreases, which improves the bond performance between the fibers. The internal bond strength of the specimens improved with increasing fiber size in the core layer, up to 24.4 mm length and 0.94 mm thickness. At higher aspect ratios, the specific surface areas of longer particles are lower than those of shorter ones of the same species. Thus, the adhesive content per unit particle surface area is higher for long particles than for short ones at a given adhesive content (Benthien *et al.* 2014). This can be an explanation for lower IB strength of MDF made from short fibers than that from long fibers. This finding was also compatible with previous literature (Suchsland and Woodson 1991; Nishimura *et al*. 2004; Bektas *et al*. 2005; Nemli *et al*. 2009; Harmaen *et al*. 2013). The internal bond strength of the MDF specimens decreased with increasing core layer ratio at the same adhesive content. As the amount of the core layer was increased from 40 to 70 wt%, the internal bond strength of the MDF specimens decreased from 0.58 to 0.53, but this decrease was not significant (Table 3). The increase in the internal bond strength of the MDF specimens having higher shelling ratio can be explained by the fact that higher amounts of fine fibers usage in the surface layers result in a compact structure. The positive influence of increasing shelling ratio on the mechanical properties of particleboard was reported in previous studies (Maloney 1993; Akbulut 1998; Benthien and Ohlmeyer 2017).

CONCLUSIONS

1. The dimensional stability and bending properties of the MDF panels increased as the length and thickness of the fibers was increased up to 11.5 mm and 0.73 mm, respectively. Further increase in the fiber size negatively affected the dimensional stability of the MDF specimens.
2. The highest internal bond strength of the specimens increased as the fiber length and thickness in the core layer reached to 17.8 mm and 0.79 mm, respectively. The bending strength of the MDF specimens decreased with increasing core layer ratio but internal bond strength was increased.
3. The optimum physical and mechanical properties for MDF panels (Type C) were obtained from fibers in the core layer having an average length of 11.5 and thickness of 0.73 mm.
4. At the same manufacturing conditions such as adhesive content, fiber size, and panel density, as the core layer ratio was increased from 30 to 70 wt%, the dimensional stability of the MDF specimens significantly increased, while the mechanical properties decreased.

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