WOOD RESEARCH
57 (3): 2012
441-452

LAYER THICKNESS SWELL CHARACTERISTICS OF MEDIUM DENSITY FIBREBOARD (MDF) PANELS AFFECTED BY SOME PRODUCTION PARAMETERS

Zeki Candan, Turgay Akbulut
Istanbul University, Faculty of Forestry, Department of Forest Products Engineering
Istanbul, Turkey

Siqun Wang
University of Tennessee, Center for Renewable Carbon
Knoxville, USA

Xinan Zhang
Louisiana State University School of Renewable Natural Resources
Baton Rouge, USA

A. Faruk Sisci
Kastamonu Integrated Wood Industry and Trade Inc.
Kocaeli, Turkey

(Received October 2011)

ABSTRACT

This study is aimed at investigating the effects of some production parameters on the layer thickness swell (LTS) properties of the medium density fibreboard (MDF). The MDF panels used in this study were manufactured using continuous press technology. A total of eighteen MDF panels, with three repetitions for each: resin content (RC), mat moisture content (MC), and continuous press speed (CPS), were produced. The vertical density profile (VDP), thickness swell (TS), and LTS tests were performed in the present study. The results obtained in this study indicate that VDP was affected by mat MC and CPS. In addition, it was found that the VDP has some effects on the TS and LTS values of the panels. The findings obtained in this study indicate that it is important to understand the influences of RC, MC, and CPS on the LTS properties of the MDF panels for optimizing the structure in the development of new wood composite products as well as improving the production process.

KEYWORDS: Layer thickness swell, vertical density profile, wood composites, medium density fibreboard, continuous press speed, moisture content.

INTRODUCTION

Medium density fibreboard (MDF) panels are commonly used in the manufacture of molding, laminated flooring, and overlaid panels for the furniture industry. MDF is one of the most rapidly growing wood composite products in the industry. A key product attribute of MDF is its density profile through the panel thickness (Wang et al. 2004). Several press technologies are used for commercial purposes in MDF and in other wood composite manufacture, such as the batch technology and the continuous press technology. The continuous press technology has become considerably popular during the last few years. Panel manufacturers all over the world prefer this technology owing to its higher production capacity and efficiency in comparison to the other technologies. In Turkey, thirteen continuous MDF press lines are available and the capacity is rapidly increasing (Candan 2007).

Dimensional stability characteristics are of a great importance for wood composite panels which were previously studied by Wu and Suchsland (1996), Velasquez et al. (2003), Brochmann et al. (2004), Garcia et al. (2005), Zisi et al. (2005), Del Menezzi and Tomaselli (2006), Medved et al. (2006), Dieste et al. (2008), Halvarsson et al. (2008), Del Menezzi et al. (2009), Dundar et al. (2009), Candan et al. (2011), Filho et al. (2011).

Vertical density profil (VDP) which is one of the most important panel characteristics is described as the density variation in the direction of thickness in wood-based composites. Typically, VDP shows higher surface layer density and lower core layer density. The density gradient is affected by the combined influences of pressure, moisture content, temperature, resin curing, and other factors during pressing and in turn affects the physical and mechanical properties of the wood composites (Strickler 1959, Kamke and Casey 1988, Wang and Winistorfer 2000a). Further, the formation of VDP in wood composites is also affected by wood species and their mixtures, mat moisture content (MC), press closing speed, continuous press speed, and continuous press pressure (Suzuki and Miyamoto 1998, Wong et al. 1998, Wang et al. 2001a, b, Candan 2007, Candan et al. 2007, Candan 2009).

The thickness swelling of wood composites can be calculated from a single overall caliper measurement of panel thickness. Therefore, the use of an optical technique makes it possible to determine the influences of individual layers on the total thickness swell percentage for various water exposure periods (Wang and Winistorfer 2002, 2003). The layer thickness swell (LTS) within the sample is important for understanding the phenomena of wood composites. Also, it is important to understand the effects of the production parameters on the LTS for optimizing the structure in the development of new products as well as improving the manufacturing process. One of the key variables in understanding LTS is the recognition of the density profile of wood composites (Wang and Winistorfer 2003).

Wang and Winistofer (2000b) examined the influence of wood species and mat structure on the LTS of OSB. In their study, they used aspen and pine for panel manufacture and reported that the wood species and the species combinations in the mat had an effect on the LTS values of the panels. Houts et al. (2003) produced flakeboard panels from acetylated wood strands and evaluated the contribution of treated layers on the thickness swell of the panels by LTS measurements. Gu et al. (2005) studied the influence of wood species, resin type, and VDP on the thickness swell and the LTS of OSB, while Wang et al. (2001b) investigated the effect of the step-closure schedule on the LTS of MDF panels. Wang et al. (2003) determined the effects of wood species, strand geometry, strand orientation, and VDP on the LTS, modulus elasticity, modulus of rupture, and internal bond of OSB.

It should be mentioned that there is limited data available in the literature regarding the LTS of the panels manufactured by continuous press technology. Thus, the present study is aimed at determining the effects of manufacturing parameters such as resin content (RC), mat moisture content (MC), and continuous press speed (CPS) on the LTS properties of the MDF panels. It has been proposed that this information regarding the influence of the manufacturing parameters on the LTS characteristics of the MDF panels produced by an industrial continuous press-line would assist in decreasing the thickness swell by means of layer property altering.

MATERIAL AND METHODS

Materials

In this study, beech (*Fagus orientalis*) and birch (*Betula pendula*) wood species were used for panel production. The mixing ratio was 70 % beech + 30 % birch wood. Urea formaldehyde resin with solid contents of 65 % and NH_4Cl hardener was used.

Methods

Panel manufacturing

The MDF panels used in this study were manufactured using Siempelkamp® Continuous Press at Kastamonu Integrated Wood Industry and Trade Inc. located in Kocaeli, Turkey. The experimental design of the panels is shown in Tab. 1.

Tab. 1: Experimental design of the panels.

Panel groups	Resin content (%)	Mat moisture content (%)	Continuous press peed ($m.min^{-1}$)
L	11.5	-	-
M	12.5	-	-
S	-	8	-
R	-	10.5	-
V	-	-	6.9
U	-	-	7.4

A total of eighteen MDF panels, with three repetitions for each RC, MC, and CPS levels, were produced. The other production parameters of the panels such as wood species, resin type, and press temperature were held constant. The general production parameters were as follows:

- Asplund defibrator was used for fibre preparation
- Steam pressure of 7.5 bar, temperature of 160°C, and time of 4 – 5 minutes
- Levels of wax and hardener loading of 1 % and 0.8 %, respectively
- Press temperature of 220°C
- All panels were sanded with a sequence of 60, 120, and 150 grit size
- Target board density of 0.75 $g.cm^{-3}$
- Dimensions of the panels were 2100 mm by 3600 mm by 18 mm

Testing procedure- Vertical density profile (VDP)

The experimental MDF panels were cut into test specimens. All specimens were conditioned in a climate controlled chamber with a relative humidity of 65 % and a temperature of 20°C until they reached equilibrium moisture content, prior to the VDP test. Nine samples with dimensions of 50 by 50 mm were prepared for the VDP test. A commercial X-Ray Density Profiler (GreCon, Germany) was used for measuring the VDP of the specimens.

Thickness Swell (TS) and Layer Thickness Swell (LTS)

Six samples with dimensions of 152 by 152 mm were prepared for the layer thickness swell (LTS) and thickness swell (TS) tests. The LTS was measured for each sample after 2-, 8-, and 24- hours of water exposure at a water temperature of 20° ± 1°C. According to ASTM D 1037-06a (2006), TS tests were performed for 2 h and 24 h water soaking time. An optical technique was used for determining the TS of 12 discrete layers within the intact samples from each test specimen. LTS tests were carried out using the QLTS Testing System located in the Center for Renewable Carbon in the University of Tennessee, TN, USA.

RESULTS AND DISCUSSION

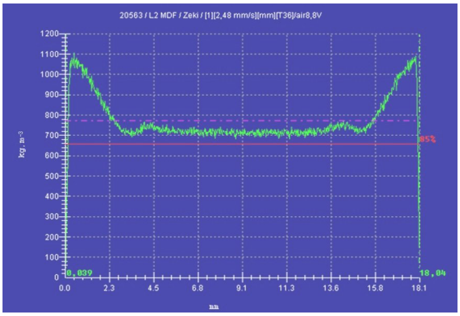
The thickness swell values of the MDF panels after 2 h and 24 h of water soaking time are shown in Tab. 2.

Tab. 2: Thickness swell results of the panels.

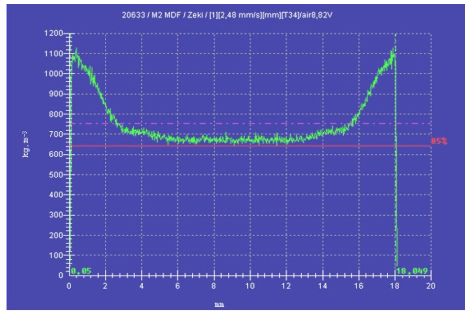
Panel Groups	2 h TS (%)	24 h TS (%)
L	0.818	4.935
M	0.663	4.419
S	1.017	6.032
R	0.85	5.504
V	1.157	5.979
U	0.985	5.902

The results indicate that both 2 h and 24 h TS values of the MDF panels decreased as the resin content increased, the mat moisture content increased, and the continuous press speed increased. This might be owing to the formation of the VDPs of the MDF panels. The VDPs of the panels are shown in Fig. 1. The VDPs were found to be affected by the production parameters.

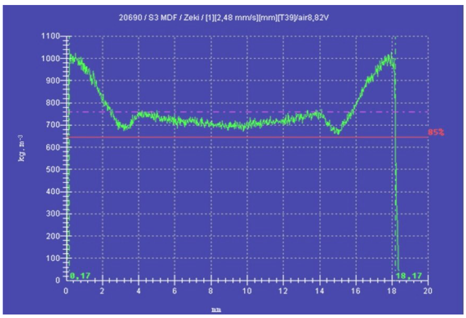
The density profiles for the M and R panels indicate steep density profiles (higher face layer density). The narrow density peaks of the surface layers are located very close to the panel surface. It was expected that panel M would have better TS properties when compared to panel L because of the higher RC of M panels. On the other hand, panel R had a steep density profile when compared to panel S. This increase in the face layer density might be owing to the higher MC level of panel R. Wong et al. (1998) examined the effects of mat MC and press closing speed on the formation of the density profile in particleboard, and reported that higher slimmer density peaks near the surface layers occurred with increasing MC of the surface layers in the mat.



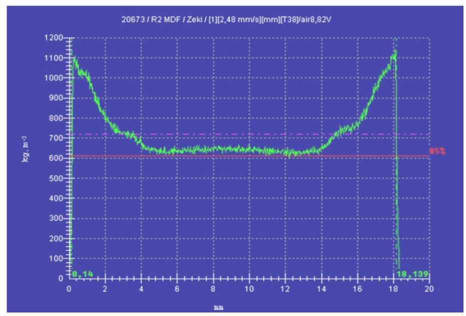
a)



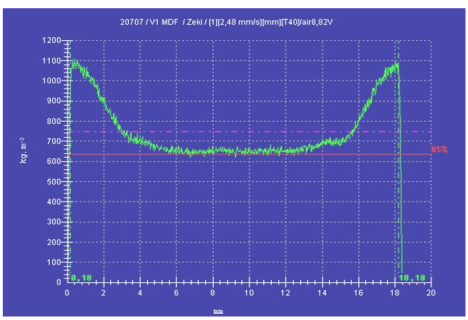
b)



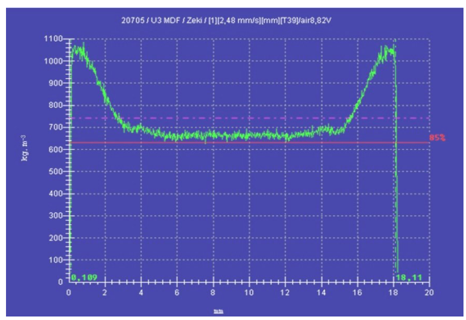
c)



d)



e)



f)

Fig. 1: Vertical density profiles of the MDF panels.

Wang et al. (2001a, b) studied the VDP of the MDF panels affected by press closing schedule, and stated that pressing schedule affects the density gradient of the final panels. Wong et al. (2000) studied the effects of mat moisture content distribution, press closing speed, and hot pressing, on the VDP and their effects on the properties of fibreboards, and reported that the peak density in VDP of the fibreboard was affected by variations in the hot pressing method and the mat moisture content. They also stated that the peak density located in the surface layers of the fibreboard panels increased with increasing mat MC, and the fibreboards with homogenous VDP showed higher thickness swelling and water absorption values as compared to those of conventional fibreboards.

The development of average actual LTS in relation to the water soak time and layer location for panel V and panel U is shown in Fig. 2.

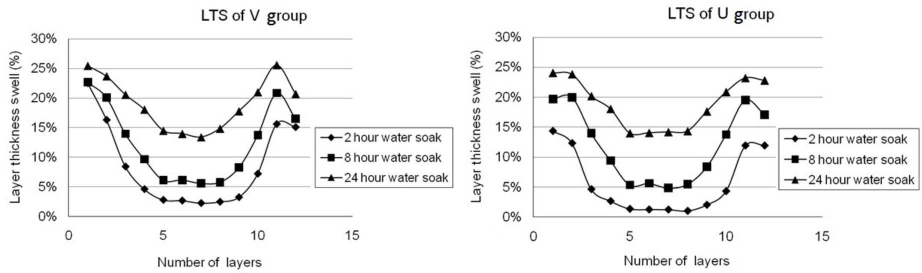


Fig. 2: LTS on individual layer of the panel V and panel.

It can be seen that LTS through the panel thickness increased with an increase in the water soak period. The maximum thickness swell was achieved after 24 hours of water exposure. There were large differences in the thickness swell results of the surface layers and the core layers of the V and U panel groups. The outside first layers (layer numbers 1-2 and 11-12) appeared to swell considerably more than the sub-layers 3 and 10. This was owing to the fact that the density peaks were located on the surface layers (Fig. 1e, 1f). The thickness swell curves were quite smooth.

The mean actual LTS on the individual layer of panel S and panel R in relation to the water soak time is shown in Fig. 3.

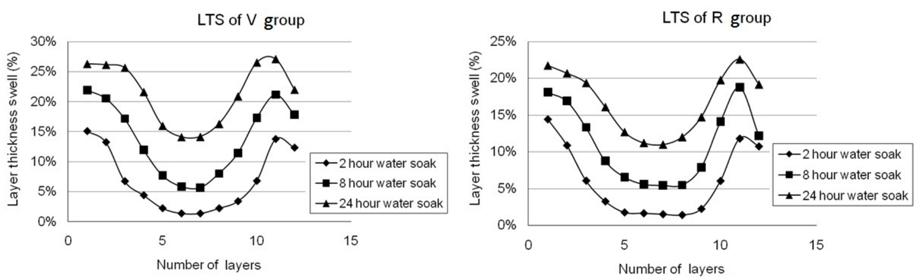


Fig. 3: LTS on individual layer of the panel S and panel.

The highest TS value was obtained after 24 hours of water soaking. Further, large differences in TS values were determined for the surface layers and the core layers of panel S and panel R. It was seen that layers 1-2 and 11-12 had higher TS values than those of layer 3 and layer 10. These results might be owing to the peak density that existed on the face and bottom layers of the panels, as shown in Fig. 1c and 1d, respectively. The LTS graphs of panel S and panel R were smooth.

The average LTS on the individual layer of panel L and panel M in relation to the water soak time and layer location is shown in Fig. 4.

It can be seen that the LTS curves of panels L and M had a smooth structure. The LTS of panels L and M increased with an increase in water exposure. The greatest TS values of the panels were determined for 24 hour water soak time. It was seen that panels L and M had large variations in the TS values of the surface layers and the core layers. The TS values of layers 1-2 and 11-12 were greater than those of the sub-layers. This result might be owing to an existing peak density on the first outer layers in the panels. The VDPs of panels L and M are illustrated in Fig. 1a and 1b, respectively.

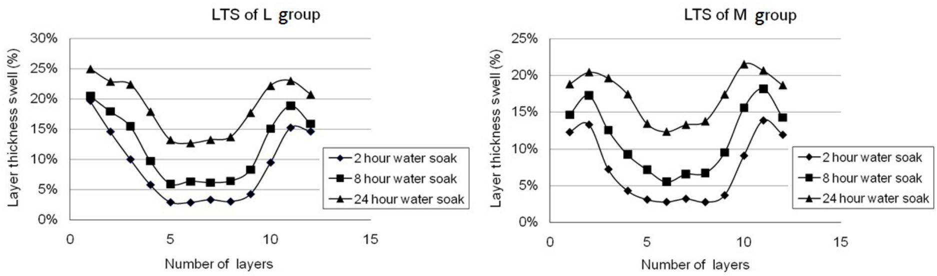


Fig. 4: LTS on individual layer of the panel L and panel M.

It can be seen in Figs. 2, 3, and 4, that in most of the LTS curves, layer 1 on the top face of the panel surface showed the highest TS value after 2, 8, and 24 hours water soaking. It can also be seen in the figures that layer 11 showed the greatest TS value on the bottom face of the panel surface.

A comparison of percentage LTS of face layers and core layers relative to the total TS is shown in Tabs. 3, 4, and 5. There were 12 discrete layers for the MDF panels. The top face layers included layers 1 – 3; the core layers included layers 4 – 9; and the bottom face layers included layers 10 – 12.

The percent contributions of the face layer and core layer TS to the total TS when compared by the resin content in the panels are shown in Tab. 3.

Tab. 3: Percent contributions of face layer and core layer thickness swell to total thickness swell compared by the resin content in the panels.

Panels groups	**Top face (layers 1-3)**	**Core (layers 4-9)**	**Bottom face (layers 10-12)**
2 hour water soak (%)			
L	41.89	20.91	37.20
M	37.54	22.55	39.91
8 hour water soak (%)			
L	36.76	29.26	33.98
M	32.40	32.57	35.03
24 hour water soak (%)			
L	31.26	39.40	29.34
M	28.39	42.25	29.36

It can be seen that the surface layer and core layer contributions to the total TS of the MDF panels were not the same. Subsequent to 2, 8, and 24 hours of water exposure, panel L exhibited top face layer TS higher than the bottom face layer. There were large differences between the percent contributions of the face and core TS to the total TS for panels L and M. The TS values of the top face of panels L and M were 41.9 and 37.5 %, respectively, which were 2 and 1.66 times those of the core TS values after 2 hour water exposure. The results obtained in the present study indicated that 79.1 and 77.5 percent of the total TS occurred mainly in the high density surface regions during the early stages of the water exposure in panels L and M. Subsequent to 24 hour water exposure, 60.6 and 57.8 % of total TS occurred in the high density surface regions of panels L and M. It was also determined that the contributions of the high density surface layers to the total TS decreased when the water soak time was increased from 2 hours to 24 hours. However, the contributions of the low density core layers to the total TS increased when increasing the water soak time from 2 hours to 24 hours in panels L and M.

The percent contributions of the face and core layer to the total TS when compared by the mat moisture content in the panels are given in Tab. 4.

Tab. 4: Percent contributions of face layer and core layer thickness swell to total thickness swell compared by the mat moisture content in the panels.

Panels groups	Top face (layers 1-3)	Core (layers 4-9)	Bottom face (layers 10-12)
2 hour water soak (%)			
S	42.27	18.08	39.64
R	43.87	16.20	39.93
8 hour water soak (%)			
S	35.79	30.42	33.79
R	36.33	29.78	33.89
24 hour water soak (%)			
S	30.40	40.15	29.44
R	30.76	38.62	30.63

It can be seen that the contributions of the surface and core layers to the total TS of panels S and R were not equal. Subsequent to 2, 8, and 24 hours of water soaking, panels S and R showed that the TS values of the top face layer were higher than that of the bottom face layer. A large difference was obtained between the percent contributions of the face and core layers to the total TS in panels S and R. The TS values of the top face layers in panels S and R were 42.3 and 43.9 %, respectively, which were 2.33 and 2.70 times those of the TS values of the core layers after 2 hours of water soaking time. The findings determined in the present study also indicated that 81.9 and 83.8 % of the total TS existed in the high density surface layers during 2 hours of water exposure in panels S and R.

In addition, it was observed that even after 24 hours water soaking period, 59.8 and 61.4 % of the total TS existed in the high density surface layers of panels S and R. The percent contributions of the surface layers to the total TS decreased as the water soaking time increased through 2 to 24 hours while the contributions of the core layers to the total TS increased as the water soaking time increased in panels L and M.

The percent contributions of face and core TS to the total TS when compared by the continuous press speed are shown in Tab. 5. It can be seen in Tab. 5 that the contributions of the surface and core layer TS to the total TS were not equal. The TS values of the top face region were greater than those of the bottom face region in panels V and U after 2, 8, and 24 hours of water soaking time. Further, it was observed that the contributions of the face and core layers to the total TS in panels V and U were significantly different. The TS values of the top face layers in panels V and U were 45.7 and 45.3 %, respectively, which were 2.60 and 3.26 times higher than those of the TS values of the core layers after 2 hours of water exposure. The high density surface layers contributed 82.4 and 86.1 % of the total TS that occurred after 2 hours of water soaking in panels V and U, respectively. About 59.7 and 59.4 % of the total TS existed after 24 hours water soaking in the surface layers of panels V and U, respectively. It was also found that the percent contributions of the surface layers to the total TS decreased when increasing the water soaking time from 2 to 24 hours whereas the contributions of the core layers to the total TS increased when increasing the water soaking time for panels V and U.

Tab. 5: Percent contributions of face layer and core layer thickness swell to total thickness swell compared by the continuous press speed.

Panels groups	Top face (layers 1-3)	Core (layers 4-9)	Bottom face (layers 10-12)
2 hour water soak (%)			
V	45.73	17.58	36.69
U	45.34	13.88	40.78
8 hour water soak (%)			
V	37.99	27.83	34.18
U	37.49	27.32	35.19
24 hour water soak (%)			
V	30.36	40.35	29.30
U	29.95	40.62	29.43

The results obtained in the present study are found to be in agreement with the results of the previous studies. Wang et al. (2003) examined the LTS properties of oriented strandboard panels, and reported that the LTS increased when increasing the water exposure period and that there were large differences in thickness swell values between the surface and core layers. In addition, they reported that 76.5 % of the TS existed in the high density surface layers after 2 hours water soaking. Similar results were obtained by Gu et al. (2005) when examining the effects of wood species, resin type, and VDP on the total TS and LTS in commercial OSB flooring products. The results obtained by Wang et al. (2001b) are also comparable to the results obtained in this study.

CONCLUSIONS

VDP is affected by the production parameters, and it has some effects on the thickness swell characteristics of the MDF panels. It was observed that the two density peaks on the VDP resulted in two peaks on the LTS curve. Further, both 2 h and 24 h TS values of the panels decreased as the resin content increased, as the mat moisture content increased, and as the continuous press speed increased.

Large differences were determined in the TS values of the surface layers and the core layers of the panels. The first layers in both surfaces showed greater TS values than those of the sub-layers. Also, the contributions of the surface and core layer TS to the total TS were not equal. The high density surface layers contributed 82.4 and 86.1 % of the total TS that occurred after 2 hours water soaking in panels V and U, respectively. The greater TS values in the surface layers of the panels suggest that efforts to enhance the dimensional stability of the MDF panels should be focused on stabilizing the high density surface layers. The percent contributions of the surface layers to the total TS decreased as the water soaking time was increased from 2 to 24 hours, while the contributions of the core layers increased for all panels.

It was found that enhanced thickness swelling properties could alter the performance of current wood composite panel products in a wide range of applications. The findings obtained in the present study also indicate that it is important to understand the influences of RC, MC, and CPS on the LTS characteristics of the MDF panels for optimizing the structure in the development of new wood composite products as well as improving the production process. Thus, RC, MC, and CPS could be efficiently used by panel manufacturers to obtain the desired panel performance.

ACKNOWLEDGMENT

The authors thank Istanbul University Research Fund for its financial support in this project. Project Number: T-906/02062006. The authors would also like to express their appreciation to Kastamonu Integrated Wood Industry and Trade Inc. in Kocaeli, in Turkey for manufacturing research materials used in this project. The authors wish to acknowledge the staff of Center for Renewable Carbon in the University of Tennessee, TN, USA for their helpful assistance in this study.

REFERENCES

1. ASTM D 1037-06a, 2006: Standard test methods for evaluating properties of wood-base fiber and particle panel materials.
2. Brochmann, J., Edwardson, C., Shmulsky, R., 2004: Influence of resin type and flake thickness on properties of OSB. Forest Products Journal 54(3): 51–55.
3. Candan, Z., 2007: Effects of some production parameters on vertical density profile (VDP) and technological properties of medium density fiberboard (MDF). M.Sc. Thesis, Istanbul University, Istanbul, Turkey, 400 pp.
4. Candan, Z., Akbulut, T., Sisci, A.F., Zhang, X., 2007: Effect of species and mixtures on the formation of the vertical density profile and bending properties in medium density fiberboard (MDF) panels. Forest Products Society 61st Annual Meeting, June 10-13, 2007, Knoxville,Tennessee, USA.
5. Candan, Z., 2009: Thickness swelling, water absorption, and vertical density profile of medium density fiberboard panels affected by continuous press pressure. Society of Wood Science and Technology 52nd International Annual Convention, June 24, 2009, Boise, Idaho, USA.
6. Candan, Z., Ayrilmis, N., Akbulut, T., 2011: Dimensional stability performance of fire retardant treated veneer-oriented strandboard composites. BioResources 6(1): 308–316.
7. Del Menezzi, C.H.S., Tomaselli, I., 2006: Contact thermal post-treatment of oriented strand board to improve dimensional stability: A preliminary study. Holz als Roh- und Werkstoff 64(3): 212–217.
8. Del Menezzi, C.H.S., Tomaselli, I., Okino, E.Y.A., Teixeira, D.E., Santana, M.A.E., 2009: Thermal modification of consolidated oriented strandboards: Effects on dimensional stability, mechanical properties, chemical composition, and surface color. European Journal of Wood and Wood Products 67(4): 383–396.

9. Dieste, A., Krause, A., Bollmus, S., Militz, H., 2008: Physical and mechanical properties of plywood produced with 1.3-dimethylol-4.5-dihydroxyethyleneurea (DMDHEU)-modified veneers of *Betula* sp. and *Fagus sylvatica*. Holz als Roh- und Werkstoff 66(4): 281–287.
10. Dundar, T., Ayrilmis, N., Candan, Z., Sahin, H.T., 2009: Dimensional stability of fire-retardant treated laminated veneer lumber. Forest Products Journal 59(11/12): 18–23.
11. Filho, R.M.B., Mendes, L.M., Novack, K.M., Aprelini, L.O., Botaro, V.R., 2011: Hybrid chipboard panels based on sugarcane bagasse, urea formaldehyde and melamine formaldehyde resin. Industrial Crops and Products 33(2): 369–373.
12. Garcia, R.A., Cloutier, A., Riedl, B., 2005: Dimensional stability of MDF panels produced from fibres treated with maleated polypropylene wax. Wood Science and Technology 39(8): 630–650.
13. Gu, H., Wang, S., Neimsuwan, T., Wang, S., 2005: Comparison study of thickness swell performance of commercial oriented strandboard flooring products. Forest Products 55(12): 239–245.
14. Halvarsson, S., Edlund, H., Norgren, M., 2008: Properties of medium-density fibreboard (MDF) based on wheat straw and melamine modified urea formaldehyde (UMF) resin. Industrial Crops and Products 28(1): 37–46.
15. Houts, J.H., Winistorfer, P.M., Wang, S., 2003: Improving dimensional stability by acetylation of discrete layers within flakeboard. Forest Products Journal 53(1): 82–88.
16. Kamke, F.A, Casey, L.J., 1988: Fundamentals of flakeboard manufacture: Internal – mat conditions. Forest Products Journal 38(6): 38–44.
17. Medved, S., Šernek, M., Šega, B., 2006: Thickness swelling and swelling pressure of wood-based panels. Cost Action E44-E49 Wood Resources and Panel Properties, June 12-13, 2006. Pp 123-129, Valencia, Spain.
18. Strickler, M.D., 1959: Effect of press cycle and moisture content on properties of Douglas fir flakeboard. Forest Products Journal 9(7): 203–215.
19. Suzuki, S., Miyamoto, K., 1998: Effect of manufacturing parameters on the linear expansion and density profile of particleboard. Journal of Wood Science 44(6): 444–450.
20. Velasquez, A.J., Ferrando, F., Salvado, J., 2003: Effects of kraft lignin addition in the production of binderless fiberboard from steam exploded *Miscanthus sinensis*. Industrial Crops and Products 18(1): 17–23.
21. Wang, S., Winistorfer, P.M., 2000a: The effect of species and species distribution on the layer characteristics of OSB. Forest Products Journal 50(4): 37–44.
22. Wang, S., Winistorfer, P.M., 2000b: Fundamentals of vertical density profile formation in wood composites. Part 2: Methodology of vertical density formation under dynamic condition. Wood and Fiber Science 32(2): 220–238.
23. Wang, S., Winistorfer, P.M., Young, T.M., Helton, C., 2001a: Step-closing pressing of medium density fiberboard. Part 1: Influences on the vertical density profile. Holz als Roh- und Werkstoff 59(1/2): 19–26.
24. Wang, S., Winistorfer, P.M., Young, T.M., Helton, C., 2001b: Step-closing pressing of medium density fiberboard. Part 2: Influences on panel performance and layer characteristics. Holz als Roh- und Werkstoff 59(5): 311–318.
25. Wang, S., Winistorfer, P.M., 2002: Process and system for determination of layer TS of wood composites. U.S. Patent 6,396.590, USA.
26. Wang, S., Winistorfer, P.M., 2003: An optical technique for determination of layer thickness swell of MDF and OSB. Forest Products Journal 53(9): 64–71.

27. Wang, S., Gu, H., Neimsuwan, T., 2003: Layer thickness swell and related properties of commercial OSB products: A comparative study. In: Proceedings of the 37th International Wood Composite Materials Symposium, April 7-10, 2003, Washington State University, Pullman, WA, USA. Pp. 65-76.
28. Wang, S., Winistorfer, P.M., Young, T.M., 2004: Fundamentals of vertical density profile formation in wood composites. Part III. MDF density formation during hot-pressing. Wood and Fiber Science 36(1): 17–25.
29. Wong, E.D., Zhang, M., Wang, Q., Kawai, S., 1998: Effects of mat moisture content and press closing speed on the formation of density profile and properties of particleboard. Journal of Wood Science 44(4): 287–295.
30. Wong, E.D., Zhang, M., Wang, Q., Han, G., Kawai, S., 2000: Formation of the density profile and its effects on the properties of fiberboard. Journal of Wood Science 46(3): 202–209.
31. Wu, Q., Suchsland, O., 1996: Linear expansion and its relationship to moisture content change for commercial oriented strand boards. Forest Products Journal 46(11/12): 79–83.
32. Zisi, N.V., Bennett, R.M., Van Houts, J.H., 2005: Dimensional stability and mechanical properties of oriented strandboard with microwave-dried flakes in the surface layers. Forest Products Journal 55(12): 136–142.

Zeki Candan, Turgay Akbulut
Istanbul University
Faculty of Forestry
Department of Forest Products Engineering
Sariyer, 34473
Istanbul
Turkey
Phone: +90 (212)-226-1100
Corresponding author: zekic@istanbul.edu.tr

Siqun Wang
University of Tennessee
Center for Renewable Carbon
Knoxville, Tn 37996
USA

Xinan Zhang
Louisiana State University
School of Renewable Natural Resources
Baton Rouge, La 70803
USA

A. Faruk sisci
Kastamonu Integrated Wood Industry and Trade Inc.
Kocaeli
Turkey