Properties of Honeycomb Paperboards Faced with Heat-Treated Thin Medium-Density Fiberboards

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In this study, 4-mm-thick medium-density fiberboard (MDF) panels were heat-treated at 140 °C for 30 or 60 min and at 180 °C for 30 or 60 min. Then, 10-mm-thick lightweight honeycomb paperboards made from kraft paper (130 g/m^2, cell diameter of honeycomb, 14 mm; compression strength, 0.21 N/mm^2) were faced with the untreated and heat-treated MDF panels (thickness: 4 mm) using a two-component polyurethane adhesive. The density, thickness swelling, water absorption, and flexural properties of the paperboards faced with the untreated and heat-treated MDF panels were investigated. The lowest flexural strength (3.76 N/mm^2) and flexural modulus (392 N/mm^2) values were found in the specimens faced with the MDFs treated at 180 °C for 60 min, while the highest flexural strength (4.20 N/mm^2) and flexural modulus (457 N/mm^2) values were found in the specimens faced with the untreated MDFs. The loss in strength was primarily attributable to the degradation of hemicelluloses, which are less stable to heat than cellulose and lignin. The thickness swelling and water absorption of the honeycomb paperboards faced with the heat-treated MDF panels significantly ($p < 0.01$) decreased with the increase in heat-treatment temperature and duration.

Keywords: Heat-treatment; Flexural properties; Water resistance; Paperboard; Medium-density fiberboard

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INTRODUCTION

The furniture industry has been showing increasing interest worldwide in the use of lightweight panels because of the significant advantages they offer, namely the lower production and transportation costs resulting from lower wood consumption, as well as their lower density and comparable mechanical properties relative to conventional wood-based panels now in use (*e.g.*, particleboards, medium-density fiberboard (MDF), plywood), which have densities in the range of 0.60 to 0.750 g/cm^3 (Barboutis and Vassiliou 2015). In particular, recent furniture designs have tended to use lightweight panels in a wide range of interior applications such as shelving, table tops, sliding doors, carcassing, worktops, and internal doors tend to use thicker panels to convey contemporary design.

The main advantages of lightweight panels in furniture applications are their high strength-to-density ratio and low weight. The mechanical properties of lightweight panels can be similar to those of solid wood panels, and in some cases, they have greater bending and tensile strength, as a high-density material is used in the face layers. A sandwich-type panel typically consists of a thicker core layer, such as honeycomb paperboards, and two thin face layers, or skins, glued onto either side of the core layer. The layers can be made of thin wood, plywood, particleboard, high-density fiberboard, or MDF, as well as of lightweight metals such as aluminum or a magnesium alloy.

Heat treatment is one type of modification strategy used to improve the dimensional stability and biological durability of wood and wood-based panels; however, the mechanical properties can be negatively affected by heat treatment, depending on the temperature and duration of the process (Garcia *et al.* 2006; Cheng *et al.* 2016). The effect of heat treatment on the physical and mechanical properties of the MDF has been extensively investigated in previous studies.

The paperboards faced with thin MDF panels have been used as a substrate for bench tops and carcasses of kitchen cabinets that may exposed to high humidity. The in-plane movements caused by increased or decreased moisture content of the MDF can cause high internal stresses due to the restraint offered by adhesive in between the MDF and paperboard. These stresses may be large enough to cause buckled panels, pushed-out of nails, and separation of the panel from the structure. Based on an extensive literature search, there has not been any research on the use of heat-treated thin MDF panels as a facing material in the production of lightweight panels. In this study, the bending properties and water resistance of paper honeycomb panels faced with heat-treated thin MDF panels at different temperatures and durations was investigated.

EXPERIMENTAL

Commercial MDF Panels and Honeycomb Paperboards

The 4-mm-thick MDF panels used in this study were supplied from a commercial MDF manufacturer, Kastamonu Integrated Wood Company, in Gebze, Turkey. The density and moisture content of the panels were 750 g/cm^3 and 6%, respectively. The MDF panels were produced with a urea-formaldehyde (10.5 wt% UF) resin and shipped without any coatings. The MDF panels were produced from a mixture of pine (50 wt%) wood and beech wood (50 wt%) fibers. The commercial MDF panels were cut to a size of 500 mm x 500 mm in the carpentry shop and totaled 20 MDF samples (four samples for each panel group).

The 10-mm-thick commercial lightweight honeycomb panels made from kraft paper (130 g/m^2; cell diameter of honeycomb, 14 mm; compression strength, 0.21 N/mm^2) were supplied from Kadoma Forest Products Industry and Trade Company in Izmir, Turkey.

The two-component polyurethane adhesive (component A, Macroplast UK 8103; component B, Macroplast UK 5400) was supplied from Turk Henkel Company in Istanbul, Turkey. The adhesive mixture consisted of five units from component A and one unit from component B (by weight). The material, Macroplast UK 8103 / Macroplast UK 5400, was a solvent-free two-component adhesive based on polyurethane. The resin part (component A) contains organic compounds with hydroxyl groups, and the hardener (component B) is based on isocyanates.

Heat Treatment of MDFs

The MDF panels were cut into samples sized 500 mm x 500 mm and then were heat-treated at 140 °C for 30 or 60 min and at 180 °C for 30 or 60 min in an oven with a fan. The mass loss rates of the heat treated MDF panels were determined and compared with the untreated MDF. The experimental design for the heat-treatment of the MDF panels is presented in Table 1.

Table 1. Experimental Design for the Heat Treatment of MDF Panels

MDF code	Heat Treatment in Oven with a Fan	
	Temperature (°C)	Duration (min)
Control	-	-
A	140	30
B	140	60
C	180	30
D	180	60

Preparation and Testing of Paper Honeycomb Panels Faced with Heat-Treated Thin MDFs

The honeycomb paperboards were constructed with a honeycomb core and two surface-layers of heat-treated MDF panels, totaling 18 mm in nominal thickness. The bonding of the two surface layers to the honeycomb core was achieved using a two-component polyurethane adhesive. The adhesive components were mixed manually with stirring. The polyurethane adhesive was spread at the rate of 200 g/m^2 on a single bonding surface of the MDF panel using a laboratory manual cylinder. During the curing, there was adequate contact pressure in the hot press and fixtures to hold the joint in place. The curing time was 1 h at 60 °C. The configuration of the honeycomb paperboards faced with thin MDFs is presented in Fig. 1. For each type of lightweight panel, two panels with dimensions of 500 mm x 500 mm x 18 mm were produced under laboratory conditions.

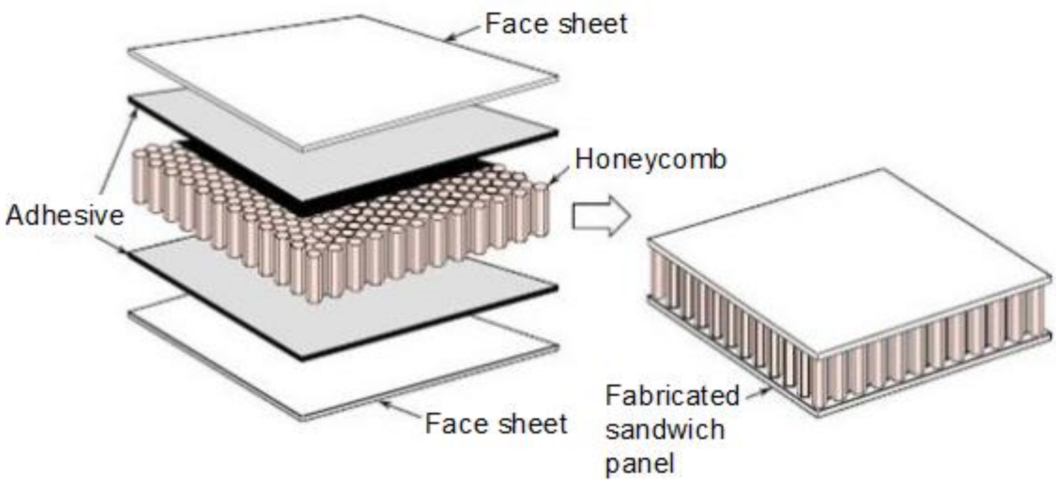

Fig. 1. The configuration of the honeycomb paperboard faced with thin MDFs (face sheets)

The resulting panels were conditioned at 65% relative humidity and 20 °C until a constant weight was achieved before being subjected to the physical and mechanical tests. The panels were then cut further into smaller specimens. Twenty samples with dimensions of 50 mm x 50 mm x 18 mm, 10 samples for each panel, were used for the thickness swelling and water absorption tests of each treatment type. Ten samples with dimensions of 410 mm x 50 mm x 18 mm, 5 samples for each panel, were used for the flexural strength and flexural modulus tests. As the paperboards had a principal axes which was not isotropic, the principal axes was taken into account in the preparation of the test samples. The physical and mechanical tests were performed according to the European standards given in Table 2.

Table 2. Physical and Mechanical Tests Performed on the Paperboards Faced with MDF

Test type	Standard number
Density	EN 323 (1993)
Thickness swelling	EN 317 (1993)
Water absorption	EN 317 (1993)
Flexural strength	EN 310 (1993)
Flexural modulus	EN 310 (1993)

Statistical Analysis

Analysis of variance (ANOVA) at $p < 0.01$ was used to compare the means of the panel groups with each other using the SPSS software program (SAS Institute Inc., Cary, NC). Significant differences among the mean values of the panel groups were determined using Duncan's multiple range test.

RESULTS AND DISCUSSION

The results for the water resistance and flexural properties of the honeycomb paperboard faced with thin MDFs are presented in Table 3. The flexural properties of the paperboards faced with the heat-treated MDF panels decreased with increasing severity of the heat treatment. The highest strength and modulus values were found in the untreated control specimens faced with the untreated MDFs. The lowest flexural strength (3.76 N/mm^2) and flexural modulus (392 N/mm^2) were found in the paperboards faced with the MDFs treated at 180 °C for 60 min, while the highest flexural strength (4.20 N/mm^2) and flexural modulus (457 N/mm^2) values were found in the paperboards faced with the untreated MDFs (Table 3). In previous studies, the primary reason for the strength loss in heat-treated wood was reported as the degradation of hemicelluloses, which are less stable to heat than cellulose and lignin (Yildiz *et al*. 2006; Kocaefe *et al*. 2008). The decreases in the flexural properties of the paperboards faced with the heat-treated MDF panels was mainly attributed to the degradation of hemicelluloses (Okino *et al.* 2007; Paul *et al.* 2007; Ayrilmis and Winandy 2009; H`ng *et al.* 2012; Kwon and Ayrilmis 2016). In addition, the depolymerization and shortening of the cellulose polymer decrease the MOE and MOR of wood, which reduce the flexural properties of the wood (Sweet and Winandy 1999). Similar results have been observed in previous studies (Ayrilmis *et al*. 2009; Wahyu *et al*. 2015; Tufan *et al.* 2016). The significant differences ($p < 0.01$) in the flexural strength and flexural modulus values are shown as different letters in Table 3. The control group and the panel types A and B did not show significant differences in terms of flexural strength and modulus values, while the panel types C and D did show significant differences. Namely, the heat-treatment of the MDFs at 140 °C for 30 or 60 min did not significantly decrease the flexural strength and flexural modulus values of the paperboards faced with the heat-treated MDFs compared to the paperboards faced with the untreated MDFs. However, the flexural strength and flexural modulus values of the MDFs treated at 180 °C for 30 or 60 min were significantly lower than those of the control panels. Furthermore, significant difference was found in the flexural strength and modulus values between the treatments at 180 °C and 140 °C (Table 3).

The thickness swelling and water absorption values of the honeycomb paperboards faced with the heat-treated MDF panels decreased considerably with increasing heat-treatment temperature and duration applied to the MDF panels. For example, compared to the control group, the thickness swelling and water absorption values of the honeycomb paperboards faced with the MDF decreased from 4.45% to 3.54% and 25.11% to 19.33%, respectively, when the MDF panels were heat-treated at 180 °C for 60 min. As the severity of the heat treatment of the MDF panels increased, the water resistance of the paperboards faced with the MDF significantly decreased (Table 3). However, there was no significant difference in the thickness swelling between the control group and panel type A. As is known, the hemicelluloses and cellulose have many hydroxyl groups and are highly hygroscopic. The hemicelluloses are the first structural compound to be thermally affected, even at low temperatures (Esteves and Pereira 2009; Xing and Li 2014). The cellulose degradation occurs at higher temperature and longer treatment time (Bhuiyan *et al.* 2000; Esteves and Pereira 2009). The heat-treatment imparts to the wood a low affinity for water. This results in a decrease in the number of hydroxyl groups. The higher water resistance of the MDF-faced paperboards treated at higher temperatures and durations could be explained by the increased hydrophobicity of the wood fibers.

Table 3. Water Resistance and Mechanical Properties of Honeycomb Paperboards Faced with Control and Heat-Treated MDF Panels

Panel code	Density (g/cm^3)	Thickness swelling (%)	Water absorption (%)	Flexural strength (N/mm^2)	Flexural modulus (N/mm^2)
Control	0.399 (0.005)	4.45 (0.42) a	25.11 (0.98) a	4.20 (0.51) a	457 (39.2) a
A	0.423 (0.012)	4.16 (0.38) ab	23.15 (1.21) b	4.02 (0.62) ab	434 (41.1) a
B	0.400 (0.007)	4.01 (0.29) b	22.36 (1.17) b	3.92 (0.44) bc	425 (29.5) a
C	0.412 (0.005)	3.72 (0.30) bc	20.17 (1.84) c	3.88 (0.65) bc	401 (35.6) b
D	0.404 (0.01)	3.54 (0.44) c	19.33 (1.12) c	3.76 (0.49) c	392 (47) b

[1] See Table 1 for the heat-treatment of MDF panels used in the production of lightweight panels.
[2] Panel types (from control to type D) with the same letters in a column show that there is no statistical difference ($p < 0.01$) among the specimens according to Duncan's multiply range test. The values in the parentheses are standard deviations.

The mass loss of the MDF panels increased with increasing severity of the heat-treatment. The highest mass loss rate was found to be 6.08% for the MDF panels treated at 180 °C for 60 min, followed by the MDF panels treated at 180 °C for 30 min (5.42%), 140 °C for 60 min (4.19%), and 140 °C for 30 min (3.24%), respectively. The mechanical properties of the honeycomb paperboards faced with the heat-treated MDF panels decreased with increasing mass loss rate of the MDF panels (Table 3). Similar results were found in previous studies (Paul e*t al.* 2007; Okino *et al.* 2007; Kariz *et al.* 2013; Lunguleasa and Spirchez 2015).The mass loss of heat-treated MDF panels is an indicator of the degree of the heat-treatment. The mass loss in wood is mainly due to the thermal degradation of the hemicelluloses, but also to the volatilization of some extractives (Esteves *et al.* 2008). Heat-treatment at lower temperatures and shorter durations results in a lower mass, which is mainly associated with loss of volatiles bound water. Loss of macromolecular components can occur at temperature above 100 °C and this assumes greater significance as the duration and temperature are increased (H`ng *et al.* 2012).

CONCLUSIONS

1. The paperboards were found to have optimal properties when faced with the MDF panels treated at 140 °C for 60 min, because the water absorption and thickness swelling of the paperboard treated this way significantly decreased compared to the control panels. The mass loss rate of the MDF panels increased with increasing severity of the heat-treatment.
2. The flexural properties of the paperboards faced with the MDFs treated at 140 °C for 60 min did not show a significant difference from the control panels, although the flexural properties of the faced paperboards decreased with the increasing severity of the heat treatment applied to the MDFs.
3. The heat-treatment of the MDF could be used as an approach to enhance the water resistance of the honeycomb paperboards faced with MDF.

REFERENCES CITED

Ayrilmis, N., and Winandy, J. E. (2009). "Effects of post heat-treatment on surface characteristics and adhesive bonding performance of medium density fiberboard," *Materials and Manufacturing Processes* 24(5), 594-599. DOI: 10.1080/10426910902748032

Ayrilmis, N., Laufenberg, T. L., and Winandy, J. E. (2009). "Dimensional stability and creep behavior of heat-treated exterior medium density fiberboard," *European Journal of Wood and Wood Products* 67(3), 287-295. DOI: 10.1007/s00107-009-0311-7

Barboutis, I., and Vassiliou, V. (2015). "Strength properties of lightweight paper honeycomb panels for the furniture," in: *Proceedings of International Scientific 2015 Conference 10th Anniversary of Engineering Design (Interior and Furniture Design)* Sofia, Bulgaria, pp 17-18

Bhuiyan, M. T. R., Hirai, N., and Sobue, N. (2000). "Changes of crystallinity in wood cellulose by heat treatment under dried and moist conditions," *Journal of Wood Science* 46(6), 431-436. DOI:10.1007/BF00765800

Cheng, S., Huang, A., Wang, S., and Zhang, Q. (2016). "Effect of different heat-treatment temperatures on the chemical composition and structure of Chinese Fir wood," *BioResources* 11(2), 4006-4016. DOI: 10.1537/biores.11.2.4006.-4016

EN 310 (1993). "Determination of bending strength and modulus of elasticity," European Committee for Standardization, Brussels, Belgium

E7 317 (1993). "Particleboards and fiberboards – determination of swelling in thickness after immersion in water," European Committee for Standardization, Brussels, Belgium

EN 323 (1993). "Wood-based panels – determination of density," European Committee for Standardization, Brussels, Belgium

Esteves, B., Domingos, I. J., and Pereira, H. M. (2008). "Pine wood modification by heat treatment in air," *BioResources* 3(1), 142-154

Esteves, B., and Pereira, H. M. (2009). "Wood modification by heat treatment: A review," *BioResources* 4(1), 370-404. DOI: 10.15376/biores.4.1.370-404

Garcia, R. A., Cloutier, A., and Riedl, B. (2006). "Dimensional stability of MDF panels produced from heat-treated fibres," *Holzforschung* 60(3), 278-284. DOI: 10.1515/HF.2006.045

H`ng, P.S., Lee, S.H., and Lum, W.C. (2012). "Effect of post heat treatment on dimensional stability of UF bonded particleboard," *Asian Journal of Applied Sciences* 5(5), 299-306. DOI: 10.3923/ajaps.2012.299.306

Kariz, M., Kuzman, M.K., and Sernek, M. (2013). "The effect of heat-treatment on the withdrawal capacity of screws in Spruce wood," *BioResources* 8(3), 4340-4348.

Kocaefe, D., Poncsak, S., and Boluk, Y. (2008). "Effect of thermal treatment on the chemical composition and mechanical properties of birch and aspen," *BioResources* 3(2), 517-537. DOI: 10.15376/biores.3.2.517-537

Kwon, J. H., and Ayrilmis, N. (2016). "Effect of heat-treatment of flakes on physical and mechanical properties of flakeboard," *European Journal of Wood and Wood Products* 74(1), 135-136. DOI: 10.1007/s00107-015-0961-6

Lunguleasa, A., and Spirchez, C. (2015). "The characteristics of thermally treated MDF panels," *Bulletin of the Transilvania University of Braşov Series II: Forestry, Wood Industry, Agricultural Food Engineering* 8(57) No:2, 55-60.

Okino, E. Y. A., Teixeira, D. E., and Del Menezzi, C. H. S. (2007). "Post-thermal treatment of oriented strandboard (OSB) made from cypress (*Cupressus glauca* Lam.)," *Maderas Ciencia y Tecnologia* 9(3), 199-210. DOI: 10.4067/S0718-221X2007000300001

Paul, W., Ohlmeyer, M., and Leithoff, H. (2007). "Thermal modification of OSB-strands by a one-step heat pre-treatment – Influence of temperature on weight loss, hygroscopicity and improved fungal resistance," *Holz als Roh- und Werkstoff* 65(1), 57-63. DOI: 10.1007/s00107-006-0146-4

Sweet, M. S., and Winandy, J. E. (1999). "Influence of degree of polymerization of cellulose and hemicellulose on strength loss in fire-retardant-treated southern pine," *Holzforschung* 53(3), 311-317

Tufan, M., Güleç, T., Peşman, E., and Ayrilmis, N. (2016). "Technological and thermal properties of thermoplastic composites filled with heat-treated alder wood," *BioResources* 11(2), 3153-3164. DOI: 10.15376/biores.11.2.3153-3164

Wahyu, H., Jang, J. H., Park, S. H., Qi, Y., Febrianto, F., Lee, S. H., and Kim, N. H. (2015). "Effect of temperature and clamping during heat-treatment on physical and mechanical properties of Okan (*Cylicodiscus gabunensis* [Taub.] Harms) wood," *BioResources* 10(4), 6961-6974. DOI: 10.15376/biores.10.4.6961-6974

Xing, D., and Li, J. (2014). "Effects of heat-treatment on thermal decomposition and combustion performance of *Larix spp.* wood," *BioResources* 9(3), 4274-4287. DOI: 10.15376/biores.9.3.4274-4287

Yildiz, S., Gezer, E. D., and Yildiz, U. C. (2006). "Mechanical and chemical behavior of spruce wood modified by heat," *Building and Environment* 41(12), 1762-1766. DOI: 10.1016/j.buildenv.2005.07.017

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