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LIGHTWEIGHT TUBULAR FIBERBOARD: EFFECT OF HOLE DIAMETERS AND NUMBER ON PANEL PROPERTIES

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ABSTRACT

Special tubular fiberboard with a density of 550 kg/m^3 was manufactured using the round rods for creation of the holes. Physicomechanical properties of tubular fiberboard (6, 8, 10, 12 (mm)) with various hole diameters and number of hole (0, 1, 2 and 3 in a constant cross section) were evaluated. The surface layers density, especially on top of the holes, considerably elevated with increasing the hole diameter. This did create higher bending properties as well as higher internal bond and surface soundness. The structure of webs between the holes, when the holes' number increases, were predominant factor influencing the panel properties. Weak and loose web structure were obtained by increasing the holes' number from 1 to 3 within a constant cross section (50 mm × 16 mm) that was due to the less transferred fiber during pressing in the webs' sections. A corresponding comparison of panel properties with those in American and European standards presents that the minimum requirements according to most of the standards (ANSI A208/2, EN 14755, EN 312/P2 and EN 622-5/P1) were obtained.

Keywords: Fiberboard, lightweight, tubular board, extrusion, furniture application.

INTRODUCTION

Among all types of wood-based panels (WBPs), production of medium density fiberboard (MDF) has drastically raised at an astonishing rate of about 5 Million m^3 per year on a worldwide basis since 2000 reaching today about 100 Million m^3 (FAO 2018). Main advantages of MDF that gain considerable part of the market are the hard, flat and smooth surfaces that makes it ideal for painting, veneering and paper lamination. Importantly, MDF has nearly 10 % higher density compared with conventional particleboard. This is far from the level required for lightweight panels having a density around 500 kg/m^3 (Shalbafan *et al.* 2013). The idea of lightweight WBPs is gained interest due to the growing of customer demands for lightweight products as well as the lowering of transportation cost (Dziurka *et al.* 2015; Colautti and Pisa 2016; Shalbafan *et al.* 2017). Density of MDF can be traditionally reduced using less compaction ratio of the fiber furnish. A negative consequence of such weight reduction, however, is a loss of mechanical properties and shape stability, especially the surface layers' quality (Rowell *et al.* 1995). In other words, conventional low-density fiberboard (LDF) has soft and loose surfaces that are not ideal for the furniture application. Such LDF is mostly used for the insulation applications where the surface layers' quality is not an important matter. Development of fiberboard having the same surface layers' quality as MDF with a much lower density is essential to improve the board functionality and applicability. To this end, hybrid panels consisting of fiber-based facings and a particle-based core layer were recently developed to benefit the MDF faces quality whilst having a lower density (Klasterka 2003; Jafarnezhad *et al.* 2018).

Most of the physical and mechanical properties of the WBPs influence by their density profile (Wong *et al.* 2000). Density profile manipulation of WBPs give the opportunity to influence the density in successive layers of a board within a certain range. In other words, improving the panel properties is possible without increasing the panel density. This means that with reducing the consumption of raw materials and just with controlling the density profile, lighter panels can be produced without decreased panel properties (Cai *et al.* 2006). Many parameters influencing the density profile in the panel e.g. mat moisture content, mat structure, geometry of wood elements, press schedule, press temperature, resin content, etc. (Wong *et al.* 2000; Cai *et al.* 2006; Thoemen and Ruf 2008). Five types of oriented fiberboard were manufactured by changing the direction of pressing the fiber mat, namely platen-pressed fiberboard, horizontally oriented fiberboard, 3-dimensionally random fiberboard, extruded fiberboard and vertically fiberboard (Ohba *et al.* 2001). The results showed that the boards with more vertical (thickness direction) orientation of fibers showed higher internal bond strength and less thickness swelling. A board with a double density difference between two horizontal layers of fiber mat was obtained in one press cycle at two different moisture content (Haas and Frühwald 2000). By applying a new technology with the commercial description Dascanova Technology, a selective arrangement of the fiberboard density did achieve in one press cycle (Déneši *et al.* 2012).

One of the oldest technologies for weight reduction in particleboard is extrusion method that is also named Okal or Lanewood process (Kollman 1975). In this process, the glued particles fall through a channel under the ram between the heating plates. Then, the ram compresses the particles and endlessly pushes the extruded board downwards (Kollman 1975). This unique process has been used for the production of extruded (tubular) particleboard for over nearly 70 years. Interestingly, research on production and characterization of the tubular/extruded fiberboard is scarce, although, a patent for the production process of extruded fiberboard date back to 1956 (Bowers *et al.* 1956). It was recently showed that MDF produced with special forming has significantly higher bending properties compared to those panel with conventional forming (Ohba *et al.* 2001; Déneši *et al.* 2012). Hence, developing a cost-efficient lightweight MDF with high rigidity for application in furniture manufacture, building, transport and exhibition construction as well as for direct painting and printing is necessary today.

Even with the high potential in extrusion method for the alignment of wood elements, no research was observed on the production of tubular fiberboard. It seems that the diameter and the number of holes (tubes) have great influence on the physical and mechanical properties of the lightweight tubular fiberboard. Hence, the aim in the current study is to find out in which diameter and number of holes the minimum required of panels properties can be achieved.

MATERIALS AND METHODS

Panel composition

Unresinated wood fibers mainly poplar, willow and eucalyptus were supplied from Kimia Chob Ltd (Gorgan, Iran). The moisture content of wood fibers prior to resination was 4,8 %. Urea formaldehyde (UF) as adhesive was supplied from Amol Resin Ltd (Amol, Iran) with solid content of 62 %, pH of 7,72 and density of 1,2 g/cm^3. The adhesive was sprayed onto the fiber furnish tumbling in a rotating drum-type blender by using a compressed air spray head. Amount of sprayed resin was 12 % based on oven dry mass of wood fibers that was calculated based on resin solid content. As hardener, 1 % ammonium chloride based on resin solid content was added to resin prior to spraying.

Effects of holes diameters (6, 8, 10, 12 (mm)) on panel properties was evaluated as the holes' number was kept constant at 1 in a constant cross-sectional area (50 mm × 16 mm). In the next experimental step, the numbers of holes in a constant cross-sectional area (50 mm × 16 mm) were varied between 1, 2 and 3 as the holes diameters were kept constant at 6 mm. Panel without holes was also produced as reference. List of panel types produced is shown in Table 1.

Table 1: List of panel types with various holes diameter and number.

Code	Hole diameters (mm)	Hole number
A	6	1
B	8	1
C	10	1
D	12	1
E	6	2
F	6	3
G	Reference sample	0

Target panel density and thickness were kept constant at 550 kg/m^3 and 16 mm, respectively. Three replicas of each panel variation were produced. Cross sectional area of samples with various holes diameter and number is illustrated in Figure 1 (prepared from the produced panels).

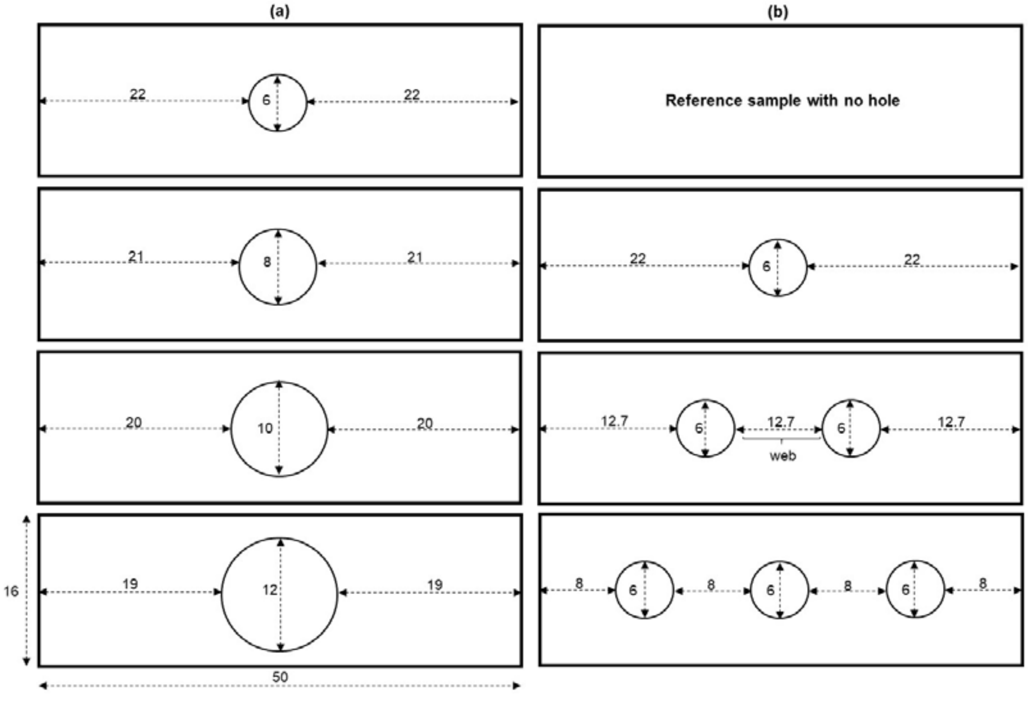
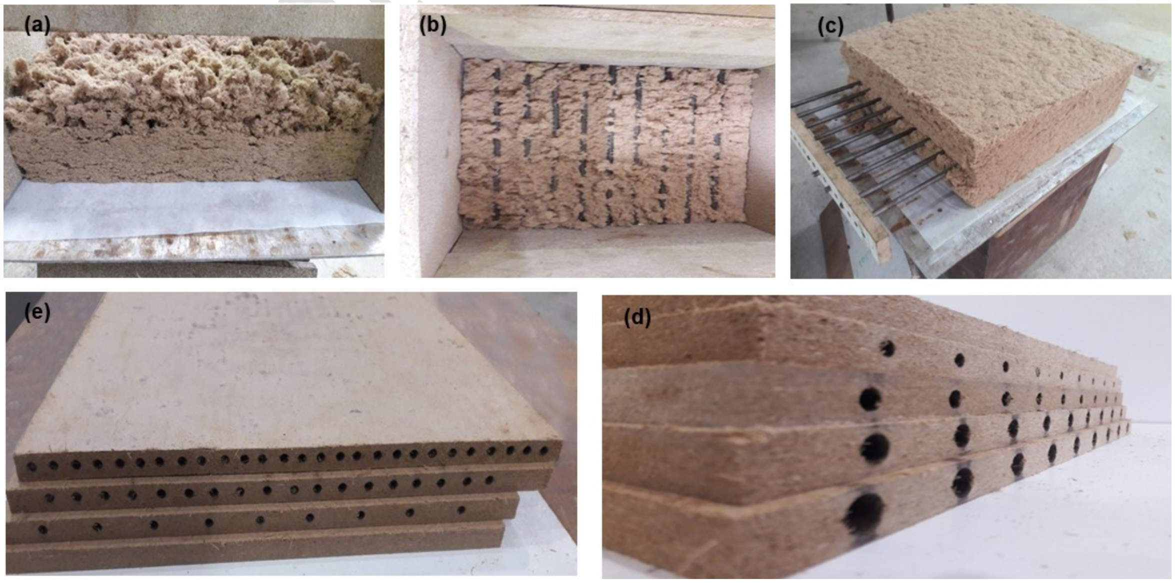


Figure 1: Cross-section of lightweight tubular fiberboard; a) various holes diameter, and b)

various holes' number (the number presented above are in mm).

Panel production

In this study, lightweight tubular fiberboard was produced in a platen-pressed direction whilst the holes' network was simultaneously created in their central part. To this end, resinated fiber was used for mat formation and smooth round rods to create the holes. After blending, half of the glued fibers was formed by hand using a 500 mm × 400 mm forming box. Then, the collection of round rods was put on top of the formed mat. Afterwards, the rest of glued fibers fall into the forming box on top of the tubes collection. The whole mat was then pre-pressed and put in the computer controlled lab-scale single opening hot press (Ranjbar Press Ltd., Isfahan, Iran). Press temperature, pressure and time were set at 160 °C, 4,5 MPa and 320 seconds, respectively. After pressing, the round rods were removed from the cooled panels. The rods were impregnated with liquid paraffin for an easier rod egressing prior to their application. Figure 2 shows the production process and final tubular fiberboard. It should be noted that the laboratory production process (horizontal mat forming/layering) used in this study differs from a potential



extrusion process (concerning the fibers alignment).

Figure 2: Production process of lightweight tubular fiberboard; a) preparation the half of the fiber mat, b) putting the rods collection in mat, c) finalizing the whole fiber mat, d) final tubular fiberboard with various holes diameter, e) final tubular fiberboard with various holes' number.

Panel characterization

The effect of different holes diameter and number on the physical and mechanical properties of lightweight tubular fiberboard is investigated. To this end, modulus of elasticity and bending strength (EN 310 (1993)), internal bond (EN 319 (1993)), surface soundness (EN 311 (2002)), thickness swelling (EN 317 (1993)) and water absorption were measured. Three-point bending properties were tested in two directions related to the holes; the holes parallel to the span of test piece and the holes perpendicular to the span of test piece. According to EN 310, the loading head was located directly above a web in case of holes perpendicular to the span of test piece. The water absorption (WA) after 24 h water soaking of the samples was calculated according to the following equation (1):

$$\mathrm{WA}\ (\%) = ((\mathrm{Wt} - \mathrm{WI})\ /\mathrm{WI}) \times 100 \tag{1}$$

where WA is the amount of absorbed water at time t, and W_t and W_I are the weights of the samples at time t (24 h) and the weight of the samples prior to water soaking, respectively.

Three sample tests of each panel were tested to measure the physical and mechanical properties. Prior to testing, all samples were conditioned in a climate chamber at 65 % ± 3 % relative humidity and a temperature of 20 ˚C ± 2 ˚C until constant mass was reached.

To get information about panel formation, vertical density profiles were measured by γ-ray densitometry (Raytest GmbH, Trivolt PK60, Germany) with measuring steps of 75 µm. Vertical density profile was investigated across the hole direction.

Data analyzing

The statistical package for social science IBM SPSS Statistics (IBM 2010) was used for analyzing the data. One-way analysis of variance (ANOVA) was used to test differences between the mean values of physical and mechanical properties. Duncan test was used to differentiate the significant of average values that is indicated by different letters in each graph. The P-value level of statistical significance was set at P<0,05.

RESULTS AND DISCUSSION

Effect of holes diameter

Density profile

Vertical density profile reflects changes in density through the panel thickness. Figure 3 shows the density profiles of panels having different holes diameter. The results showed that the reference sample has a nearly homogeneous density profile where there was not a large variation between the face and core layers density. As seen in Figure 3, density in surface layers was increased by using the round rods to create the holes in fiberboard. Increasing the holes diameter (from 6 mm to 12 mm) are also positively raised the density of surface layers. Surface layers density was nearly 600 kg/m^3 in reference sample and reached to more than 1300 kg/m^3 in panels with 12 mm holes diameters. This was due to reduced space in panel with large tubes (holes) to compress more a fixed amount of fiber. Panel density is closely related to the rate of panel compression (Cai *et al.* 2006). An increase in the surface and mean panel density and high rate of panel compression can be resulted to increase of bond strength and bending resistance. Accordingly, this can positively influence most of the properties of WBPs like bending properties and surface soundness (Geimer *et al.* 1975; Wong *et al.* 2000; Thoemen and Ruf

2008). In other words, more compacted surface layers are significantly affected the surface-depended properties.

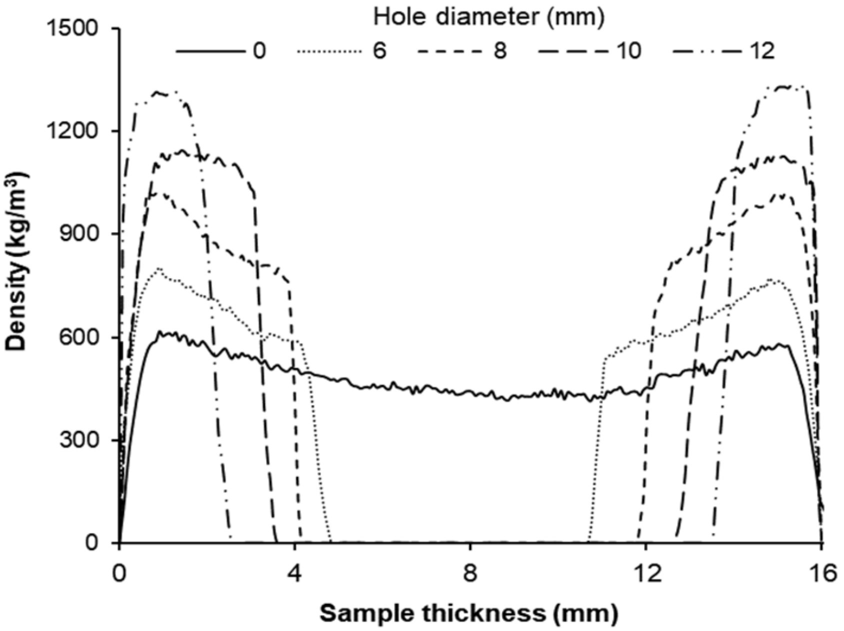


Figure 3: Vertical density profile of the lightweight tubular fiberboard with various holes diameter.

Mechanical properties

The effect of holes diameters on bending strength (MOR) and modulus of elasticity (MOE) of lightweight tubular fiberboard is illustrated in Figure 4. The MOR and MOE of samples with holes parallel to the span of test pieces shown that the MOR and MOE were significantly increased using the round rods for creation the holes. The lowest (12,5 MPa) and highest (18,2 MPa) MOR obtained for reference sample and the one with holes diameters of 10 mm. In other words, using the rods up to 10 mm was increased the MOR value to about 45 % in respect to reference sample. However, increasing the holes diameter above 10 mm brought an inferior value of MOR to about 14 MPa. Density of surface layers was the most important factor influenced the MOR in samples with holes diameter up to 10 mm (Wong *et al.* 2000). Increasing the holes diameter to 12 mm led to further weakening of webs between the holes, as was resulted more shear stresses in those regions and thus reduced the MOR values. Like an I-beams, the web resists shear forces, while the faces resist most of the bending moment experienced by the panel (Shalbafan *et al.* 2017). Although, the faces can resist higher bending moment in panels with larger holes diameter, but their corresponding webs was get thinner that cannot resist the created shear forces. The lowest (1200 MPa) and highest MOE (2055 MPa) were observed in reference panel and the one with holes diameters of 12 mm. Increasing the holes diameter up to 12 mm brought nearly 70 % higher MOE compared to reference panel. As mentioned earlier, the bending properties of WBPs can be improved with increasing the density of surface layers (Thoemen and Ruf 2008). The MOE was not decreased in samples with 12 mm holes diameter unlike the MOR. MOE is related to elastic region and the linear section of stress-strain curve, the observed shear stresses during the tests can be related to plastic region of material, which had no effect on the elastic modulus of the samples (Kollman 1975).

The MOR and MOE of samples with holes perpendicular to the span of piece is shown that the bending properties were significantly raised by increasing the holes diameters up to 10 mm. The highest MOR and MOE were obtained at about 17 MPa and 1800 MPa for panels with 10 mm holes, respectively. Both MOE and MOR were drastically decreased as the hole’s diameters increased to 12 mm. This was due to the extreme weakening of the webs (distance) between the holes that result to the more shear stresses during testing. A closer look at Figure 4 showed that the bending properties in samples with holes perpendicular to the span of test piece is nearly 10 % lower in comparison to those samples with holes parallel to the span of test piece, except the sample with 12 mm holes. This can be explained by more shear stresses created within the samples with holes perpendicular to the span of test piece. Shear stress during bending test has unrealistic effects on the bending results (Hein and Brancheriau 2018).

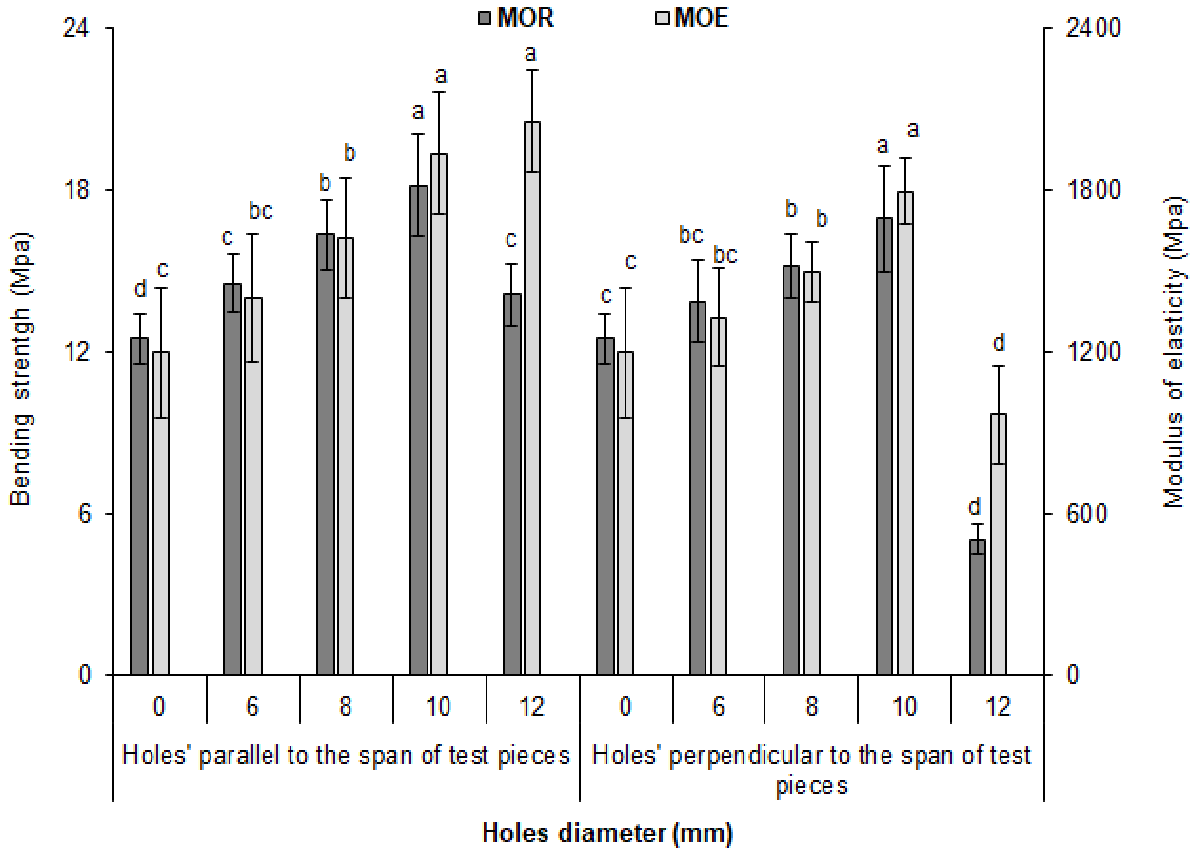


Figure 4: Bending strength and modulus of elasticity of lightweight tubular fiberboard with various holes diameter.

The effect of holes diameter on internal bond (IB) values is shown in Figure 5. Referring to Figure 5, the IB value for the reference sample and the one with 6 mm holes diameter was recorded about 0,36 MPa and 0,4 MPa, respectively. However, given the results of statistical analysis, the lowest changes in IB were recorded for reference sample and the one with holes diameter of 6 mm (identical homogeneous group), and increasing the holes diameter above this value (up to 12 mm) significantly reduced the IB values. The density of core layer and its structure significantly influence on IB values (Wong *et al.* 2000; Jafarnezhad *et al.* 2018). The reduction of IB values with increasing the holes diameter can be attributed to the weakening of webs at core layer. The larger holes in the core layer, the weaker webs and thus the lower IB values. It is important to note that a slight increase in IB values of samples with 6 mm holes diameter compared to reference sample can be probably related to better configuration of webs between the holes.

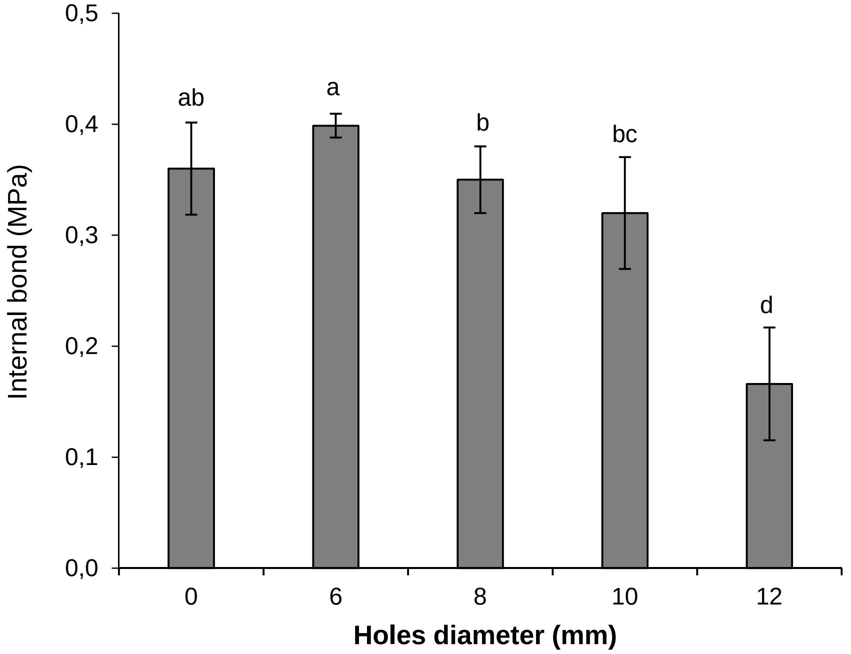


Figure 5: Internal bond values of lightweight tubular fiberboard with various holes diameter.

Surface soundness (SS) of lightweight tubular fiberboard with various holes diameters has been tested and the results are presented in Figure 6. Using the round rods in tubular fiberboard shows positive influence on the SS values. As shown, the highest SS was recorded for panels with 10 mm holes diameters (0,86 MPa) that is nearly 145 % higher than that of the reference sample (0,35 MPa). Referred to Figure 3, the peak density in samples with 10 mm holes diameter was raised about 87 % compared to that samples with no holes. The higher the surface layers density, the higher the values of SS (Wong *et al.* 2000; Thoemen and Ruf 2008). The SS was significantly reduced with further increasing of holes diameters to 12 mm, although the surface layers density was the highest. Observation of tested samples showed that the fractures happened in the web parts of the samples with 12 mm holes. This indicates that the webs between the holes of this sample (12 mm holes) were too weak. Adequate SS is very essential for the veneering, paper lamination, direct painting and printing of the fiberboards. Conventional lightweight fiberboards have soft and loose surfaces that are not ideal for the furniture application (Rowell *et al.* 1995). In this study, the SS was drastically improved using the round rods to create the holes. Lightweight tubular fiberboard is a moderate density fiberboard that weighs approximately 30 percent less than conventional MDF and can be a perfect material for furniture applications when the weight matters.

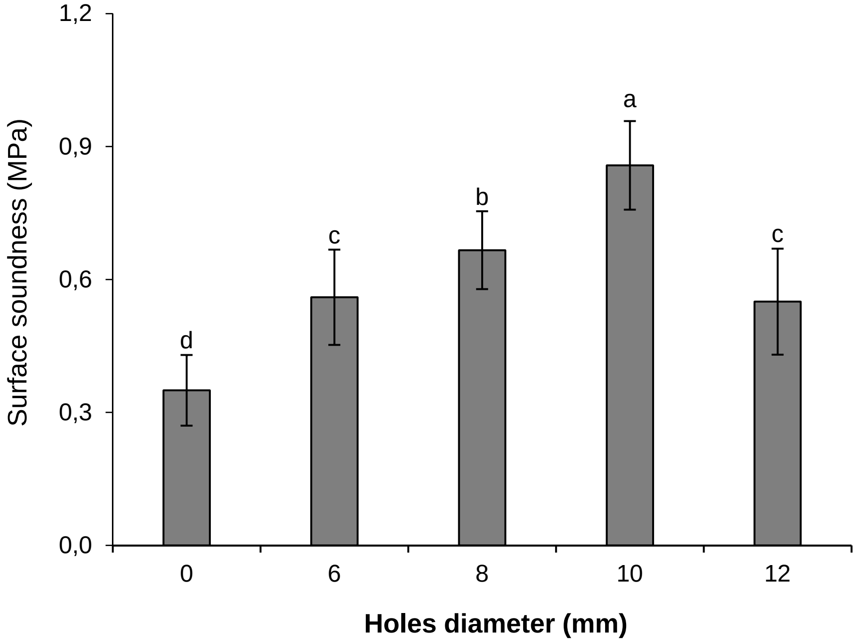


Figure 6: Surface soundness values of lightweight tubular fiberboard with various holes diameter.

Physical properties

Effect of holes diameter on the thickness swelling (TS) and water absorption (WA) after submersion for 24 hours are summarized in Figure 7. Results indicated that increasing of holes diameter has a positive influence on TS and WA. The larger the holes diameter, the lower the TS and WA. The lowest TS (12,5 %) and WA values (77 %) were obtained for panels having holes diameter of 10 mm. As mentioned, using the round rods led to more densification in the surface layers. It was reported that the accessibility of water molecules to the hydroxyl group of wood fiber was postponed with increasing the panels' densification (Shalbafan *et al.* 2013). Furthermore, the interior sections of holes were indirectly impregnated with that paraffin existed in the outer part of the rods, which postpone the accessibility of water molecules to the fiber structure. Importantly, the TS and WA values in samples with 12 mm holes diameter were significantly increased.

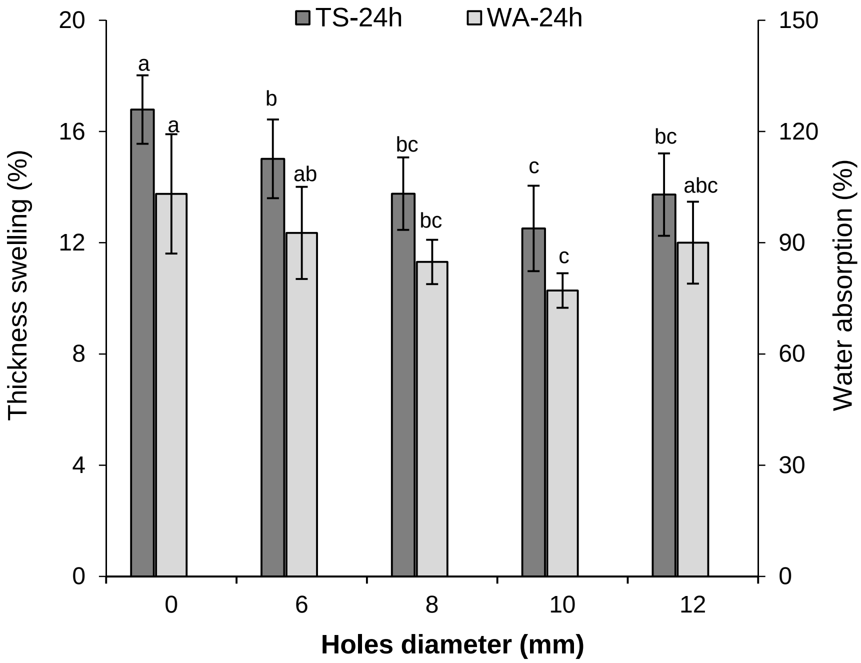


Figure 7: Thickness swelling and water absorption of lightweight tubular fiberboard with various holes diameter.

Referring to Figure 3, panels with 12 mm holes diameter had surface layer density about 1300 kg/m^3 that is relatively close to pure density of wood cells (Kollmann 1975). More compressive stresses during hot pressing were stored in panels with 12 mm holes. These internal stresses were possibly released during water soaking of samples that is scientifically named the spring-back of samples (Thoemen and Ruf 2008). Such spring-back was weakened the integrity of sample structure and increased the TS and WA. In other words, higher spring-back creates more free spaces within the panel that then water can more easily pass through the fibers.

Effect of holes' number

Holes diameter of 6 mm was selected to show the effect of holes' number (within a constant sample cross section) on physical and mechanical properties of the samples.

Mechanical properties

Bending properties (MOR and MOE) of lightweight tubular fiberboard with various number of holes parallel and perpendicular to the span of test pieces are presented in Figure 8. As shown, the lowest and highest MOR were observed in samples with holes' number of 1 and 3 (holes' parallel to the span of test pieces) about 14,6 MPa and 4,2 MPa, respectively. In other words, the MOR was declined nearly 70 % with raising the holes' number from 1 to 3 (in sample cross section with 50 mm × 16 mm). This was due to the increased shear stresses within the webs during bending tests whilst the holes' number increased (Hein and Brancheriau 2018). As mentioned earlier, most of the shear forces are resisted by the web and most of the bending forces by the faces (like an I-beam). Increasing of holes number within constant cross sections of panels means thinner webs that cannot resist the created shear forces. Figure 8 also shows that the MOE in samples with up to 2 holes' parallel to the span of test pieces were significantly improved (in constant cross section of 50 mm × 16 mm). Further increasing the holes' number to 3, drastically reduced the MOE reaching to a value about 600 MPa. Referring to Figure 1, the webs width was smaller whilst the holes' number was increased. This means that more stresses during bending were concentrated in this region and thus created more shear stresses and decreasing the MOE.

As exhibited in Figure 8, bending properties (MOR and MOE) in samples with holes perpendicular to the span of test piece have similar trends like those with parallel holes to the span of test piece. Referring to Figure 8, the lowest bending properties were obtained for panels with 3 holes in constant cross section. It was observed during the bending tests that the samples with 3 holes were more shear-stressed in the central part. Improved bending properties in samples with 1 and 2 holes can be attributed to the increased density in their surface layers while still having a strong web structure.

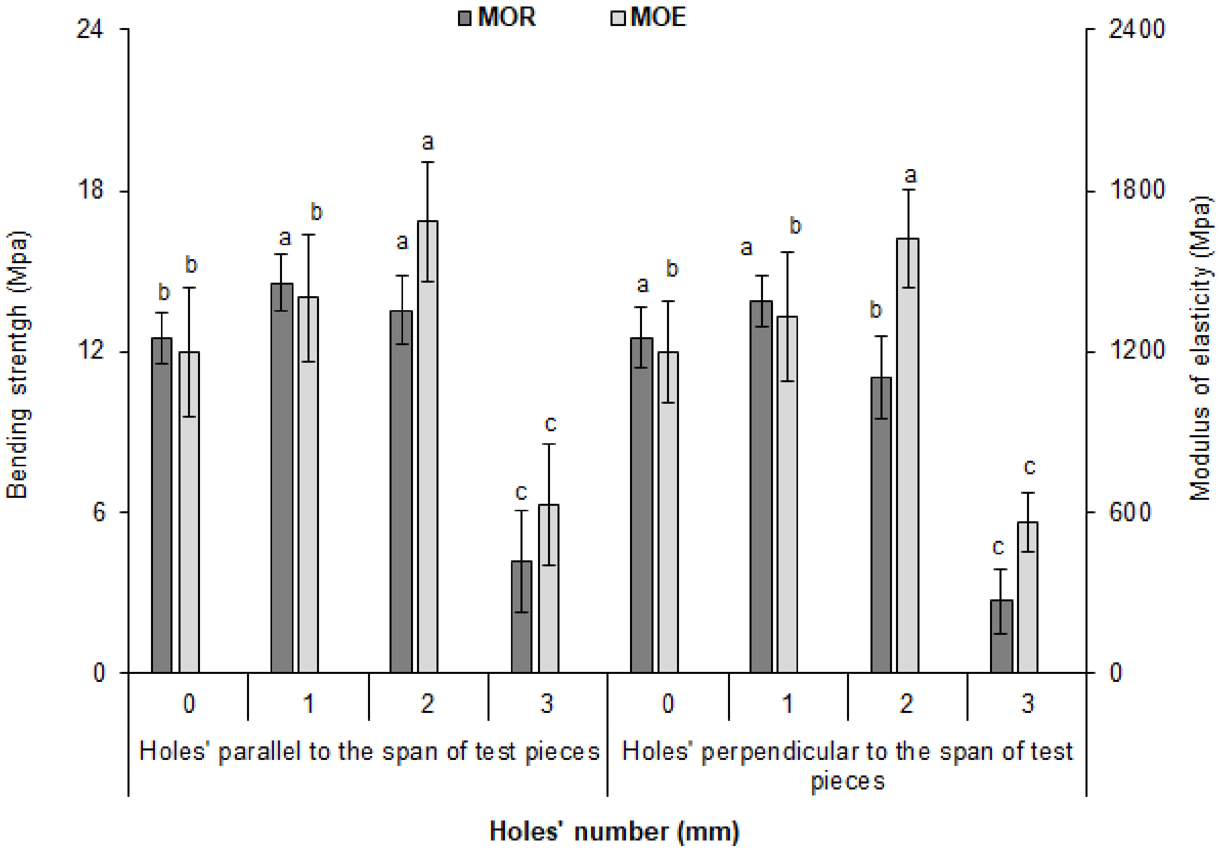


Figure 8: Bending strength and modulus of elasticity of the lightweight tubular fiberboard with various holes' number.

Figure 9 shows the IB values in lightweight tubular fiberboard with various holes' number. As shown, the IB values were significantly reduced with increasing the holes' number up to 3 in a constant cross section. As described, distance between the holes (webs width) was smaller when the holes' number increased. The transfer of fibers in the webs were probably reduced whilst the webs width were smaller. In other words, in addition to the existed holes in samples, the webs had possibly lower density than it was aimed. The lower the web density, the lower the IB values (Wong *et al.* 2000).

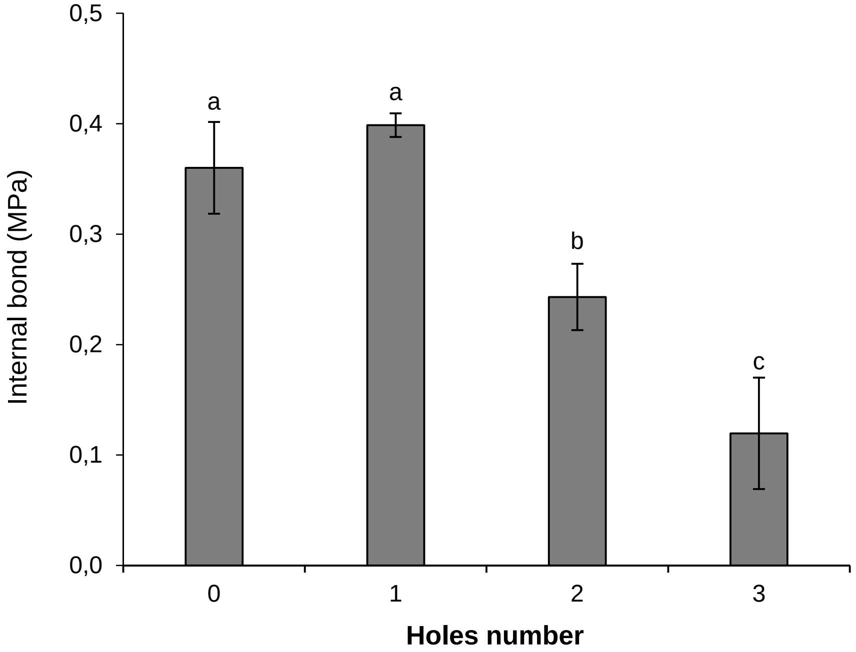


Figure 9: Internal bond values of lightweight tubular fiberboard with various holes' number.

Effect of holes' number on the SS of lightweight tubular fiberboard is pictured in Figure 10. The highest SS was observed at about 0,56 MPa for the samples with one hole. Increasing the holes' number reduced the SS, although the peak density at surfaces increased. Fractured samples showed that rupture occurred in core layer. This confirmed the webs weakness between the holes with increasing the holes' number. As described, fewer fibers were likely transferred in the webs between the holes.

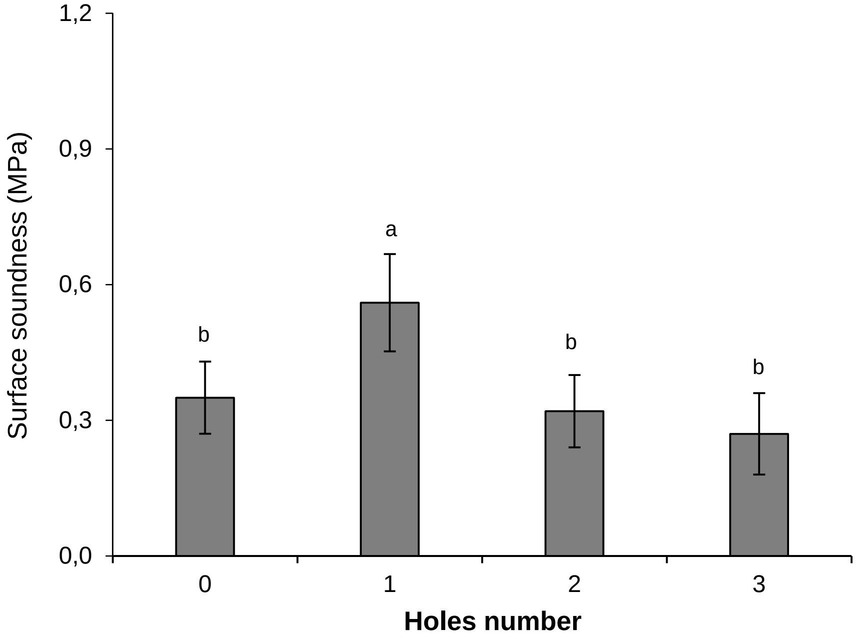


Figure 10: Surface soundness values of lightweight tubular fiberboard with various holes' number.

Physical properties

Effect of holes' number on thickness swelling (TS) and water absorption (WA) after submersion for 24 hours are presented in Figure 11. Thickness swelling was significantly reduced by increasing the holes' number from 1 to 3. The lowest TS ad WA (at 13,8 % and 82 %, respectively) were observed for panels having 2 holes in a constant cross section (50 mm × 16 mm). Considering the Figure 3, surface layers density in samples with 6 mm holes was increased about 27 % compared to that of reference sample. This resulted in less accessibility of water molecules to the OH groups of fibers and thus reduced the TS and WA (Shalbafan *et al.* 2013). Further raising of holes' number to 3 brought a negative effect on the TS and WA. The very narrow and weak webs can explain the trend observed in panels with 3 holes. It is possible that the webs had less density that significantly accelerated water absorption.

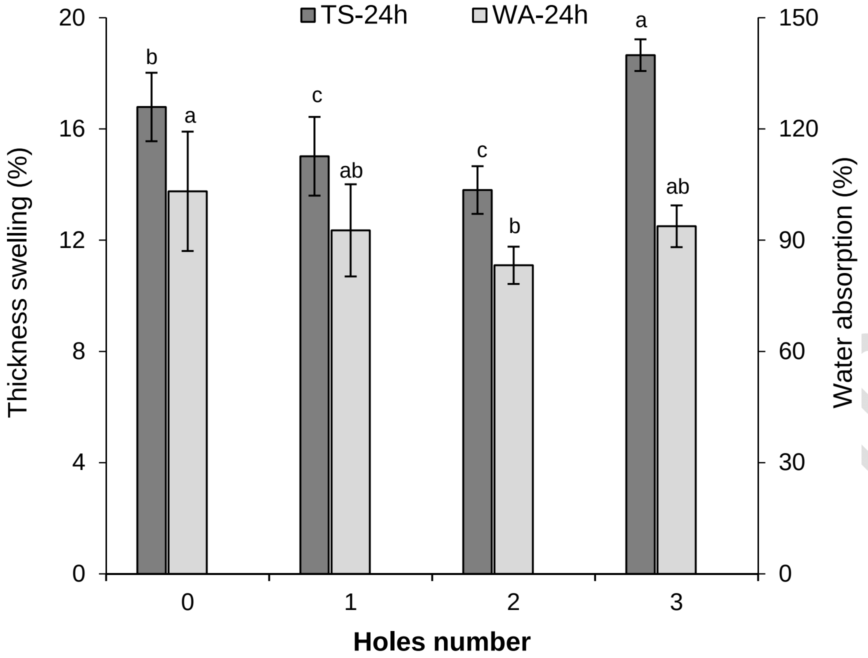


Figure 11: Thickness swelling and water absorption of lightweight tubular fiberboard with various holes' number.

The values of physical and mechanical properties of panels with 10 mm holes were compared with corresponding values in American and European standards (Table 2) to see the real potential for further application of developed lightweight tubular fiberboard. Referring to Table 2, the minimum requirements of bending properties according to ANSI A208/2 (2009), EN 312/P2 (2010) and EN 622-5/P1(1993) have been obtained in panels with 10 mm holes. Bending properties (MOR and MOE) in wood-based panels strongly influenced by their density and density profile (Wong *et al.* 1999). Hence, nearly 10 % lower MOR and MOE in lightweight panels in comparison to EN 622-5/P1 (1993) is due to their lower panel density (nearly 27 %).

The minimum requirements for IB are also obtained according to EN 312/P1 (2010) and EN 14755. Lower IB compared to those of EN 622-5/P1(1993) and ANSI A208/2 (2009) is surely due to the perforated structure in panels (Eckelman 1975; Sackey *et al.* 2008). A corresponding comparison in TS values showed that nearly similar TS achieved in lightweight tubular fiberboard compared to those of American and European standards. It should be noted that the isotropy and homogeneity of MDF, especially in boards' edges, allows intricate and precise machining and finishing techniques. Although, the edge homogeneity of lightweight tubular fiberboard is somehow reduced, but it still can be used for furniture application. In general, tubular core provides an ideal combination of lightweight and stability.

Table 2: Minimum requirements for different wood-based panels.

Standards	**MOE (MPa)**	**MOR (MPa)**	**IB (MPa)**	**TS (%)**
ANSI A208/2[a]	1241	12,4	0,47	11
EN 312/P1[b]	-	10	0,24	14
EN 312/P2[c]	1600	11	0,35	14
EN 14755[d]	-	4	0,17	-
EN 622-5/P1[e]	2200	20	0,55	12
Tubular fiberboard (10 mm hole)	1937	18,2	0,32	12

a) American standard for fiberboard (115) for interior application (<600 kg/m^3)
b) European standard for particleboard used for interior application (650 kg/m^3)
c) European standard for particleboard used for general purpose application (650 kg/m^3)
d) European standard for ES type tubular particleboard (550 kg/m^3)
e) European standard for medium density fiberboard for interior application (750 kg/m^3)

CONCLUSIONS

Lightweight tubular fiberboards were produced in a platen-pressed direction using round rods to create the holes. The results showed that the surface layers density and the quality of the webs between the holes had predominant influence on the board properties. The surface layers density were significantly improved by increasing the holes diameter. Holes number mostly influenced quality of webs between the holes. The higher the holes number, the lower the webs quality and accordingly the weaker boards was achieved. Briefly, superior values were obtained in panels with 10 mm holes diameter and 1 hole in a constant cross section (50 mm × 16 mm). A corresponding comparison of values with those in standard values showed that the minimum requirements according to the most of American and European standards (ANSI A208/2, EN 14755, EN 312/P1, EN 312/P2 and EN622-5/P1) were obtained.

In summary, this study showed that the lightweight tubular fiberboard has characteristic properties according to the holes structure (holes diameter and number). The optimum holes' structure can then be chosen to obtain the required board properties. Lightweight tubular fiberboard weighs approximately 30 percent less than conventional MDF and is perfect for furniture applications when the weight matters, although further research is needed to analyses the machinability characteristics of the boards.

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