THERMAL AND ACOUSTIC CHARACTERISTICS OF INNOVATIVE FOAM CORE PARTICLEBOARDS

*Ali Shalbafan**

Assistant Professor, PhD
Department of Wood and Paper Science and Technology
Faculty of Natural Resources and Marine Sciences,
Tarbiat Modares University, Noor, Iran
E-mail: ali.shalbafan@modares.ac.ir

Johannes Welling†

Senior Researcher, PhD
Thünen-Institute (TI) of Wood Research
Hamburg, Germany
E-mail: johannes.welling@thuenen.de

(Received November 2016)

Abstract. Innovative foam core particleboards have potential to be used for the thermal and sound insulation applications. The insulation properties of novel foam core particleboards (19 mm) produced with various production process parameters were analyzed in this study. It was revealed that both surface layer thickness of panels and press temperature were the two major parameters influencing the thermal properties of novel foam core particleboards. The lower the surface layer thickness, the better the thermal insulation. A higher thermal resistance was also obtained for panels produced with higher press temperature (160°C), due to their better structure for thermal resistance (less compaction of surface layers and higher foam cell density). Sound insulation characteristics of foam core particleboards revealed that the sound transmission loss (TL) and sound transmission class (TC) were enhanced by increasing the surface layer thickness from 3 to 5 mm. Changing press temperature, pressing and foaming times had no influence on the sound TL and TC. In general, the foam core panels having lower density (30-50% lower) than those of conventional panels showed promising thermal and sound insulation properties, while still, further modifications would be necessary.

Keywords: Acoustic property, thermal insulation, particleboard, lightweight panel, sandwich panel.

INTRODUCTION

Energy efficiency is one of the most important features for buildings to be continuously improved by research and technology innovation. Energy savings during not only production but also, in particular, the use phase of buildings is likely to provide the greatest benefits and in many cases will be the most economical option (Asdrubali et al 2016). Within the European Union (EU) countries, 40% of energy consumption and 36% of CO_2 emissions are associated with buildings. With improved energy efficiency in buildings, the total energy consumption of the EU can be reduced by 6% and CO_2 emission by 5% (Afram and Farrokh 2014; Fouquet et al 2015). The proper selection of materials used for building construction can enhance the energy efficiency in buildings. In comparison with the conventional panels, lightweight sandwich panels (having about 30-50% lower density) achieved attention both in the worldwide market and in the research area due to their multiple effects:

i. Reduction of overall greenhouse gases emissions (Feifel et al 2013).
ii. Improvement of resource efficiency and environmental sustainability (Chedeville and Diederichs 2015).
iii. Higher specific *strength* and stiffness than those of conventional panels (Davies 1993).
iv. Good thermal and sound insulation characteristics (Allen 1969; Moore and Lyon 1991).

* Corresponding author
† SWST member

The introduction of sandwich structures in the wood-based panel industry is rather slow mainly due to two main reasons: the high costs for material and process and specialized processing technology (Shalbafan et al 2013). High costs are caused either by labor-intensive production processes or by the substituting core material. In addition, specialized processing technology is needed for bonding the separate layers. An integrated one-step process for producing foam core sandwich panels has recently been developed to overcome these challenging factors (Luedtke 2011). This integrated approach has been derived from the conventional production principle of particleboards. The use of glue between the surface layers and a lightweight core layer is not needed anymore, due to the in situ foaming and simultaneous production of all layers in one single production step.

In addition to the application of the lightweight panels in the furniture industry, the specific design of sandwich panels has the potential to strengthen the applicability of foam core sandwich panels for roofs, separating walls, nonstructural uses, etc. (Kurtze and Watters 1959). Polymeric foams are known as conventional thermal insulators in building applications. They are normally sandwiched within a batch process between two wood-based panels (eg particleboard and oriented strand board). The foam in the middle of a sandwich panel contributes to insulating property; the millions of tiny air bubbles trapped in the foam stop the transmission of heat and sound through the panel. The rigid face layers add some thermal resistance as well (Gu and Sharp 2005). Generally, heat transfer occurs via gaseous convection and thermal conduction through solid matter and radiation. The convective heat transfer associated with the circulation of gases within a foam cell can be generally ignored and considered insignificant for cell diameters less than 4 mm (Collishaw and Evans 1994). The radiative heat transfer can be also neglected in foam core particleboards, due to the rigid face layers. Hence, the heat transfer in foam core panels is mainly governed by thermal conductivity (Kuhn et al 1992). It is worth mentioning that the geometrical structure (eg cell wall thickness, foam cell size, foam cell density) of cellular foams plays an important role in the study of thermal conductivity (Placido et al 2005). The insulation performances can be improved for a constant foam density by modifying suitable cell wall thickness, foam cell size, and most of all cell density (Kuhn et al 1992). It was shown that the cell morphology in the foam core layer of sandwich panels can be varied by changing the production process parameters of in situ foaming (Shalbafan et al 2016a). Hence, it is necessary to verify the effect of various foam cell morphologies on the thermal performance of foam core panels.

Furthermore, the sandwich panel is a useful way to improve the sound insulation, wherein the core acts as a spacer construction that has mass and that does transmit shear, whereas the skins respond as elementary bent plates (Zhu et al 2014). Sound insulation (reduction) can be achieved either by sound transmission loss (TL) and sound transmission class (TC) or by sound absorption (Moore and Lyon 1991). Sound absorption is mainly a surface phenomenon, but also depends on the size and shape of the panel. In sandwich structures, core materials generally do not contribute much to sound absorption since they have faces on both sides. However, they do contribute significantly to sound TL. Sound TL, also known as a sound reduction index, is the ability of a material to isolate a sound. The sound TL characteristics of building construction are recognized as one aspect of the total design criteria (Karlinasari et al 2012). Sound TL of gypsum bonded board (19 mm thickness) was below 40 dB in the frequency range of 50-5000 Hz (Ballagh 2004), whereas the sound TL for rice straw boards (20 mm thickness) were measured about 10-20 dB in the frequency range of 500-1000 Hz (Mediastika 2008). Sound TL is mostly affected by the mass and the dynamic stiffness of the structures. A high mass to stiffness ratio usually produces a high TL. Dynamic stiffness of sandwich structures is strongly dependent on frequency and decreases with increasing frequency, due to the presence of the core layer. Therefore, the sound TL of foam core panels can be much different from that of single-layer panels.

The aim of the proposed study is the determination of the sound and thermal insulation properties of novel foam core particleboards, which have been produced by a one-step process using different processing parameters (press temperature, pressing time, and foaming time). Within this research, the thermal conductivity (λ) and thermal resistance (R) were measured for analyzing the thermal insulation of the foam core panels. For the characterization of the acoustic performance, common parameters such as sound TL and sound TC were determined.

MATERIALS AND METHODS

Face and Core Materials

Conventional wood particles (mainly spruce and pine) for the face layers were supplied from a particleboard mill (Rauch Spanplattenwerk GmbH, Markt Bibart, Germany). Wood particles (having dimension of ≤2 mm) were mixed with 12% urea formaldehyde resin (Kaurit 350 from BASF, Ludwigshafen, Germany) based on the oven-dry mass of particles. One percent ammonium sulfate based on solid content of resin was added as a hardener. The adhesive and hardener were sprayed onto the particles furnish tumbling in a rotating drum-type blender by using a compressed air spray head. The target density for the bottom and surface layers was calculated as 750 kg/m^3. Three different face layers (3, 4, and 5 mm) were used for panel production. Density and thickness of the surface and bottom layers were identical in each panel.

It should be noted that increasing the surface layer thickness more than 5 mm was not easy to perform in the laboratory scale. Increasing the surface layer thickness means decreasing of core layer thickness (within a constant panel thickness of 19 mm). Minimum amount of core layer materials is needed for a homogeneous scattering during the mat forming. A homogeneous scattering during the core layer formation was not possible to reach, if the surface layer thickness increased by more than 5 mm.

The heat-sensitive material for the core layer was an expandable polystyrene granulate (EPS) named Terrapor 4, which was supplied by Sunpor Kunststoff GmbH, Sankt Pölten, Austria. The *activation* temperature for the EPS was 95°C. Granulate diameter of EPS beads was 0.3-0.8 mm. The calculated target density of the foam core layer was 124 kg/m^3. The core layer thicknesses were varied between 13, 11, and 9 mm, depending on the thickness of surface and bottom layers.

Production of the Panels

Foam core particleboards (19 mm thickness) were produced from a three-layered mat without additional gluing between the face and core layers. The resinated wood particles for the faces were laid by hand within the forming box of 700 × 600 mm^2. The EPS for the core layer was also laid manually between the two surfaces after the bottom and before the top surface layer was formed. The three-layered mat was then pressed in a computer-controlled lab-scale single-stage opening hot press (Siempelkamp, Krefeld, Germany) with the press area of 800 × 600 mm^2. The press cycle consisted of three consecutive phases; pressing phase, foaming phase, and stabilization phase. The simulation of a continuous hot press with a cooling zone for stabilization of the core layer was achieved by controlling the pressing schedule and initiating the internal cooling of the press plates after approximately 1/3 of pressing cycle.

A previous study (Shalbafan et al 2013) showed that the foaming conditions (press temperature, press, and foaming times) are crucial parameters influencing the properties of the foam core panels and especially the foam cells' structure. Hence, two different sets of foaming conditions (named group 1 and group 2) were used for panels' production. The temperature of the press plates was set at 130°C (group 1) and 160°C (group 2). The pressing time, foaming time, and

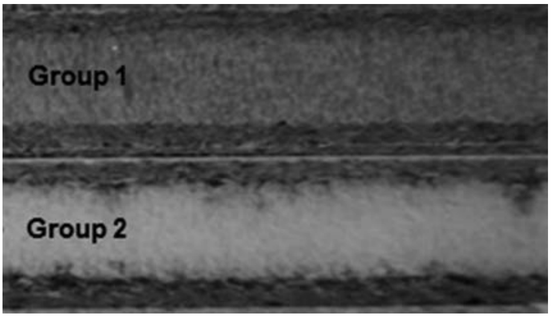

Figure 1. Foam core particleboards produced with different press temperature of 130°C (group 1) and 160°C (group 2).

stabilization time were accordingly changed by varying the press temperature from 130°C to 160°C. For instance, at low press plate temperature (130°C), the foaming time naturally was longer (45 s) than at the higher press temperature (160°C with 10 s), because of the less-intense heat penetrating from the surfaces to the thermosensitive materials in the core. The resultant constitution of the foam formed at 130°C was like molten plastic with a glassy state, whereas the texture of the foam produced at 160°C resembled EPS foams for packaging applications (Fig 1). For each press temperature program, three surface thicknesses (3, 4, and 5 mm) with three repetitions were produced (total of 18 panels) for each series of test (sound test, thermal test, and mechanical test). Table 1 shows the composition of the variables.

Sample Preparation and Testing Procedures

All samples were kept in a conditioning chamber at 65% RH and a temperature of 20°C for 2 wk prior to testing. For panels' characterizations, the microstructure of the foams, density, and MOR for bending strength according to EN 323 (for minimal 9 valid samples with dimension of 50 × 50 mm^2) and EN 310 (for minimal nine valid samples with dimension of 430 × 50 mm^2) had been carried out. The vertical density profile of foam core panels was also determined using gamma-ray densitometry (Raytest GmbH, Straubenhardt, Germany) with measuring steps of 75 μm. The micrographs of the foams were taken with a Quanta field-emission scanning electron microscope (FE-SEM, Quanta FEG 250, Oregon, USA) at an acceleration voltage of 5 kV. After gluing the samples on support pieces (12 × 8 mm^2), the surfaces were coated with gold prior to microscopy characterization. Foam cell numbers were measured within an area of 4 mm^2 in the middle of the foam. The foam cell density was calculated according to Eq 1 proposed by Han et al (2003).

$$D_{\text{cell}} = \left(\frac{N \times M^2}{A}\right)^{3/2} \tag{1}$$

where D_{cell} is the foam cell density (cells/cm^3), N is the cell number in the defined area, M is the microscope magnification, and A is the measured area (mm^2). One sample was randomly selected from each panel repetition ($n = 3$) and their average value was accounted as cell density.

Thermal performance of foam core particleboards was determined using steady state guarded hot plates according to the methods described in EN 12667 (2001). For analyzing the thermal insulation, thermal conductivity (λ) and thermal resistance (R) of the lab-manually fabricated foam core particleboards were recorded. The sample

Table 1. Technological parameters of the 19-mm foam core particleboard variables.

Specification		Panel density (kg/m^3)	Face thickness (mm)	Core thickness (mm)	Press temperature (°C)	Pressing time (s)	Foaming time (s)
A	Group 1	320	3	13	130	80	45
B		390	4	11		105	
C		460	5	9		130	
D	Group 2	320	3	13	160	45	10
E		390	4	11		55	
F		460	5	9		65	

size used for measuring the thermal performance was 600 × 580 mm^2. Two of the foam core panels (each with a nominal thickness of 19 mm) were put together on the guarded hot plates to measure the thermal parameters (λ and *R*). The thermal resistance (*R*) was calculated according to the equation:

$$R = \frac{T}{\lambda} \tag{2}$$

where *R* is the thermal resistance (m^2·K/W), *T* is the thickness of the two foam core panels on the guarded hot plates (m), λ the thermal conductivity (W/m·K).

The acoustic properties were characterized by airborne sound insulation using the methodology described in EN ISO 140-3 (2005) (the pressure method). The testing was carried out in the reverberation room in the FCBA Physics Laboratory in Bordeaux, France. The required sample size for testing was 1300 × 600 mm^2, which was achieved by connecting two laboratory panels (800 × 600 mm^2) using tongue and groove joint. Then, the panel was positioned as a wall with an opening between the two rooms in the testing area. One room with a volume of 75 m^3 was the sound source room (emission room) and contained the noise generator. The other room with a volume of 80 $m^3$was the receiving room (reception room). The temperature and humidity in both rooms were 18.5°C and 77%, respectively. The sound pressure level was measured using one-third-octave band filters having the center frequencies ranged from 100 to 5000 Hz. The sound TL and sound TC were determined for characterizing of the acoustic performance. Sound TL is defined as the logarithm ratio of the acoustic incident energy to acoustic energy transmitted through the wall, in decibels (dB). It was calculated based on the following equation:

$$\mathrm{TL} = L_1 - L_2 + 10\log\left(\frac{S}{A}\right) \tag{3}$$

where TL is the sound TL (dB), L_1 is the energy average sound pressure level (dB) in the source room, L_2 is the energy average sound pressure level (dB) in the receiving room, *S* is the area (m^2) of the free test opening in which the test element is installed, *A* is the equivalent sound absorption area (m^2) in the receiving room. *Good soundproofing insulation* is determined by low energy being transmitted through the wall.

Single-number quantities or sound TC of airborne sound insulation from one-third-octave bands for foam core panels was determined using ISO 717-1 (2013). Furthermore, two spectrum adaptation terms ($C = -1$ and $C_{tr} = -2$) were calculated based on two typical spectra within the frequency range up to 5000 Hz. Spectrum adaptation terms (C and C_{tr}) use a standard reference curve according to the ISO 717-1 to determine the weighted value of airborne sound insulation.

The data analysis for thermal analysis was performed at the end of the study using statistical package for the social science (SPSS software, IBM). After approval of the data normality assumption, Leven test for checking the homogeneity of variances was applied. At this stage, given the assumptions to be approved, parametric ANOVA tests were performed to evaluate possible significant differences between the panel properties with different pressing schemes. Statistical differences between variations were done by multiple comparisons using Duncan test depending on variance status. And the *p*-value level of statistical significance was set at $p < 0.05$.

RESULTS AND DISCUSSION

Foam Cell Density

The cell density of the foam core layer was calculated and the results are presented in Fig 2. Each point presented in Fig 2 is an average of three samples measurement (one from each panel repetition). It is visible that the cell density of panels of group 2 is significantly higher than those of group 1, because of press temperature and time differences. Calculated cell density within a specified area (4 mm^2) is a function of

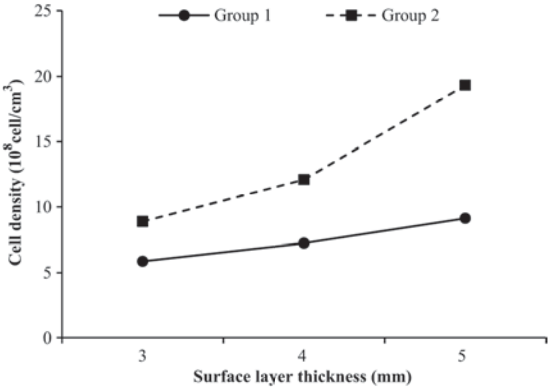

Figure 2. Foam cell density of foam core panels.

cell numbers, which is influenced by the cell size. There are various factors known to affect the size, number, shape, and uniformity of the cells in polystyrene foam (eg amount and type of blowing agents, nucleation agents, and production process). Increased levels of blowing and nucleation agents are known to increase the cell size (Han et al 2003); however, their contents and types were held constant in this study. It has to be noticed that the process parameters (eg foaming temperature and time) were changed in this study. The press temperature was increased from 130°C (group 1) to 160°C (group 2), whereas the foaming time was nearly halved. Lower press temperature or longer foaming time is known to yield foams with larger average cell size and lower cell density (Shalbafan et al 2013). An increase in the pressing temperature results in faster foaming of EPS and, accordingly, smaller and more uniform foam cells are achieved (Doroudiani and Kortschot 2003). The higher the foam cell density in a specified area (smaller foam cell sizes), the higher a foam insulation performance can be (Ionescu 2005). Increasing the surface layer thickness leads to an increased foam cell density. This is attributed to the fact that more steam is generated from the thicker surface layers and which travels toward the expandable heat-sensitive materials in the core. The higher the MC, the smaller is the resulting cell size (Shalbafan et al 2013).

Mechanical Characterization

The vertical density profile reflects changes in density over the panel thickness. Figure 3 shows two density profiles of panels (code B and E) with similar surface layer thicknesses (4 mm), which were produced by varying pressing parameters. Both panels had the same mean density of 390 kg/m^3. Although asymmetric density profile was observed for each panel, more compact surface layers were observed for panels produced with lower press temperature (group 1). The formation and shape of the density profile over the cross-section of panels during hot pressing influences most of the panel's properties (Plath and Schnitzler 1974; Geimer et al 1975).

The results for MOR for bending strength of foam core panels are presented in Table 2. It shows that the bending strength is slightly enhanced by increasing the surface layer thickness for both panel types (group 1 and group 2). The findings also display that the average bending strength of samples produced by lower press temperature (group 1) is approximately 10% higher than bending strength of group 2 samples. Mechanical properties of the foam core panels are affected by the surface layer quality as well as by the foam morphology (Gibson and Ashby 1982; Gendorn 2005). The compact surface layers, as observed in group 1 of panels, are the reason for their high bending strength. Additionally, a thicker foam cell wall thickness can

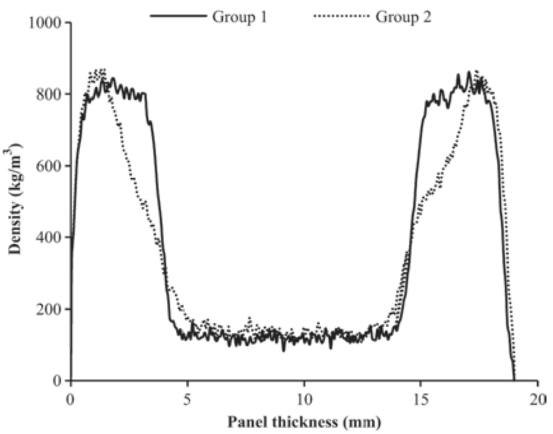

Figure 3. Density profile of foam core panels.

Table 2. Bending strength and actual density of foam core panels.

	Actual density (kg/m^3)		MOR for bending strength (N/mm^2)	
Face layer thickness (mm)	130°C (group 1)	160°C (group 2)	130°C (group 1)	160°C (group 2)
3	332	328	9.01	8.23
4	395	394	9.95	9.15
5	459	462	11.52	10.61
Conventional particleboard (19 mm)[a]	650		13	

[a] According to EN 312/P2.

be expected for group 1 panels due to their larger cell size (while the target density of the core layer is kept constant in both groups). The thicker the cell wall of the foam core, the higher the mechanical properties of the foam core particleboard panels (Shalbafan et al 2016a).

Thermal Insulation

Thermal conductivity (λ) of foam core panels was measured as an important thermal insulation index and the results are presented in Fig 4. The graphs show that the λ of panels was significantly raised by the increasing surface layer thickness in both panel groups. In group 1 panels, the λ was increased from 0.063 W/m·K for panels having 3 mm surface layer to 0.075 W/m·K for a panel having 5 mm surface layer thickness. In group 2 panels, the λ was increased from 0.057 W/m·K (3 mm surface layer thickness) to 0.071 W/m·K (5 mm surface layer thickness). It can be said that the λ was increased approximately 5% for each millimeter increase of surface layer thickness. Increasing surface layer thickness led to the rise of the panels' density from 320 to 460 kg/m^3. It was stated that the λ values of wood-based specimens generally rise in correlation with an increase of panel density (Kamke and Zylkowski 1989; Kawasaki and Kawai 2006). Hence, the concept of lightweight wood-based panels improves the thermal insulation. The lower the panel density, the better the insulating performance (due to the three layers in the panels' structure).

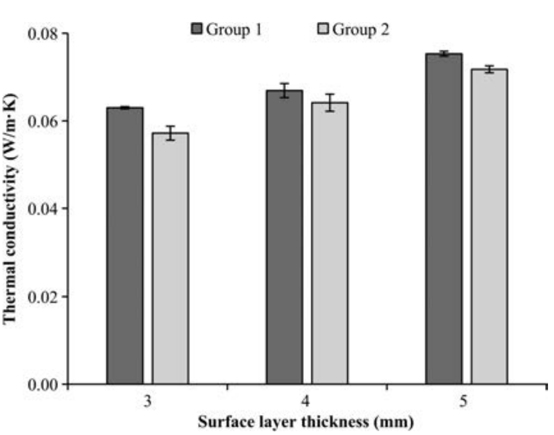

Figure 4. Thermal conductivity values of foam core panels.

A comparison of panels in group 1 and 2 shows that the λ for panels produced with higher press temperature (160°C) is significantly (statistical analysis) lower than the λ of panels manufactured with lower press temperature (130°C). Since the thickness and density of the corresponding panels are similar, such differences can be attributed to the panels' structure (density profile and foam cell morphology). As mentioned earlier, the panels produced by lower press temperature (group 1) had denser surface layers compared with those of group 2 of samples. Denser surface layers lead to a better heat transmission through the wood particles. In other words, the lower conductivity is most likely due to the loose contact between adjacent wood particles in the surface layers of the group 2 panels. Furthermore, the cell density of the foam can influence the λ of panels. The cell density of group 1 panels was lower than the cell density of group 2 panels. This means that the foam cell numbers were lower in group 1 samples, and accordingly, the foam cell size was larger. Lower cell numbers and large cells size within a constant foam density (124 kg/m^3) correspond to a thicker foam cell wall (Shalbafan et al 2016b). A thicker foam cell wall absorbs and transfers more heat than a thin one (Boetes 1984). Hence, the thicker the foam cell wall, the higher the λ value can be.

Total heat transmission through a wall can be characterized by its thermal resistance (*R*). *R* is defined as the thickness (in meter) divided by λ. Comparing the *R* values of different materials is a useful approach when the materials are used with a distinct thickness and density in building applications. A higher value of *R* means better thermal insulation. The calculated *R* values of foam core panels are illustrated in Fig 5. It can be seen that by increasing the surface layer thickness, the *R* values is significantly (statistical analysis) reduced in both sample groups. It has to be noticed that the increasing surface layer thickness from 3 to 5 mm was accompanied with the decrease of the foam core layer thickness from 13 to 9 mm. It is well understood that polymeric foams like polystyrene have better thermal resistance, and accordingly, higher insulation performance than wood and wood-based panels. The lower the surface layer thickness (means higher core layer thickness) within a constant panel thickness (19 mm), the better the thermal insulation is. A higher *R* value is also obtained for panels produced with higher press temperature (160°C) due to the formation of a more favorable structure for thermal resistance (less compaction of surface layers and higher foam cell density).

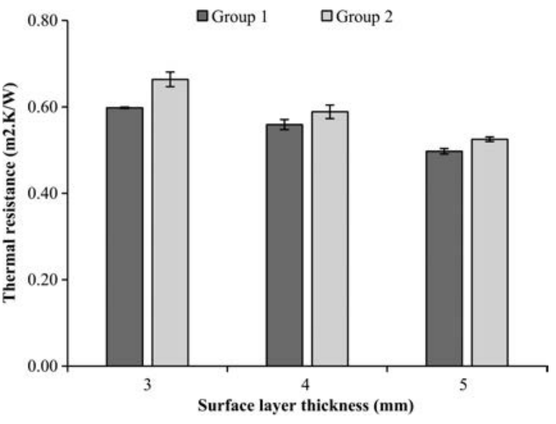

Figure 5. Thermal resistance values of foam core panels.

Generally, warmth-keeping performance has a proportional relation to λ and an inversely proportional one to *R* (Kawasaki and Kawai 2006). Hence, a low λ and high *R* mean better warmth-keeping performance in terms of insulation in the nonsteady state condition of heat flow. It can be concluded that the process parameters (eg press temperature, face layers thickness, and pressing and foaming times) have an effective influence on the insulation properties of foam core panels.

Acoustic Performance

The sound TL is the most important physical indicator defining the acoustical quality of buildings and its airborne sound insulation properties. The sound TL measurement for lightweight foam core particleboard with 19 mm thickness is presented in Fig 6. The experimental results showed that at low (f = 100-500 Hz) and medium (f = 500-1000 Hz) frequencies, the sound TL value varied between 13 dB and approximately 30 dB for the 19-mm-thick panels. The foam core panels with 3-mm face thickness had the lowest sound TL level. The

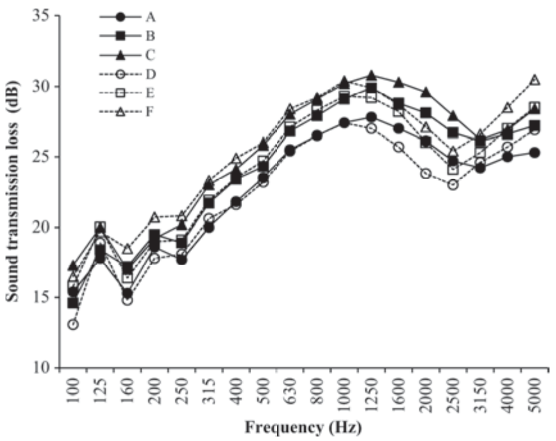

Figure 6. Sound transmission loss values in the frequency range of 100-5000 Hz for 19-mm-thick foam core panels (solid lines denote panels in group 1 (130°C) with face layer thickness of 3 mm (code A), 4 mm (code B), and 5 mm (code C); dashed lines denote panels in group 2 (160°C) with face layer thickness of 3 mm (code D), 4 mm (code E), and 5 mm (code F).

sound TL values were higher for panels with thicker surface layers (5 mm). The thicker the surface layer, the less the sound was transmitted through the panel. The highest TL was obtained for panels with 5-mm face thickness (code C and F). The TL values did not significantly vary for high frequencies (>1000 Hz). It has to be also noticed that the TL did not change in corresponding samples of group 1 and 2. This means that the foam morphology had no influence on the TL. This can be due to the closed porosity of polystyrene foam cells. It has to be noticed that the aim of using such novel structure for panel production was not only for the sound insulation purposes. The main idea was developing a lightweight particleboards to be used for the furniture industry, while improving the insulation properties.

Transmission of sound through a panel depends on several factors such as density, thickness, and material stiffness. The sound TL of homogeneous panels is controlled by the mass per unit area of the panel surface in what is well known as the "mass law." In other words, the level of acoustic insulation of a panel depends on the mass law. The heavier the panel, the better is its acoustical insulation performance (Fahy 1985; Rudder 1985). It has to be considered that the theoretical rule is applied to materials within a certain frequency range. The sound TL values generally depend on the panels' stiffness at low frequencies. Panels tend to bend as the sound waves strike the panels at low frequencies. Hence, stiffer panels show more resistance to bending while the sound waves strike them. In this study, the panels with lower surface layer thickness showed a lower bending stiffness when the sound waves struck the panels. This resulted in lower values of the sound TL (<13 dB), especially for the panels with 3-mm face thickness. The sound TL is raised with the mass of the panel at frequencies ranged from 500 to 1000 Hz (medium frequencies). The panel with thicker faces (5 mm) showed better insulation, especially at frequencies close to 1000 Hz. The sound TL at high frequencies (>1000 Hz) always follows the mass law (Karlinasari et al 2012). The mass law describes a good working rule to predict the airborne sound insulation of a panel until the "coincidence" effect occurs. When the wavelength of the sound in air is similar to the bending waves in panels, the coincidence effect normally happens (Bucur 2006). In another word, the coincidence effect happens in the critical frequency which has not been observed within this study as presented in Fig 6, in which the sound TL values continued to increase with an oscillation up to a frequency of 5000 Hz. A reduction of 20-30% at medium to high frequency (1000-3000 Hz) was observed, probably produced by the mechanical impedance of the wall and by the energy dissipation properties of the constitutive materials (Bucur 2006).

It is worth to compare the results of this study with those of the previous ones to get a better overview of the acoustical performance of foam core panels. Mediastika (2008) revealed that the sound TLs for rice straw boards (20-mm thickness) were about 10 and 20 dB at a frequency of 500 and 1000 Hz, respectively. Ballagh (2004) also presented that sound TL of gypsum-bonded board (19-mm thickness) had a sound TL below 40 dB in the frequency range of 50-5000 Hz. In general, it can be said that the foam core panels had moderate sound insulation properties than those of other conventional panels, because their sound TLs were between 15 and 30 dB in the frequency range of 50-5000 Hz (Fig 6).

Sound TC is the single-number rating for airborne sound TL, which is presented in Table 3. The sound TC values for 19-mm-thick panels were slightly increased by thickening the face layers from 3 to 5 mm in both panel groups. Panels having 5-mm face layer thickness seemed to possess highest sound TC value, followed by

Table 3. The sound TC value of 19-mm-thick foam core panels.

	Sound TC(dB)	
Face layer thickness (mm)	130°C (group 1)	160°C (group 2)
3	25	25
4	26	26
5	27	27

TC, transmission class.

face layer thickness of 4 and 3 mm. A sound TC of at least 25 is needed for wood frame interior partition design (Rudder 1985) which was also observed in foam core panels. Referring to the study findings, foam core particleboard having a different surface layer thickness showed good potential for development as insulation panels and for novel applications eg wall sheathing and subflooring in wood frame construction. Nevertheless, further research and modifications are necessary to enhance the sound insulation property of this type of panels.

CONCLUSION

The thermal and acoustical performance of 19-mm-thick foam core panels was determined within this study using various production process parameters. Results showed that the production process parameters (eg press temperature, face layer thickness, pressing and foaming times) have a significant influence on the thermal insulation properties of foam core panels. The λ and R of the foam core panels were influenced by the panel characteristics eg panel density, density profile, and foam cell morphology. Better thermal insulation was obtained in panels produced by higher press temperature (160°C) and having lower face layers thickness (3 mm).

The sound TL and TC obtained were used for analyzing the acoustical performance of foam core panels. The results showed that the thicker the surface layer thickness (heavier panel), the better the acoustical insulation performance is. Additionally, different foam morphology showed no influence on the sound TL. Foam core particleboard having different surface layer thickness showed good potential for applications where the weight reduction would be of high importance (eg wall sheathing and subflooring in wood frame construction). In general, to sustain a pleasant indoor environment (good thermal and acoustic insulation) that is independent of outdoor environment fluctuations, panels need to be developed that have superior thermal and acoustical insulation abilities (lower λ, higher R, higher sound TL and TC).

ACKNOWLEDGMENTS

The authors would like to thank Dr. Frédéric Wielezynski from Institut Technologique FCBA (Bordeaux, France) for providing advice and laboratory facilities for carrying out this research. We also would like to express our gratitude to the organizers of the EU project "Trees4Future" for providing the platform for provision of access to specific laboratory infrastructure. Tarbiat Modares University, Iran is also acknowledged for providing funds for compensation of materials expenses.

REFERENCES

Afram A, Farrokh JS (2014) Theory and applications of HVAC control systems: A review of model predictive control (MPC). Build Environ 72:343-355.

Allen HG (1969) Analysis and design of structural sandwich panels. Oxford, Pergamon, UK.

Asdrubali F, Bianchi F, Cotana F, D'Alessandro F, Pertosa M, Pisello AL, Schiavoni S (2016) Experimental thermo-acoustic characterization of innovative common reed bio-based panels for building envelope. Build Environ 102:217-229.

Ballagh KO (2004) Accuracy of prediction methods for sound transmission loss. The 33rd International Congress and Exposition on Noise Control Engineering, August 22-25, Prague, Czech Republic.

Boetes R (1984) Heat transfer reduction in closed cell polyurethane foams. Dissertation, Technische Hogeschool, Delft, The Netherlands.

Bucur V (2006) Acoustic of wood. 2nd ed, Springer-Verlag, Berlin Heidelberg, Germany.

Chedeville CG, Diederichs S (2015) Potential environmental benefits of ultralight particleboards with biobased foam cores. Int J Polym Sci 2015:14. Article ID 383279.

Collishaw PG, Evans JRG (1994) Review, an assessment of expressions for the apparent thermal conductivity of cellular materials. J Mater Sci 29:2261-2273.

Davies JM (1993) Sandwich panels. Thin Wall Struct 16:179-198.

Doroudiani S, Kortschot M (2003) Polystyrene foams. I. Processing-structure relationships. J Appl Polym Sci 90:1412-1420.

EN 310 (1993) Wood-based: Determination of modulus of elasticity in bending and of bending strength. European Committee for Standardization, Brussels, Belgium.

EN 312 (2010) Particleboards. Specifications. European Committee for standardization, Brussels, Belgium.

EN 323 (1993) Wood-based panels: Determination of density. European Committee for Standardization, Brussels, Belgium.

EN 12667 (2001) Thermal performance of building materials and products. Determination of thermal resistance by means of guarded hot plate and heat flow meter methods. Products of high and medium thermal resistance. European Committee for Standardization, Brussels, Belgium.

EN ISO 140-3 (2005) Acoustics - Measurement of sound insulation in buildings and of building elements - Part 3: Laboratory measurements of airborne sound insulation of building elements. European Committee for Standardization, Brussels, Belgium. Fahy F (1985) Sound and structural vibration: Radiation, transmission and response. Academic Press, London and Orlando, FL.

Feifel S, Poganietz WR, Schebek L (2013) The utilization of light weight boards for reducing air emissions by the German wood industry: A perspective? Environ Sci Eur 25(5):1-12.

Fouquet M, Levasseur A, Margni M, Lebert A, Lasvaux S, Souyri B, Buhé C, Woloszyn M (2015) Methodological challenges and developments in LCA of low energy buildings: Application to biogenic carbon and global warming assessment. Build Environ 90:51-59.

Geimer RL, Montrey HM, Lehmann WF (1975) Effects of layer characteristics on the properties of three layer particleboards. Forest Prod J 25(3):19-29.

Gendorn R (2005) Thermoplastic foam processing: Principal and development. CRC Press, Washington, DC.

Gibson LJ, Ashby MF (1982) The mechanics of three-dimensional cellular materials. P Roy Soc Lond A Mat. 382:43-59.

Gu HM, Sharp AZ (2005) Geometrical model for softwood transverse thermal conductivity. Part 1. Wood Fiber Sci 37(4):699-711.

Han X, Zeng C, Lee J, Koelling KW, Tomasko DL (2003) Extrusion of polystyrene nanocomposite foams with supercritical CO_2. Polym Eng Sci 43:1261-1275.

Ionescu M, ed (2005) Chemistry and technology of polyols for polyurethanes. Smithers Rapra Technology Limited, Shrewsbury, UK.

ISO 717-1 (2013) Acoustics: Rating of sound insulation in building and of building elements. Part 1: Airborne sound insulation. International Organization for Standardization, Geneva, Switzerland.

Kamke FA, Zylkowski SC (1989) Effects of wood-based panel characteristics on thermal conductivity. Forest Prod J 39:19-24.

Karlinasari L, Hermawan D, Maddu D, Martianto B, Lucky IK, Nugroho N, Hadi YS (2012) Acoustical properties of particleboards made from betung bamboo (*Dendrocalamus asper*) as building construction material. BioResources 7(4):5700-5709.

Kawasaki T, Kawai S (2006) Thermal insulation properties of wood-based sandwich panel for use as structural insulated walls and floors. J Wood Sci 52:75-83.

Kuhn J, Ebert HP, Arduini-Schuster MC, Buttner D, Fricke J (1992) Thermal transport in polystyrene and polyurethane foam insulations. Int J Heat Mass Trans 35(7):1795-1801.

Kurtze G, Watters B (1959) New wall design for high transmission loss or high damping. Acoust Soc Am 31(6):739-748.

Luedtke J (2011) Development and evaluation of a concept for the continuous production of lightweight panels comprising a polymer core and wood-based panel facings. Dissertation. Hamburg University, Germany.

Mediastika CE (2008) Kualitas akustik Panel dinding berbahan bakujerami. Dimensi 36(2):127-134.

Moore JA, Lyon RH (1991) Sound transmission loss characteristics of sandwich panel constructions. Acoust Soc Am 89(2):777-791.

Placido E, Arduini-Schuster MC, Kuhn J (2005) Thermal properties predictive model for insulating foams. Infrared Phys Technol 46(3):219-231.

Plath L, Schnitzler E (1974) The density profile: A criterion for evaluating particleboard. Holz Roh Werkst 32(11):443-449.

Rudder FFJr (1985) Airborne sound transmission loss characteristics of wood-frame construction. General Technical Report FPL-43, USDA Forest Service, Madison, WI.

Shalbafan A, Luedtke J, Welling J, Fruehwald A (2013) Physiomechanical properties of ultra-lightweight foam core particleboards: Different core densities. Holzforschung 67(2):169-175.

Shalbafan A, Chaydarreh KC, Welling J (2016a) Development of a one-Step process for production of foam core particleboards using rigid polyurethane foam. BioResources 11:9480-9495.

Shalbafan A, Rheme M, Thoemen H (2016b) Ultra-light particleboard; characterization of foam core layer by digital image correlation. Eur J Wood Wood Prod 1-11.

Zhu X, Kim BJ, Wang Q, Wu Q (2014) Recent advances in the sound insulation properties of bio-based materials. BioResources 9(1):1764-1786.