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EFFECT OF EXPANDED POLYSTYRENE CONTENT AND PRESS TEMPERATURE ON THE PROPERTIES OF LOW-DENSITY WOOD PARTICLEBOARD

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ABSTRACT

In this study, three-layer low-density (about 400 kg/m^3) particleboards consisting of a mixture of wood particles and expanded polystyrene (EPS) were manufactured. EPS bead was incorporated in the core layer as a light filler. The influence of EPS content (0 %, 2,5 %, 5 %, 7,5 %, 10 % and 12,5 %) and press temperature (110 °C and 140 °C) on the microstructure, density profile, bending properties, internal bond and thickness swelling of the panels was investigated. Results showed that incorporation of EPS beads filled in the voids between wood particles, improved the core layer integrity, and generated a more pronounced density profile. Consequently, the bending properties and internal bond of panels adding EPS were remarkably improved, and the thickness swelling was decreased. However, the variation of the amount of EPS from 2,5 % to 12,5 % had no significant effect on the bending properties and thickness swelling. Comparing the two press temperatures, although higher temperature (140 °C) was more favourable in control panels without EPS as filler, it had a negative effect on the properties of panels with addition of EPS filler, especially for high EPS contents (10 % and 12,5 %), attributing to the shrinkage of EPS bead under press temperature that is much higher than its glass transition temperature (104 °C).

Keywords: Density profile, expanded polystyrene (EPS), low-density particleboard, mechanical properties, microstructure, press temperature,

INTRODUCTION

Global wood-based panel industries have undergone a rapid growth in recent years. Inevitably, such increasing demand put strain on the wood supply. Nowadays, density reduction becomes a topical issue in wood-based panels industry due to limited supply and increased price of wood material (Benthien and Ohlmeyer 2016). As one of the most important types of wood-based panel, particleboard is increasingly used in furniture and interior decoration, especially in custom furniture sector in China. The mean density of conventional particleboards usually ranges between 600 kg/m^3 and 750 kg/m^3 (Thoemen *et al.* 2010). Development of lightweight particleboards (density below 600 kg/m^3) bring many advantages such as more efficient utilization of wood, easier transportation and handling, lower transportation cost due to mass reduction (Barbu 2016; Monteiro *et al.* 2018).

Simply using less amount of wood for panel manufacture leads to less compacted and density-reduced particleboard accompanied by deterioration of properties. Meanwhile, there will be a significant increase in the proportion of voids and empty spaces between wood particles (Bajzová *et al.* 2018). Incorporation of non-wood light filling materials (e.g. expanded polystyrene, foamed starch or even popcorn) in the core layer of particleboard is one strategy to achieve the light construction of panels (Monteiro *et al.* 2016; Monteiro *et al.* 2019). It is expected that the light fillers can fill up the voids and pores, making the structure of the panel more uniform and therefore counteracting the decreased properties (Dziurka *et al.* 2015). Sundquist and Bajwa (2016) investigated the use of dried distillers grains with solubles (DDGS) as a functional filler in particleboards and manufactured the products with an average density of 580 kg/m^3 to 640 kg/m^3. The results show that concentration of 5 weight percent (wt%) DDGS produced superior properties compared to the control panel concerning water absorption and mechanical tests. Thus, light fillers play an important role in improving the performance of the low-density panels.

EPS bead is a very low-density material that contains 98 % air and only the rest is polystyrene (Fernando *et al.* 2017). EPS (including expandable and pre-expanded) has been investigated to use as foam core material in the sandwich panels (Shalbafan *et al.* 2015), mix with wood in the core layer of low-density panels (Jafarnezhad *et al.* 2018), and make lightweight wood plastic composites (Lyutyy *et al.* 2018). Dziurka *et al.* (2015) produced density-reduced particleboards (500 kg/m^3 to 650 kg/m^3) with 7 % wood chips substituted with EPS beads in the core layer. This study found that wood chip-EPS boards with density of 600 kg/m^3 met the bending properties requirement for boards intended for interior fitments (including furniture) for use in dry conditions (P2 boards) according to EN 312: 2010. However, there are few studies about the influence of the EPS content on the properties of panel and the optimal content to be used.

Additionally, the glass transition temperature (T_g) of EPS affects the processing conditions of the panel manufacture, such as press temperature. On the other hand, the press temperature during hot press process is a key parameter because it is crucial to obtain a high enough temperature in the core to get the adhesive fully cured, and at the same time the temperature should not be too high to avoid thermal degradation (Monteiro *et al.* 2018) or severe EPS softening. Therefore, the selection of press temperature requires additional research.

In this study, three-layer low-density particleboards with a target density of 400 kg/m^3 were manufactured. The panels consisted of a mixture of EPS beads with wood particle as the core layer. The aim of this study was to investigate how the amount of EPS and press temperature affected the properties of the studied panels.

MATERIALS AND METHODS

Raw materials

Poplar (*Populus* spp.) particles (air-dried moisture content of about 8 %) were provided by Ningfeng Wood-based Panels Corporation, China. The particles were sieved to obtain fine (< 1 mm) and coarse (1 mm to 4 mm) fractions for use, as shown in Figure 1. EPS beads with a spherical shape (average diameter of 2,2 mm, density of 50 kg/m^3 to 60 kg/m^3) were used as light fillers. A polymethylene isocyanate (pMDI) resin (WANNATE® PM-200, viscosity of 150 ~ 200 mPa·s at 25 °C, NCO content of 30 ~ 32 wt%), was obtained from the Wanhua Chemical Corporation, Beijing, China. Acetone was used as resin diluent for better adhesive distribution.

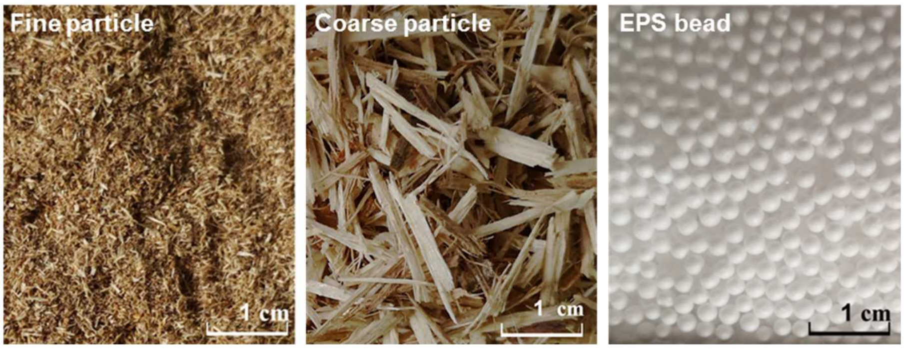

Figure 1: Fine and coarse wood particles and expanded polystyrene beads used for manufacture of low-density particleboard.

Particle size analysis

Particle size distribution of the fine and coarse particle samples was measured using the image analysis-based particle size measurement equipment (SCREENCAM 100 Optical Lab Screen for Wood Chips, IMAL-PAL GROUP, Italy). The wood particles were separated by the system without altering their dimensional characteristics, imaged by a digital camera, and analysed by the software. The distribution of wood particles was given as a percentage over the total weight based on their dimensions. Approximately 100000 particles were evaluated for each sample.

Differential scanning calorimetry (DSC) analysis of EPS

Glass transition temperature (T_g) of the EPS bead was determined using a Q100 DSC (TA instruments) in flowing nitrogen (50 mL/min). An initial thermal program was performed using a heating rate of 10 °C/min to 140 °C and held isothermally for 3 min to erase any previous thermal history. Then the sample (about 5 mg) was cooled at a rate of 20 °C/min to 50 °C and held isothermally for 3 min. After that, the same heating program as the initial one was repeated.

Particleboards manufacturing

Three layered particleboards with a target density of 400 kg/m^3 and thickness of 15 mm were manufactured. The face layer was made of fine wood particles (16 % moisture content), while the core layer contained a mixture of air-dried coarse wood particles (8 % moisture content) and different amounts of EPS. To obtain a more pronounced density profile, the fine wood particles used in the face layer were sprayed with required amount of deionized water and conditioned to reach 16 % moisture content. The pMDI and acetone were weighed out at a mass ratio of 4:1 into a beaker and then mechanically stirred for 10 s to obtain a homogeneous mixture. The adhesive content was 7 % for core layer and 10 % for face layer (based on the oven-dry mass). The code number and composition of the low-density particleboards and their mean density is shown in Table 1. The three-layer mat was made manually using a 340 mm × 360 mm forming box, and then pressed at 110 °C for 15 min or 140 °C for 9 min at an initial pressure of 2 MPa. Then the press was set to distance mode, applying a variable pressure to maintain the desired panel thickness using thickness gauges. Panels without EPS beads were also manufactured at the two press temperatures as the controls. For each panel variable, according to Table 1, two replicates were manufactured.

Table 1: Composition of low-density particleboards and their actual mean density.

Code	EPS bead content (%)[1]	Press temperature (°C)	Mean Density (kg/m^3)
1	0,0	110	364
2	0,0	140	372
3	2,5	110	391
4	2,5	140	375
5	5,0	110	371
6	5,0	140	364
7	7,5	110	384
8	7,5	140	369
9	10,0	110	389
10	10,0	140	371
11	12,5	110	377
12	12,5	140	375

[1]The EPS content was based on the oven-dry mass of wood particles in core layer.

Evaluation of particleboards

The internal region in core layer was sputtered with gold and characterized using a scanning electron microscope (Hitachi S-3400N) at an acceleration voltage of 5 kV.

Vertical density profile was measured on a DENSE-LAB X densitometry (EWS, Germany), using X ray transmitted across the thickness of sample at a scanning speed of 0,5 mm/s.

Mechanical properties were evaluated by determining internal bond (IB), bending strength (MOR) and modulus of elasticity in bending (MOE) according to Chinese standard

GB/T 17657-2013, using an Instron 5582 universal testing machine. Physical properties were characterized by measuring thickness swelling (TS) after 2 h of water immersion at 20 °C (GB/T 4897-2015). Twelve replicates were tested for MOR and MOE, and eight replicates were tested for IB and TS, respectively.

Statistical analysis

Data analysis was performed using the IBM® SPSS Statistics software (Version 19). The homogeneity of variances was checked using Leven test. Thereafter, comparison of mean values using one-way ANOVA test was conducted to determine whether the differences between the properties of the particleboards prepared at different conditions are statistically significant or not. Multiple comparisons using Scheffe test was performed to evaluate the statistical differences between variations, at a significance level of $P < 0,05$.

RESULTS AND DISCUSSION

Particle size characterization

The particle size (length and width) distributions are displayed in Figure 2. Coarse particle sample had larger average length and width than fine particle. The length of coarse particle ranged from 1 mm to 13 mm and centered on 3 mm to 6 mm, while the width ranged from 0,3 mm to 3,6 mm and centered on 0,9 mm to 2,1 mm. In the case of fine particle, the length was less than 3,25 mm and centered on 0,25 mm to 1,25 mm, while the width was less than 0,84 mm and centered on 0,24 mm to 0,36 mm.

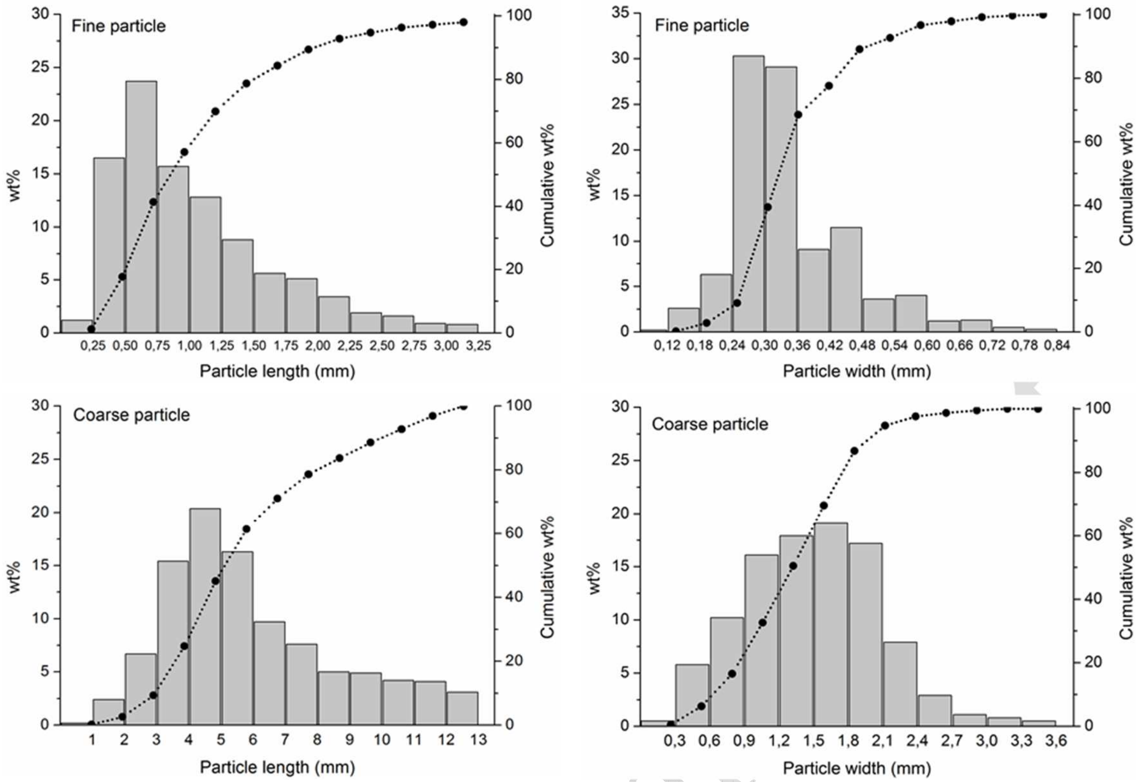

Figure 2: Histogram of the distribution and cumulative distribution of the particle length and width.

T_g of EPS bead

As the glass transition occurs over a temperature range, the midpoint temperature of the glass transition region (step change in specific heat capacity) in the second heating curve was selected to represent T_g. DSC analysis of EPS bead revealed a T_g of approximately 103 °C with a good reproducibility (Figure 3). This result was in agreement with previous research by Shalbafan *et al.* (2012) that reported T_g of expandable polystyrene of 103 °C.

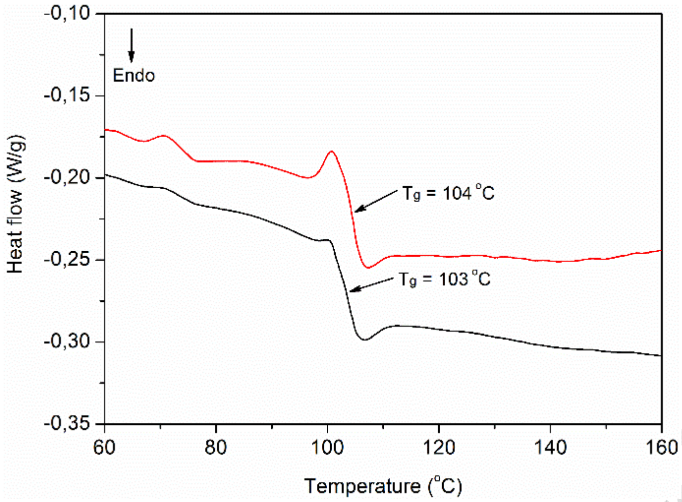

Figure 3: DSC second heating thermogram of EPS bead (two curves represent test on two duplicate samples)

Internal structure

The internal section of the low-density particleboards is shown in Figure 4. In this study, the coarse particle was applied in the core layer, due to the large particles are expected to give better mechanical strength, while the fine particles were good for surface quality (Monteiro *et al.* 2018). It is clearly seen that with the increase of EPS bead content from 0 % to 12,5 % in the core layer, more and more wood particles were surrounded by EPS bead, and the empty spaces between particles were decreased.

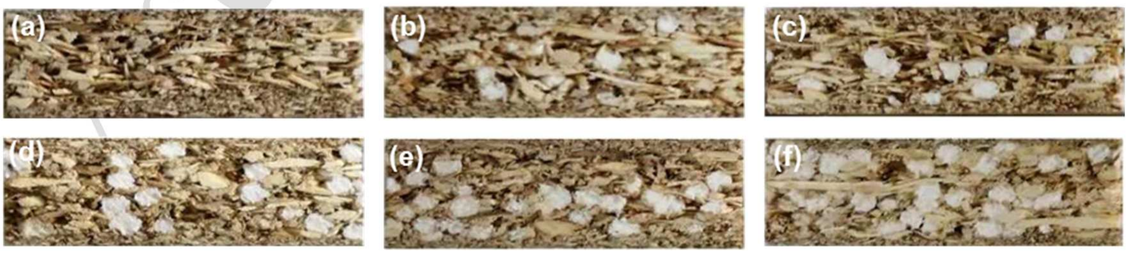

Figure 4: Internal section of the 15 mm three-layer particleboards, containing fine particle in the face layers (3 mm) and a mixture of coarse particle with different contents of expanded EPS bead in the core layer (12 mm): (**a**) 0 % EPS; (**b**) 2,5 % EPS; (**c**) 5 % EPS; (**d**) 7,5 % EPS; (**e**) 10 % EPS; (**f**) 12,5 % EPS.

The microstructure of the panel core layer is shown in Figure 5. It can be clearly seen that in control panel there were empty spaces between wood particles in the core layer. EPS bead filled the voids between particles and improved the core layer integrity, making the core layer more uniform. The EPS bead consisted of numerous closed cells. With the increased press temperature from 110 °C to 140 °C, the size of foam cells became smaller.

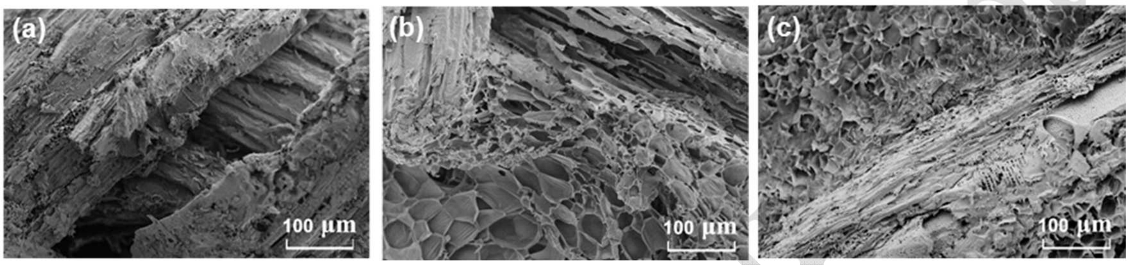

Figure 5: Scanning electron micrographs of structure in the core layer of low-density particleboard: (**a**) control with 0,0% EPS; (**b**) addition of 12,5 % EPS and press temperature of 110 °C; (**c**) addition of 12,5 % EPS and press temperature of 140 °C.

Density profile

The mean density of all these particleboards is similar (Table 1). It is well-known that the density profile over the cross-section of the particleboard formed during hot pressing influences mechanical and physical properties of panels. Therefore, it is necessary to investigate the density gradient of the panels. The vertical density profile over the panel thickness generally resembles a U-shape, as shown in Figure 6. For both press temperature (110 °C and 140 °C), adding EPS bead to the core layer led to a more pronounced density gradient of the panel with higher face layer densities compared to the controls. The increase of EPS content in the core layer led to a higher face layer density. This effect was probably due to the higher volume of core particles, causing increased counterpressure during compression and thus more compacted face layer. The maximum face layer density (about 650 kg/m^3) appeared in panels with 10 % and 12,5 % EPS content, while the minimum face layer density (about 530 kg/m^3) appeared in control panel without EPS bead as filler.

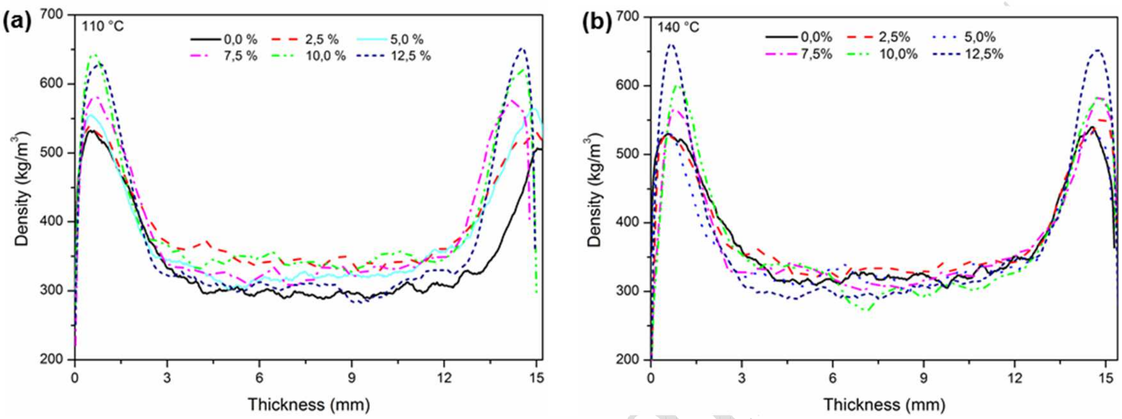

Figure 6: Vertical density profiles of the low-density particleboards made with different contents of EPS bead in the core layer and (**a**) pressed at 110 °C or (**b**) 140 °C.

Bending properties

The bending properties of the low-density particleboards are shown in Figure 7. Incorporation of EPS bead in the core layer had a positive effect on the bending properties, which was related with the improved density profile. The lowest MOR (1,8 MPa) and MOE (517 MPa) was observed for the control panel pressed at 110 °C. The highest MOR and MOE values were observed in the panel with addition of 12,5 % EPS bead as filler and pressed at 110 °C, with values of 5,7 MPa and 1059 MPa, respectively. Adding EPS bead significantly increased the MOR and MOE compared with the control, however, the variation of the amount of EPS from 2,5 % to 12,5 % had no significant effect on the MOR and MOE.

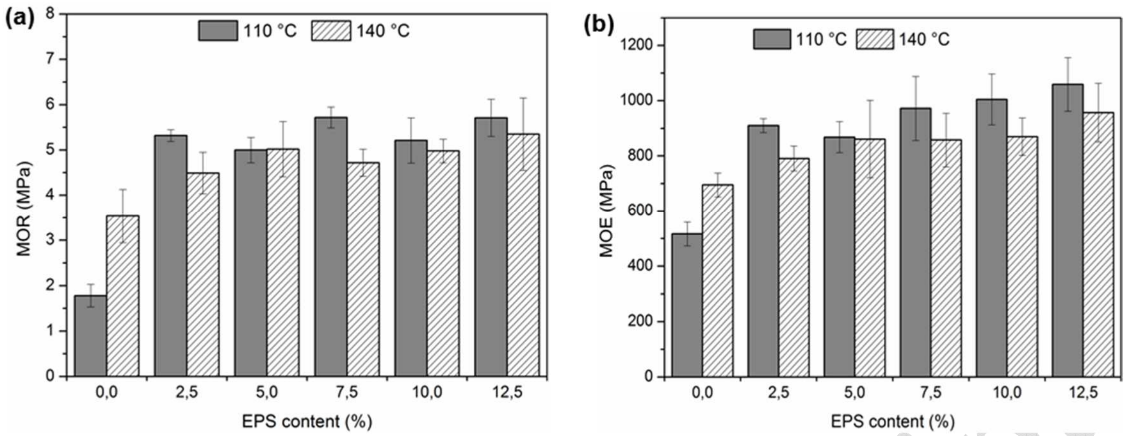

Figure 7: (**a**) Bending strength (MOR) and (**b**) modulus of elasticity (MOE) of the low-density particleboards with addition of different contents of EPS bead in the core layer and pressed at 110 °C or 140 °C.

Comparing the two press temperatures, higher temperature (140 °C) was more favorable in reference panels without EPS as filler, because it is necessary to get a high enough temperature in the core to make sure the adequate curing of the adhesive. However, higher temperature had a negative effect on the bending properties of panels with addition of EPS filler, resulted in lower MOR and MOE compared to that of panels pressed at 110 °C. This is probably attributed to the shrinkage of EPS bead under press temperature that is far beyond than its glass transition region (100 ºC to 110 °C).

Internal bond (IB)

The values for IB of the low-density particleboards are shown in Figure 8. Examinations of the tested samples revealed that the fractures were occurred in the core layer. When pressed at 110 °C, adding EPS bead in the core layer as filler significantly increased the IB of panels compared with that of control. The EPS bead filled the voids between particles caused by the reduction of the amount of wood, allowing for improved core layer integrity and cohesive strength, and accordingly enhanced IB strength. For the press temperature of 110 °C, it is noted that IB values of the panels with 10 % and 12,5 % EPS bead (0,38 MPa and 0,43 MPa) were significantly higher than that of panels with 2,5 % to 7,5 % EPS and the control.

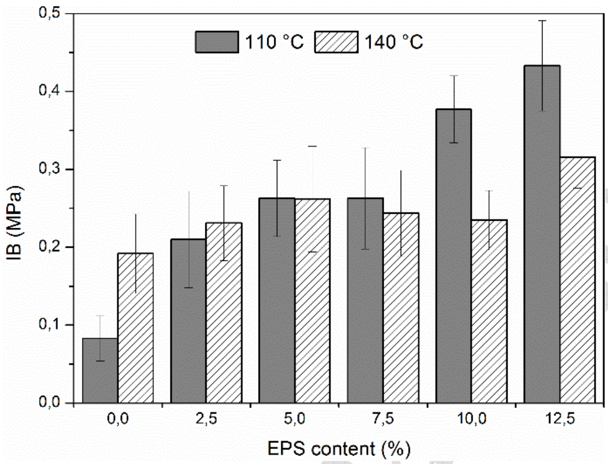

Figure 8: Internal bond (IB) values of the low-density particleboards with addition of different contents of EPS bead in the core layer and pressed at 110 °C or 140 °C.

Compared with the control panel (0 % EPS content) pressed at 110 °C, higher press temperature (140 °C) resulted in a significant increase in IB strength value from 0,08 MPa to 0,19 MPa. However, in the case of panels with addition of EPS bead, higher press temperature had a negative effect on the IB strength, especially in high EPS contents (10 % and 12,5%). This phenomenon is consistent with the previous study by Mir *et al.* (2016) who found that increasing press temperature had a negative effect on IB of lightweight particleboard using EPS as filler.

Thickness swelling (TS)

The thickness swelling after 2 h of water soaking (Figure 9) was measured to determine the thickness change of the low-density particleboards. The highest TS (4,4 %) was observed in panels pressed at 110 °C without adding EPS bead, due to the voids between wood particles. Adding 2,5 % content of EPS bead reduced the TS to 2,2 %, because EPS has the hydrophobic characteristic with a closed cell structure. Additionally, hydrophobic EPS bead filled in the empty spaces in the core layer, which reduced the water accessibility to the wood particles. However, there was no significant difference between TS of panels adding different contents of EPS from 2,5 % to 12,5 %. Compared with press temperature of 110 °C, pressing at 140 °C resulted in decreased TS (3,1 %) for panels without adding EPS bead, whereas TS was increased in panels adding EPS bead.

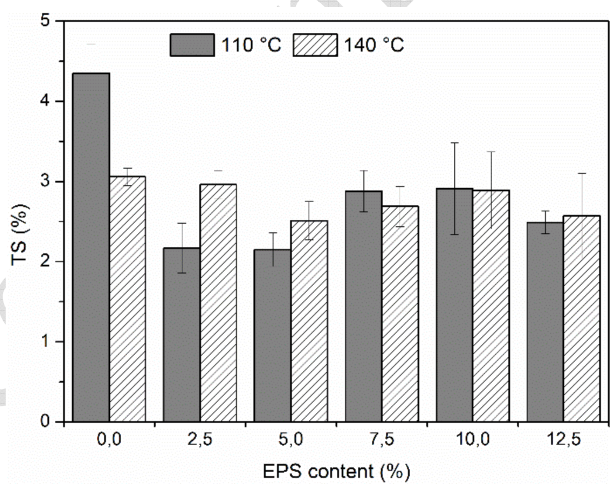

Figure 9: Thickness swelling (TS) of the particleboards with addition of different contents of EPS bead in the core layer and pressed at 110 °C or 140 °C.

Conclusions

EPS bead filled in the voids and empty spaces between wood particles caused by decreased density. As a result, adding EPS bead significantly improved the physical and mechanical properties of the panel compared with the control, but the increase of the amount of EPS from 2,5 % to 12,5 % had no significant effect, except in the case of internal bond where high contents of EPS bead (10 % and 12,5 %) had a more remarkable effect than low contents. Comparing two press temperatures, 110 °C was preferable than 140 °C to avoid softening and shrinkage of the EPS bead. The best formulation corresponded to the panel with density of 377 kg/m^3, MOR of 5,7 MPa and MOE of 1059 MPa, IB of 0,43 MPa and thickness swelling after 2 h water soaking of 2,5 %. These findings provide fundamental data for developing lightweight panels used in furniture and interior decoration.

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