# Investigation of Foam Materials to be Used in Lightweight Wood-Based Composites

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As a native speaker of the English language I find that the Ph.D. Dissertation titled, **Investigation of Foam Materials to be Used in Lightweight Wood-Based Composites,** authored by Ali Shalbafan has been checked and fulfills requirements for an English dissertation (grammar and dictation).

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**Shalbafan A.,** Luedtke J., Welling J., and Thoemen H. 2012a. Comparison of Foam Core Materials in Lightweight Wood-Based Panels Made by Continuous Process, *European Journal of Wood and Wood Products*, 70(1): 287-292.

## Publication II

**Shalbafan A.,** Welling J. and Luedtke J. 2012b. Effect of Processing Parameters on Mechanical Properties of Lightweight Foam Core Sandwich Panels. *Wood Material Science & Engineering*, 7(2):69-75.

## Publication III

**Shalbafan A.,** Welling J. and Luedtke J. 2013a. Effect of Processing Parameters on Physical and Structural Properties of Lightweight Foam Core Sandwich Panels. *Wood Material Science & Engineering*, 8(1):1-12.

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## Explanation* of the authors share to the publications

| | | |
|---|---|---|
| **I** | **A. SHALBAFAN,** J. LUEDTKE, J. WELLING, H. THOEMEN | **Shalbafan:** D, E, L, S, I & M<br>Luedtke: D, E, I & CM<br>Welling & Thoemen: CI & CM |
| **II** | **A. SHALBAFAN**, J. WELLING, J. LUEDTKE | **Shalbafan**: D, E, L, S, I & M<br>Luedtke & Welling: CI & CM |
| **III** | **A. SHALBAFAN**, J. WELLING, J. LUEDTKE | **Shalbafan**: D, E, L, S, I & M<br>Luedtke & Welling: CI & CM |
| **IV** | **A. SHALBAFAN**, J. LUEDTKE, J. WELLING; A. FRUEHWALD | **Shalbafan**: D, E, L, S, I & M<br>Luedtke, Welling & Fruehwald: CI & CM |
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| **VI** | **A. SHALBAFAN**, J. T. BENTHIEN, J. WELLING, M. C. BARBU | **Shalbafan**: D, E, L, S, I & M<br>Benthien: D, I & CM<br>Welling & Barbu: CI & CM |
| **VII** | **A. SHALBAFAN**, M. A. DIETENBERGER, J. WELLING | **Shalbafan**: D, E, L, S, I & M<br>Dietenberger & Welling: CI & CM |
| **VIII** | M. A. DIETENBERGER, **A. SHALBAFAN**, J. WELLING, Ch. BOARDMAN | Dietenberger: D, E, L, I & M<br>**Shalbafan**: D, E, S, I, CI & CM<br>Welling & Boardman: CI & CM |

* **D**: Design of work, **E**: Experimental work, **L**: Literature review, **S**: Statistical analysis, **I**: Interpretation of data, **M**: Manuscript, **CI**: Contribution to the ideas, **CM**: Contribution to the manuscript, **FEM**: FEM modeling & simulation.

# Abbreviations and Terms

| | | |
|---|---|---|
| ASEA | Average Specific Extinction Area | $M^2/kg$ |
| CA | Coupling Agent | % |
| CIS | Charpy Impact Strength | $kJ/m^2$ |
| DSC | Differential Scanning Calorimetry | - |
| EHOC | Effective Heat of Combustion | MJ/kg |
| EMC | Equilibrium Moisture Content | % |
| EPS | Expandable Polystyrene | - |
| ESWR | Edge Screw Withdrawal Resistance | N |
| FESEM | Field Emission Scanning Electron Microscopy | - |
| FSWR | Face Screw Withdrawal Resistance | N |
| h | Hours | - |
| HRR | Heat Release Rate | $kW/m^2$ |
| IB | Internal Bond | $N/mm^2$ |
| LCA | Life Cycle Assessment | - |
| LEL | Lower Explosion Limit | % |
| MDF | Medium Density Fibreboard | - |
| MOE | Modulus of Elasticity | $N/mm^2$ |
| MOR | Modulus of Rupture | $N/mm^2$ |
| MS | Microspheres | - |
| PB | Particleboard | - |
| PLA | Poly Lactic Acid | - |
| PS | Polystyrene | - |
| PU | Polyurethane | - |
| PVC | Polyvinyl Chloride | - |
| RTA | Ready-to-Assemble | - |
| SPSS | Statistical Package for the Social Science | - |
| SS | Surface Soundness | $N/mm^2$ |
| SWR | Screw Withdrawal Resistance | N |
| $T_g$ | Glass Transition Temperature | °C |
| THR | Total Heat Released | $MJ/m^2$ |
| TS | Thickness Swelling | % |
| TSI | Time to Sustained Ignition | S |
| UEL | Upper Explosion Limit | % |
| VHP | Virtual Hot Press | - |
| WA | Water Absorption | % |
| WF | Wood Flour | % |
| WPC | Wood Plastic Composite | - |
| X | Press Temperature | °C |
| Y | Press Factor | s/mm |

# Summary

The future supply with raw materials is of major concern for particleboard producers due to a steadily increasing competition on wooden biomass in the form of wood chips. There is currently competition between particleboard manufacturers, pulp mills and energetic usages of wood chips, in form of fresh fiber material or recovered fiber. The lightweight sandwich panels could offers a solution through the development of wood-based foam core panels for furniture constructions that fulfill the same function as particleboard while the amounts of raw material input is reduced. Furthermore, the customer demand for flat-pack furniture is also a driving force for the development of light panels. Lightweight panel has been also favored by furniture producers because of its low density, high resource efficiency and advantageous strength to weight ratio. Recent technological developments lead to an innovative one-step process which simplifies the multi-step process for production of foam core panels (Luedtke et al. 2008).

In this thesis, foam core particleboards were produced with the newly developed process having either expandable microspheres or polystyrene as core layer. Comparisons of produced panels having different core layer materials were done as the first analysis. It was observed that there are several press parameters (e.g. press temperature, pressing and foaming time) and panel features (e.g. face layer thickness, core layer density) which affect the process set up and final panel properties. The effects of press and panel parameters were experimentally analyzed in a series of tests. To assist marketability of novel foam core particleboards, their fire performance was examined with cone calorimetry tests (ISO 5660). Additionally, the composition behavior of foam core particleboards without and with fire retardant treatments has been analyzed by the advanced cone calorimetry techniques. As a recycling option for trimming waste and rejected foam core panels at industrial scale, flat pressed wood plastic composites were made from foam core particleboard residues. The physical and mechanical properties of these boards were tested.

As the main result, it is concluded that with varying the press and panel parameters foam core particleboards having different performances can be achieved. This gives more options to the manufacturers by which they can produce foam core particleboards in different varieties. Foam core particleboards can be used as alternative to conventional particleboard in certain applications.

# Zusammenfassung

Die zukünftige Versorgung mit Rohstoffen besorgt die Holzwerkstoffhersteller wegen einer stetig zunehmenden Konkurrenz um Holzbiomasse in der Form von Hackschnitzeln. Zu nennen in diesem Zusammenhang ist der starke Wettbewerb zwischen Holzwerkstoffherstellern, Faserstoffproduzenten und der energischen Verwendung von Hackschnitzeln, sowohl in Form von frischem Holz (fresh fibre) als auch in Form von Altholz (recycled fibre). Leichte Sandwichwerkstoffplatten können durch die Entwicklung einer auf Holz basierenden Schaumkernplatte mit vergleichbaren Eigenschaften wie herkömmliche Spanplatten für den Möbelbau einen Beitrag dazu liefern, den Rohstoffeinsatz zu reduzieren. Zudem ist die Nachfrage der Kunden nach sogenannten Mitnahmemöbeln eine treibende Kraft für leichte Holzwerkstoffe. Leichte Holzwerkstoffe werden außerdem von den Möbelerzeugern wegen ihrer niedrigen Dichte, der hohen Ressourceneffizienz sowie wegen der günstigen Festigkeits/Gewichts-Relation favorisiert. Neue technologische Entwicklungen führten zu einem innovativen einstufigen Prozess, der den aufwendigen mehrstufigen Prozess für die Produktion von Schaumkernplatten vereinfacht(Lüdtke et al. 2008).

In dieser Arbeit wurden Schaumkernplatten nach dem kürzlich entwickelten Prozess hergestellt, der als Kernlage expandierbare Microspheren oder Polystyrol vorsieht. Eine erste Analyse beinhaltet einen Vergleich von Holzwerkstoffenplatten mit unterschiedlichen Kernschichtmaterialien. Es wurde nachgewiesen, dass die Pressparameter (z.B. Presstemperatur, Press- und Schäumungszeit) und Plattencharakteristika (z.B. Deckschichtdicke, Kernlagendichte) einen Einfluss auf die Abläufe bei der Plattenherstellung sowie auf die Platteneigenschaften haben. Der Einfluss der Pressfaktoren sowie die Plattencharakteristika auf die Platteneigenschaften wurden experimentell analysiert. Um eine mögliche Markteinführung der neuartigen Schaumkernplatte zu unterstützen, wurde die Feuerresistenz mittels des „cone calorimetry tests“ (ISO 5660) ermittelt. Unterschiedlich zusammengesetzte Schaumkernspanplatte mit und ohne zusätzliche flamm-hemmendem Mittel wurde untersucht. Als eine Option der Verwertung von Produktionsresten und Ausschussmaterial im industriellen Maßstab wurden WPC-Flachpressplatten aus den im Labor produzierten Schaumkernspanplatten hergestellt und deren mechanischen physikalischen Eigenschaften bestimmt.

Als Hauptergebnis ist festzuhalten, dass sich durch Variation der Press- und Plattenparameter Schaumkernspanplatten mit unterschiedlichen Eigenschaften herstellen lassen. Hieraus ergeben sich für die Plattenproduzenten vielfältige Optionen Schaumkernplatten mit unterschiedlichen Eigenschaften herzustellen. Zudem lassen sich diese Platten in bestimmten Fällen als Alternative zur herkömmlichen Spanplatte einsetzen.

# 1 Introduction

## 1.1 BACKGROUND

The European countries hold the world leadership for production volume, process and product innovations in the wood-based panel industry. In the last 20 years the production capacity of wood based panels has been considerably increased in Europe from 32 Mill. m³ (1994) to 51 Mill. m³ (2012). Figure 1 illustrates the share of wood based panels in Europe, excluding Russia and Turkey (EPF 2011, Döry 2012). About 70 % of the output volume is used in the furniture industries as the main consumer (EPF 2011, Eurostat 2011). Here the topic of providing lightweight panels for weight reduction is gaining interest. As a general rule, wood based panels having a density less than 500 kg/m³ are considered as lightweight panels (Forest Products Laboratory 2010).

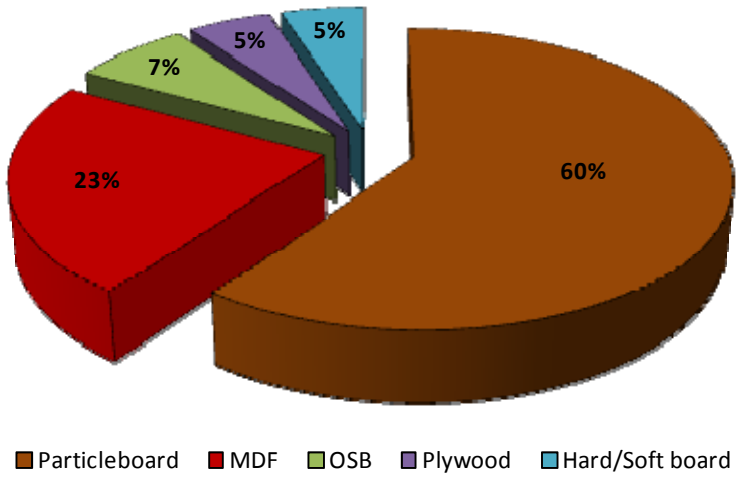


Figure 1: Wood based panel production in Europe excluding Russia and Turkey (Döry 2012)

The main reasons for the lightness of wood based panel are design trends (thick elements with low price and weight), handling, transport cost and ease of assembly for the customers. These reasons alone could not justify the importance of lightness for wood based panel industries (Michanickl 2006, Frühwald 2009). Since recent years the raw material availability is decreasing which results in increasing prices of raw materials (Mantau et al. 2010, Pepke 2010). This is mainly driven by the both increasing demand for wood as a renewable energy source (Teischniger 2010) and the increasing prices for fossil-based energy (Energy Information Administration 2012). This shows that the wood based panel industry is confronted with a competition for raw materials and increasing growing prices for both materials and

energy. It is assumed that the cost for raw material and energy will continue to increase (Hetsch 2007).

As a matter of fact these trends lead to draw attention towards the both usage of so far underutilized resources and the innovation of new products and production concepts which increase the resource efficiency (Eder et al. 2010). In this concept, the reduction of panel density would be an option to strengthen the competitiveness of the wood based panel industry with the considerably growing wood energy market. Additionally, the customer demand for flat-pack or RTA (ready-to-assemble) furniture may also act as a driving force for the development of lightweight panels. In reality, European furniture production is reduced about 13 % between 2006 and 2011, conversely the RTA furniture production is increased by approximately 4 % in the same period (Paoletti et al. 2012). Additionally, Thoemen (2008) presented that in central Europe from each two Euros spent for furniture more than one is already paid for take-away furniture. The heaviness of the elements used for the modern RTA furniture is the provocative factor towards lightness.

In general, the use of lightweight panels opens up several advantages for manufacturers, designer and consumers: a) cost reducing as a result of lowering the wood consumption and transportation cost, b) alternative supply options in the case when wood based raw materials get shorter in volume and increase in price, c) flexibility in responding to the trends in design (by using of thicker elements), d) enhancing consumer mobility, and e) reducing the environmental burden and improving the environmental friendliness of the product. These factors have caused considerable interest during recent years for the weight reductions of wood based panels, i.e. particleboard (PB) and medium density fiberboard (MDF) which are considerably heavier than the solid timber product they are made of. The relative importance of attributes for forming a priority list for selecting a product, i.e. household furniture, and making a buying decision are presented in Figure 2. It shows that design and price are the two most factors determining the customer's buying decision, followed by the weight, brand and service. The ranking of weight is more or less equal to the more traditional product attributes (brand and service) and shows the potential of lightweight panels (Stosch and Lihra 2010).

## 1.2 STRATEGIES FOR PANEL WEIGHT REDUCTION

The various strategies applied for panel weight reduction are much dependent on the final panel application. Thus, it is hard to generalize the selection criteria for weight reduction. Nevertheless, all of the strategies used for the reduction of panel density during recent decades can be segregated in three major groups; technology,

materials and sandwich concept. An overview of the different strategies applied for weight reduction is illustrated in Figure 3.

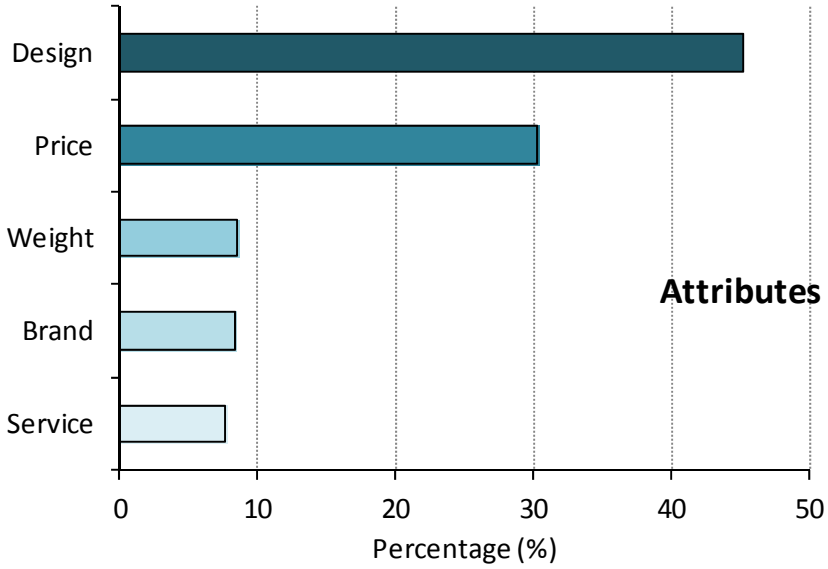


Figure 2: Relative importance of attributes in formation a priority when buying household furniture (Stosch and Lihra 2010)

Less compaction of the wood-furnish mat and hollow-tube profile fabrication of the panel (extruded boards) are the two technological methods for panel weight reduction which have found wide application in industrial practice. There have also been several attempts in the field of material selection used to produce light panels, e.g. by using low density wood species, annual or perennial plants (agriculture residues like maize, sunflower, hemp and etc), mixing of polymer beads or starch granulates in the core and foamed adhesives (Forest Products Laboratory 2010). To create low-density spaces between the particles while maintaining the inter-particle connection foamed adhesives were used. The density reductions which can be achieved with most of these techniques are about 150 to 200 kg/m³. It is worth to mention that today the density of particleboard is approximately 100 kg/m³ lower than 20 years ago. But, nevertheless, these techniques all have certain restrictions or disadvantages that require resolution (Schirp et al. 2008). In brief;

- remarkable decline of mechanical properties what makes many lightweight panels unsuitable for applications requiring load bearing capacity,
- the lack of continuous supply and appropriate storage techniques of non-wood bio-based materials (e.g. agriculture crops and/or its residues) is a problem for the industry,
- high ash content and high resin consumption when using agricultural resides,

- limitations to the surface finishing and post-forming,
- enforcing companies to have more varied stocks of raw materials and also requiring special production technologies and more training for their staff which increases the complexity of the manufacturing process,
- the need for using special or more different binders due to the lower bonding strength of the alternative materials which increases the production cost.

However, the weight reduction by these techniques does not always imply a cheaper product compared with the conventional panels. This is due to the higher cost for the substituting raw materials, more sophisticated production technology and reducing of the production capacity.

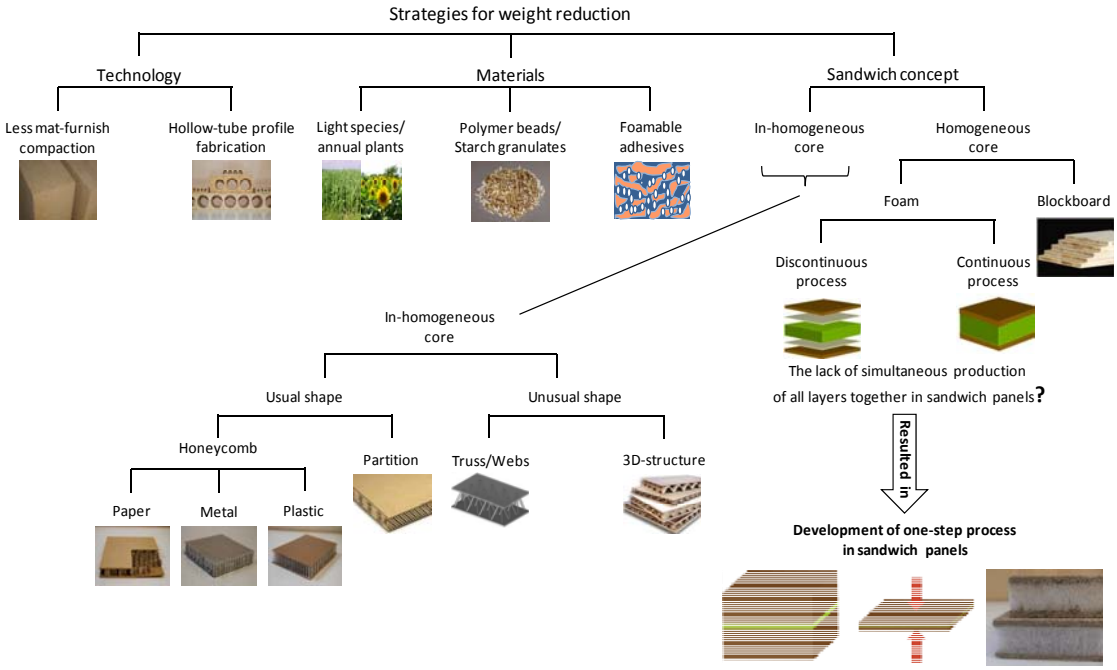


Figure 3 An overview of different strategies used for the weight reduction of panels

It is generally agreed that multi-layered composites with a lighter core layer than their surface layers which are also called sandwich can reach remarkable weight reductions and material saving (Allen 1969). A Sandwich-structured panel is fabricated from a thick but lightweight core for absorption of shear stresses which is covered by two thin but stiff skins to absorb tensile and compression stresses when the panel is under bending forces (Zenkert 1997). The European Technical Specification prCEN/TS 00112189:2011.2 defines a sandwich board for furniture as follows: "*a laminar composite product consisting of at least two skins positioned on either side of a core, which is firmly connected to the skins (e.g. by bonding, by core-*

*generated adhesion) so that the three (or more) components act compositely when under load. Wood or other lignocellulosic materials constitute at least one of the components."* The main advantage of the sandwich structures is reaching structural performance comparable to conventional monolithic materials while saving weight. Using of a sandwich concept breaks up the monolithic panel cross-section and replaces heavy core material by either an in-homogeneous or homogeneous lightweight core material (Allen 1969, Karlsson and Aström 1997). More information relating to the sandwich panels is presented in the next section.

## 1.3 SANDWICH PANEL HISTORY

A basic principle in nature is the efficient use of material and energy which leads to minimizing the weight. The sandwich concept was firstly developed by nature (like iris leaf and bird wing) before mankind start to create structures, buildings and machines. About two centuries ago, Duleau (1820) first described the use of two cooperating faces separated by a distance in between (Zenkert 1997). But the first description of sandwich structure was documented by Fairbairn (1849). Octave Chanute (1894) presented a sandwich biplane aircraft construction consisting of wooden struts and diagonal wires as a sandwich type structure in an aerospace application. Claude Dornier (1937) solved the core-skin bonding problem for aircraft structures (Werke and Dornier 1937). The extensive use of sandwich in construction was in the Mosquito night bomber of World War II utilizing veneer faces with a balsa core, mainly because of the shortage of other materials in England during the war (Vinson 2005). Marguerre (1944) in Germany has written the first research paper relating to the sandwich structures in construction (Vinson 2005). Plantema (1966) published the first book entitled sandwich construction, followed by another fundamental book in sandwich structures by Allen (1969). At this time, Forest Product Laboratory in USA was considered to have a remarkable portion of research subjected to sandwich structures in construction.

As illustrated in Figure 3, the core layer material of sandwich can be divided in two major groups; in-homogeneous or homogeneous material. Basically the in-homogeneous core layer material of sandwich board can itself have either unusual shape (e.g. truss/webs, 3D-structures) or usual shape (e.g. honeycomb, partition). Honeycomb panels are a sandwiched type assembly made of a metal, plastic or paper based structure as core layer with two load carrying surface layers made of glass or carbon fiber reinforced polymers (thermoplastic or thermoset), metal skins, wood or wood based composites. For several decades honeycomb panels used in furniture industry and for panel doors have been developed. They are different by cell size and shapes, expandable or corrugated papers, frame-on-board or frameless panels. Large numbers of developments is related to machining, edge-banding and

fitting technologies. Beside these developments and evolutions, there are still some drawbacks and challenges for the honeycomb panels. Analyzing of the production cost for a board-on-frame honeycomb panels shows that about 88 % of the cost factors are independent from the panel thickness. Further analysis also shows that paper based honeycomb panels (board-on-frame) having thicknesses below 24.5 mm (1 inch) have a relative higher price in comparison with the conventional particleboards (Stosch and Lihra 2010). This makes honeycomb panels more ideal for the elements having final thickness of more than 25 mm, but not for the thinner boards.

Homogeneous core layers like softwood strips (block board) and foams sandwiched between two thin sheets minimize the difficulties of edge-processing and integration of connectors and fittings compared to the in-homogeneous core layer (e.g. hollow sections of honeycomb panels). Core layer materials for block boards are usually made of strips of Balsa (*Ochroma lagopus*), Cottonwood (*Ceiba spp.*), Poplar (*Populus spp.*) or low density Pine (*Pinus spp.*) to reach low density at core layer of sandwiched panels. Different dimensional stability of face and core layers of the block board have to be considered when using of this type of product, which may result in unwanted deformations when moisture content and/or temperature is changed.

Usage of polymeric foams (e.g. thermoset or thermoplastic) with open or closed cells which can be produced with different manufacturing process is another approach for fabricating a homogeneous core in sandwich panels. A human skull is an example of foam core sandwich structure in nature. Foams are produced from a variety of synthetic polymers supplied in various densities which can be used for a wide range of applications. In the United States in 1938 the polystyrene (PS) was first commercially produced. Eight years later, the PS was introduced in Germany. Polystyrene foam was introduced in the early 1940s. Polyvinyl chloride (PVC) has been developed in Germany in the early 1940s. PVC was not commercially used until 15 years later due to its softness. In the late 1950s and early 1960s, improved PVC and other cellular polymers especially polyurethane (PU) were produced, suitable as core materials for sandwich structures (Akovali 2005).

The procedure of manufacturing foam core sandwich structure was firstly done by the batch process where the prefabricated faces and foam core are glued/assembled together (Karlsson and Åström 1997, Zenkert 1997). Another process to manufacture foam core sandwich panels is the mould forming where the bottom of the mould is covered by the lower facing and the upper facing located in position supported on spacers. Then, the mould cavity if filled by the spraying of exact foam quantity through a nozzle (Davies 2001). Although complicated shapes of panels can be manufactured with this method, but the production process is

relatively slow. Continuous processes can be used for mass production of foam core sandwich panels. In continuous processes, the coiled up sheets are used as face layers (like foils or impregnated paper) in an endless manner. The core layer is formed either by continuously inserting prefabricated foam sheet or a foaming liquid is injected (*in-situ* foaming) between the uncoiled facings to form the core layer material. The using of adhesive between the face and core layers is not needed if the core is formed by *in-situ* foaming. The continuous technique is more preferable than the batch and mould process due to less production steps and accordingly higher efficiency in time, material and labor. This has an important influence on the final panel cost as an important requirement. It is supposed that the difficulties of edge-processing and integration of connectors can be minimized with having foam as the core layer compared to the hollow sections of honeycomb sandwich panels.

The implementation of the sandwich concept with foam core in wood based panel industries is rather slow mainly due to two main reasons; high material and process cost and specialized processing and assembling technology. High cost are caused by low output, labor-intensive production processes, and by the high cost of the substituting core layer material. Specialized processing technologies are needed for bonding the separate layers together and for further processing steps like integration of connectors and fitting. These are the challenging factors causing a slow spread of higher volumes of foam core sandwich panels in the wood-based panel market. Recent developments to produce foam core sandwich panels in an integrated (one-step) process to consider some of the aforementioned problems can open a new opportunity for enhancing the application of foam core sandwich structures in the furniture industries (Luedtke et al. 2008).

## 1.4 ONE-STEP SANDWICH PANEL MANUFACTURING

One of the disadvantages of the aforementioned process to manufacture sandwich panels is the lack of simultaneous manufacturing of all layers together at one time. This has been considered by Luedtke et al. (2008) who have developed a novel process for manufacturing foam core sandwich panels in a one-step process with wood based panel type's surfaces. The process consists of three consecutive stages named; pressing, foaming and stabilization stages. More detailed information about this process is presented in section 3.4.1 (Chapter 3) of this dissertation and in Luedtke (2011). This integrated approach can be carried out by a conventional production line for particleboard with some modifications. The produced panel consists of resinated wood particles for the faces and *in-situ* expanded foam as core layer material. Due to the *in-situ* foaming, no additional glue has to be applied in the interface between the face and core layer materials.

For producing of foam core sandwich panels in a one-step process, three important categories of manufacturing requirements have to be considered; material, panel and process requirements.

### 1.4.1 Core layer material requirements

Beside the material cost, core layer materials should meet some characteristics to be applicable for the *in-situ* foaming in the one-step process. These materials should:

- be able to expand,
- expandable under heat,
- expand, when a certain activation temperature (about 100 °C) level is reached,
- have a solid shape (powder or granulate) to allow mat forming before expansion,
- not be too tacky to allow easy and uniform felting/scattering and,
- be pressure resistant in its un-expanded state.

These traits narrow the selection range for the core layer materials. Up to now, two types of expandable materials available on the market have been distinguished to fulfill the requested characteristics mentioned above: Expancel Microspheres (MS) and Expandable Polystyrene (EPS). Luedtke et al. (2008) were used of Expancel microspheres as core layer material in his first laboratory production tests. Expandable microspheres (MS) consist of a thermoplastic copolymer (acrylonitrile or vinylidene) as shell material encapsulating a blowing agent, mostly a liquid hydrocarbon with a low boiling point. When heating the microspheres the pressure of the blowing agent trapped inside the shell increases and, at the same time, the thermoplastic shell softens, leading to a dramatic volume increase of microspheres shell. To stiffen the microsphere shell in order to remain in its new expanded volume, cooling of the thermoplastic shell is necessary. Expandable polystyrene (EPS) used in this thesis is made of thermoplastic polystyrene and dispersed pentane as blowing agent.

Foam core particleboard should compete with the conventional particleboard to be used for the furniture industries. In this product, heavy and cheap wood-chips as core material are replaced with lightweight foam core material which (up to now) mainly are oil-based substances (polymeric materials). Beside the requirements which have to be fulfilled by the core layer materials, the cost of the core material is a critical point, when this foam core product should be able to compete in price with conventional particleboard. According to the both suppliers of Expancel microspheres used by Luedtke (8000-12000 €/ton) and of the expandable

polystyrene (1300 €/ton) used in this study, it can be said that the EPS material is much cheaper compared to MS (approx. one tenth). This makes foam core particleboard more economically when using EPS as core layer material.

### 1.4.2 Foam core panel requirements

It should be possible to use lightweight foam core panels for many applications for which conventional particleboard can be used. With a reduction to half or even less of the weight of conventional particleboard, it is possible to meet some of the ambitious requirements of the furniture industry relating to the weight reduction of the packaging units and lowering of the transport cost. The foam core panels should be interesting for the furniture industry especially for the flat packed furniture ready to assemble. It should be able to produce panels in a wide range of sizes (length, width and thickness). Surface and edge coat banding has to be possible with all types of lacquers, foil and impregnated papers. Fixing of hinges, grips and connectors should be also feasible with the available products. Wood-based surface layers with high density and rigidity in the foam core particleboards make it possible to meet the aforementioned requirements e.g. coating, edge banding, use of conventional connectors and etc..

Utilization of production residuals and recycling of the panels to the end of life of foam core particleboard containing products are also important requirements which have to be considered for this new product.

In the context of technical properties, it is reasonable to mention that the conventional particleboard is an over-engineered material when is used for certain applications in furniture production. In other words, different minimum requirements for particleboard properties have to be defined depending on its placement and function in the final product. This gives an opportunity to use boards with reduced density which may have lower mechanical and physical properties but still sufficient to meet the requirement for being used as furniture elements. Foam core panels with only half density of normal particleboard can fulfill such requirements. Foam core particleboard might be ideal for applications where very high strength and elevated properties are not needed.

### 1.4.3 Process requirements

It may be assumed that wood based panel producers are not willing to change their production machinery or install a new production line for making lightweight panels when a market for the new product is not yet fully established. Hence, producing foam core particleboard should be possible by applying the already existing industrial production techniques. As explained earlier, the process of foam

core panels has been derived from the conventional continuous production principle for particleboards. In the adapted particleboard process expandable materials are used as the core layer instead of coarse wood particles (Luedtke et al. 2008). This leads to the necessity of *in-situ* foaming of core layer materials inside the continuous press.

One important challenge of producing foam core panel in a continuous press is changing the steel belts (press plates) distance during the production. During hot pressing the steel belt has to be moved to generate sufficient pressure for densification. Due to the *in-situ* foaming one of the steel belts (press plates) also have to be moved/opened actively to the final panel thickness to allow expansion of the core layer material. For achieving this, a bidirectional movement of the press is needed. Modern continuous presses already do fulfill this requirement. One important factor which determines when and at which position in the continuous press the steel belt should be opened is the moment when the activation temperature of core layer material is reached. The activation temperature for the MS material is between 80 to 90 °C, while for the EPS material a higher and wider temperature range is obtained (95-115 °C). In a constant situation (the same press speed and press length) a wider range of activation temperature gives more flexibility for changing the steel belts distance. When producing panels with MS the steel belt should open to final panel thickness after quite a short time span which makes it difficult for process control. Due to the wider range of activation temperature for EPS material the adjusting of steel belts distance can be implemented during a longer time span or distance from the press input which allows a wide range of press operations in industrial scale. Additionally, the higher activation temperature of EPS compared to that of MS materials can lead to the higher densification and better curing of the resinated wood particles in the surface layers (higher density and strength of face layers).

Another important requirement for manufacturing foam core panels is depended on the polymer type of core layer material (e.g. thermosetting or thermoplastic). As explained earlier, two types of materials are already in the market which can be used in the core layer of foam core particleboard. Both materials (MS and EPS) are based on thermoplastic polymers. It is clear that thermoplastic polymers after expansion need to be cooled down below their glass transition temperature (Tg) for solidification/stabilization. This means that particleboard with thermoplastic core layer can only be produced using a continuous press which has a cooling section at the outlet side. It should be mentioned that the EPS material has higher glass transition temperature (103 °C) compared to MS material (85 °C). Due to this, the EPS material will need less time to be cooled down. The shorter the cooling the higher production capacity can be achieved.

# 2 Objectives

The overall objective of this thesis focuses on the reduction of costs and improvement of properties of foam core particleboard produced in a one-step process. Luedtke (2011) used of Expancel microspheres (MS) as core layer materials for the process development. He did not further discussed about the product and process variables which can influence panel properties. In this study lightweight foam core particleboards were produced using resinated wood particles for the faces and expandable polystyrene (EPS) as core layer material. There are a wide range of variables for both product and process parameters which have to be determined before bringing foam core panels to the market. The effect of the type of core layer material, core layer density, the surface layer thickness and accordingly core layer thickness, press temperature, pressing time, foaming time and etc. would be investigated in this thesis.

The aim of this Ph.D project is to show different processing options to the potential manufacturers by which they can produce foam core particleboard with distinct properties so that the product can meet the requirements for specific applications. The outline of the thesis can be divided in four general sections:

- Characterization of core layer materials

There are already two types of expandable thermoplastic polymer in the market which fulfilled the required characteristics to be used as the core layer material in foam core particleboard: a) Expancel microspheres (MS) and b) Expandable polystyrene (EPS). Apart from the significant price difference of both materials, it is important to get information regarding the properties of panels produced with these two foamable materials (Publication I). The objective of the first set of experiments in this thesis was to obtain information on some selected mechanical and physical properties of multi-layered lightweight panels using expandable microspheres (MS) and expandable polystyrene (EPS) as core layer materials.

- Influence of processing parameters

It is assumed that the production process parameters determine different foam structures which affect foam properties. In the process for foam core panels, there are different process variables like press temperature, pressing and foaming times. The question was whether it is possible to reach different foam structures in the foam core particleboard. If so, how far will this affect the mechanical and physical properties of the panels (Publication II and III)? Since the foam density can have important influence on the foam structure and on the mechanical and physical properties of the foam, in this part of the project a constant foam density of

124 kg/m³ was selected. Two different press temperatures (130 and 160 °C) were used to evaluate processing parameters by reaching different foam structure.

One of the product parameters influencing the foam core particleboard is the substitution of the cheap wood particles (coarse wooden particles) by a more expensive material (oil based foamable polymer) in the core layer of particleboard. This leads to an increased panel price of foam core panels in comparison with the conventional particleboard. The foam core density was identified as the major parameter influencing the panels' production cost. The question was how much the core density of the board can be reduced? Would the panel's properties be good enough at lower level of core density (Publication IV and V)? A constant surface layer thickness of 3 mm was used in this set of experiments for 19 mm of sandwich type particleboard. Two different press temperatures (130 and 160 °C) were applied. Three different target core densities of 80, 100 and 120 kg/m³ were tested.

- Recyclability of foam core panels residues

In general, recycling is playing an increasing role in everyday life. Recycling options and utilization of residues is an important issue to be considered for each new product development. The possibility for recycling of trimming waste and production rejects of foam core particleboard was investigated by manufacturing wood plastic composites (WPC) panels made from laboratory produced foam core particleboard as residues (Publication VI). Physical and mechanical properties of produced WPC panels are tested.

- Fire performances

A joint statement has been published by the Alliance Consumer Fire Safety in Europe (ACFSE), which declares that ''the introduction of controls on the ignitability and fire performance of foam filled furniture throughout Europe would produce major benefits and would complement existing efforts on fire safety'' (Kobes et al. 2009). This shows that for further progress and marketability of novel foam core panels it is necessary to evaluate fire performance and flammability parameters of foam core panels and carry out a comparison with conventional particleboard as reference panel material (Publication VII). This has been considered in a series of experiments. Afterwards, the composition behavior of foam core particleboard without and with fire retardant treatments has been analyzed by the advanced cone calorimetry techniques (Publication VIII). In this study four different thermocouples were embedded at various depths of foam core particleboard to analyse the fuel composition.

# 3 Materials and Methods

In this thesis 19 mm foam core particleboard having either MS or EPS as core layer material were produced in a one-step process with different processing parameters. Evaluation of panel properties is based on testing physical and mechanical properties and visualization of foam and interface characteristics by means of FESEM microscopy.

## 3.1 FACE LAYER MATERIAL

For the face layers fine softwood-particles (≤ 2 mm) mainly spruce and pine were supplied by a particleboard mill. The particles were mixed with 12 % urea formaldehyde resin (Kaurit 350, BASF, Germany) based on oven dry mass of the wood particles. Ammonium sulphate (1 % based on solid content of the resin) as hardener was added to the resin prior to spraying on the wood particles. The adhesive-hardener mixture was sprayed onto the particle furnish tumbling in a rotating drum-type blender by using a compressed air spray head. The target density for the surface layers was 750 kg/m$^3$ which were kept constant in all the panel variations. The surface layer thicknesses were selected (3, 4 and 5 mm) depending on the experimental designs described later.

## 3.2 CORE LAYER MATERIAL

### 3.2.1 Expandable microspheres (MS)

Two different types of expandable materials were used for the core layer; a) Expandable microspheres (MS), b) Expandable Polystyrene (EPS). Microsphers were supplied by AkzoNobel. This microsphere is a thermoplastic copolymer consisting of acrylonitrile, methacrylate and acrylates (>70 % of the mass) and trapped isobutene (approx 28 % of the mass) as blowing agent. The activation temperature for the microspheres used in this study is 85 ˚C. The microspheres are delivered in form of a very fine white dry powder, the individual spheres having a size distribution of 3-30 µm. The type of Expancel microspheres used by Luedtke (2011) was 031 DUX 40 (AkzoNobel, Expancel Inc, Sweden). Since the microspheres are very fine, the powder type material was mixed with unresinated particles to ease scattering and allow for a better mat forming of the core layer. The amount of unresinated particles contained in the foamed core layer was 450 g/m$^2$ in each type of panel. Studies conducted by Luedtke (2011) revealed that this amount of unresinated particles in the core has only minor influence on the panel properties.

## 3.2.2 Expandable polystyrene (EPS)

The second type of core material used in this thesis was expandable polystyrene granulate provided by Sunpor Kunststoff GmbH, Austria. The type of EPS used in this study is Terrapor 4. The trapped blowing agent is pentane. The amount of pentane dispersed in polystyrene is 5.7 % by weight (at the time of packaging). With increasing temperature, the expandable polystyrene turns into a softened state and the pentane changes state from liquid to gaseous state. The heat-softened polystyrene granulates expand to reach the desired thickness. During expansion, the connectivity between the expanded beads and between the bead and the particles in the faces is achieved. The activation temperature for EPS lies within 95 - 115 ˚C. Granulate diameter of EPS particles was 0.3 - 0.8 mm. Because of the granulate size the EPS material can easily be spread evenly and therefore had not to be mixed with unresinated wood particles. Due to the usage of expandable polystyrene as the main core layer material in this Ph.D thesis, a short explanation for the polystyrene and EPS manufacturing process is presented here.

### *3.2.2.1 Polystyrene*

Plastics are classified as synthetic polymers consisting of organic compounds of high molecular weight, made from repeated units with low molecular weight called monomers (Hilado 1990). If a plastic contains lots of cells or bubbles is called foamed plastic, plastic foam or even polymeric foam. Lightweight, shock absorption, and good insulation are important traits of foamed plastics (Lee and Scholz 2009). Properties of plastic foam (e.g. physical, mechanical and thermal) are strongly depended on the polymer matrix, cellular structure and gas composition. Cell density, cell size distribution, expansion ratio and cell integrity are the major structural parameters determining the polymer foam characterization (Lee et al. 2007). These parameters result from the foaming technology which itself depends on the type of plastic to be foamed. This reveals that the different polymers exhibit variant properties depending on the foam characteristics, and hence they need distinct processing technology to accommodate these differences. Due to that, different foaming technologies (e.g. batch, semi-continuous and continuous processes) have gradually evolved for each polymer over the years.

Depending on the polymer type used in the polymerization process three distinct types of foamed plastics are achieved; thermoplastic, thermosetting and elastomeric foams (Troitzsch 1990). Polystyrene is a thermoplastic material mainly produced from the polymerization of styrene monomer (Figure 4). Styrene is produced either by dehydration of ethylbenzene or as byproduct during the production of propylene oxide. Polystyrene has a higher flexural modulus at room temperature compared to that of other thermoplastics (Lee et al. 2007). This results in higher rigidity of the

polystyrene foams at the same density in comparison to other thermoplastics. In other words, to reach the same flexural strength less polystyrene materials is needed when compared to other thermoplastics. Such advantages in material properties place other polymers out of competition against polystyrene in the thermoforming area. Furthermore, fine cell structure of polystyrene makes it ideal for insulation application (Gibson and Ashby 1988).

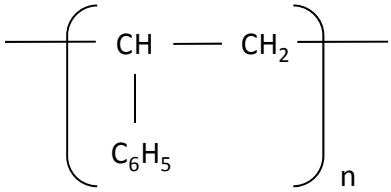


Figure 4: Styrene monomer

Both chemical (e.g. azodicarbonamide derivative) and physical (e.g. carbon dioxide, nitrogen, hydrocarbons and hydroflurocarbons) foaming agents can be used for foaming polystyrene (Lee et al. 2007). In case of using chemical foaming agent a closed cell structure with density ranging from 600 to 800 kg/m³ is achieved, while by using physical blowing agent PS foam with density less than 100 kg/m³ having either closed cell structure or open cell structure is obtained. Batch and continuous process are general methods for manufacturing of PS foam (Lee and Scholz 2009).

Spherical and small EPS beads ranging from 0.5 – 1 mm in diameter result from the styrene monomer polymerization (a batch-wise radical polymerization) in a styrene/water suspension process. A low boiling point hydrocarbon, called ‘‘blowing agent’’ is added at the end of the polymerization process of the beads. Different variety of hydrocarbons can be applied as the blowing agent like butane, propane, pentane, propylene, alcohols, esters and ketones. Pentane is most frequently used as the blowing agent in EPS due to its best cost/performance ratio.

### *3.2.2.2 Expanded polystyrene foam*

There are two major methods for manufacturing polystyrene foam block; molding of pre-expanded beads and direct extrusion. Generally, expanded polystyrene is made in three stages. First stage is called the pre-expansion. The expandable beads are heated with steam in a closed vessel while stirring constantly. The dispersed pentane is also heated up and gasified. At this stage the polymer softens and the increasing pressure of the pentane leads to the dramatic increase of the beads’ volume (approximately 40-50 times of its original volume). It is important to mention that the final density of the expanded foam is controlled at this stage. The cooling and drying of the pre-expanded beads are done at the end of the first stage.

The second stage is entitled maturing phase. The pre-expanded beads are stored to silos for aging, approximately 12-48 hours to stabilize. An internal vacuum inside the expanded beads is results from the expansion process and the release of the pentane. Equalization of this vacuum to the atmospheric pressure takes place during the maturing stage to control the undesired collapse or implosion of the expanded beads. Air slowly diffuses through cell walls into the expanded beads foam and substitutes the released pentane, so that equilibrium is attained.

The third stage involves the moulding of matured beads into the block. The pre-expanded beads still contain about 4 % pentane while being pumped into a mould. After filling of the mould, steam is injected for softening and further expanding of the beads. Fusion of the softened beads takes place due to the pressure resulting from the remaining pentane and the constraining effect of the mould. Cooling of the fused block under vacuum is done to remove the moisture from the block which determines the final foam performance.

## 3.3 PANEL PRODUCTION

### 3.3.1 Foam Core Particleboard

The three layered foam core particleboards were manufactured in a one-step process. After blending, the resinated wood particles for the faces were formed by hand using a 600 * 550 mm² forming box. The core layer material was also laid manually between the two surfaces after the bottom and before the top surface layer was formed. The three layered mat then was pressed in a computer controlled lab-scale single opening hot press (Siempelkamp, Germany) in three consecutive stages: pressing, foaming and stabilization.

The press cycle (pressure-time control) was performed as follows: 1) pressing stage; increasing of the specific pressure from 0 to 3 MPa during the first 10 seconds and sustaining pressure for the compaction and curing of the faces until the core materials reached the activation temperature; 2) foaming stage; decreasing of the specific pressure from 3 to 0 MPa with opening of the press plates to the final panel thickness (19 mm) to allow core expansion; 3) stabilization stage; active cooling of the press plates for stabilization of the panel by lowering the temperature of core layer material below its glass transition temperature (Tg). The panels having MS in the core were produced with a press temperature of 160 °C, while the press plate temperature was set to either 130 ˚C (1-$EPS_{130\ ^{\circ}C}$) or 160 ˚C (2-$EPS_{160\ ^{\circ}C}$) for the EPS panels. Table 1 shows the composition of the foam core particleboards produced in this thesis and tested their physical and mechanical properties.

At the second stage of the press schedule, the press plates should open to the predefined distance to allow core expansion. This opening of the press plates has to take place at the appropriate time to make sure that the panel will meet the expected requirements. There are two important conditions that have to be fulfilled; 1) surface layers should be compacted and its resin cured 2) the core layer materials should have reached the activation temperature for expansion. Apart from the type of core layer material, there are three main factors affecting the opening time of the press plates, e.g. pressing temperature, surface layer thicknesses and moisture content of the mat prior to pressing.

Table 1 Composition of the panel variables

| NO | Face thickness (mm) | Press temperature (°C) | Target density (kg/m³) | Foam density (kg/m³) | Pressing time (s) | Foaming time (s) | Stabilization time (s) |
|---|---|---|---|---|---|---|---|
| **MS** | | | | | | | |
| 1 | 3 | 160 | 300 | 120 | 45 | 10 | 160 |
| 2 | 4 | 160 | 400 | 150 | 55 | 10 | 200 |
| 3 | 5 | 160 | 500 | 180 | 65 | 10 | 240 |
| **1-EPS** | | | | | | | |
| A | 3 | 130 | 320 | 124 | 80 | 45 | 130 |
| B | 4 | 130 | 390 | 124 | 105 | 45 | 140 |
| C | 5 | 130 | 460 | 124 | 130 | 45 | 150 |
| **2-EPS** | | | | | | | |
| D | 3 | 160 | 320 | 124 | 45 | 10 | 140 |
| E | 4 | 160 | 390 | 124 | 55 | 10 | 170 |
| F | 5 | 160 | 460 | 124 | 65 | 10 | 200 |
| **3-EPS** | | | | | | | |
| Ad1 | 3 | 130 | 290 | 80 | 80 | 45 | 130 |
| Ad2 | 3 | 130 | 305 | 100 | 80 | 45 | 130 |
| Ad3 | 3 | 130 | 320 | 120 | 80 | 45 | 130 |
| **4-EPS** | | | | | | | |
| Dd1 | 3 | 160 | 290 | 80 | 45 | 10 | 140 |
| Dd2 | 3 | 160 | 305 | 100 | 45 | 10 | 140 |
| Dd3 | 3 | 160 | 320 | 120 | 45 | 10 | 140 |

In order to normalize pressing conditions, the time needed for the compaction and resin curing (100 °C at the face-core interface) of the surface layers is divided by the surface layers thickness. The resulting ratio is called ‘‘Press Factor’’. Using of press factor indicator shows the exact time for the opening of the pressing steel belt. By inserting thermocouples at the interface between the expandable material in the core and the wood particle in the face layers the temperature at the interface can be determined. It is assumed that the surface layer resin is cured and activation temperature of the core material is reached when a temperature of 100 °C is determined at the interface. This experimental procedure at the lab was followed

while the pressing temperature and surface layer thickness were changed. For these experiments four different press temperatures of 130, 160, 190 and 220 °C and also three surface layer thicknesses of 3, 4 and 5 mm were used. It should be mentioned that the panels using press temperature of 190 and 220 °C were only being produced for determination of opening time of the press belt (not for testing of physical and mechanical tests). Mat moisture content was kept constant at 8 % during the laboratory experiments for determination of the time needed to reach 100 °C at the interface. It should be mentioned that these experimental measurements have been conducted in panels having EPS as core layer material (Shalbafan et al. 2012b, Shalbafan et al. 2012d).

Heating the core layer of a panel is supported by the influx of steam generated by evaporation of the water contained in the surface layers of the mat (Thoemen 2000). Due to the combined process of conduction and convection, the core layer temperature will rise to the required level to allow the expansion of the core material. Hence, increasing moisture content of the wood furnish mat leads to more steam being generated from the surface layers and accordingly to more heat flux towards the core layer. The higher the heat flux, the faster is the heating up of the core layer to the required level for the expansion (Shalbafan et al. 2012b). The effect of the increasing moisture content from 8 to 12 % on the time needed to reach 100 °C in the face-core interface was only be analyzed by computer simulation using Virtual Hot Press (VHP) software.

### 3.3.2 Recycled Foam Core Particleboard (EPS Panels)

To investigate the recycling option of trimming waste and production reject resulting from a future foam core particleboard production, the 19 mm foam core panels produced in the laboratory (EPS as core layer material) were used as raw materials to make WPC panels. The foam core panels were manufactured with press temperature of 160 °C and had different surface layer thicknesses of 3, 4 and 5 mm (panel D, E and F). This leads to wood flour (WF) contents (by weight) of 75, 83 and 88 % in the final mixtures for making WPC panels. Particle size distribution of raw materials was determined according to DIN 66165. Raw materials prior to the flat pressing of the WPC panels were prepared in two ways; a) dry blending and b) pre-compounding in a twin-screw extruder. It should be mentioned that the dry blend of wood particle and polymer was directly received from milling without further processing needed. For a better interfacial bonding between the polar-hydrophilic wood and the non-polar-hydrophobic polymer, poly styrene-co-maleic anhydride oligomer, SMA2000 was used as coupling agent (CA) supplied from Sartomer Co., Exton/USA. The amount of SMA2000 incorporated in the mixture was 2 % based on the oven dry mass of the wood-polymer mixture. The composition of the WPC panels is shown in Table 2.

Table 2 Composition of the WPC panels

| Sample | Wood content (%) | Polymer content (%) | Coupling agent (%) | Mixing methods |
|---|---|---|---|---|
| 1 | 75 | 25 | - | Dry blend |
| 2 | 75 | 25 | 2 | Dry blend |
| 3 | 75 | 25 | - | Compounded |
| 4 | 75 | 25 | 2 | Compounded |
| 5 | 83 | 17 | - | Dry blend |
| 6 | 88 | 12 | - | Dry blend |

WPC panels were manufactured using a single opening hot press with temperature of 210 °C. Target panel density was kept constant at 1000 kg/m³. The mat was compressed for 400 s to the desired nominal thickness of 10 mm. At the end of the pressing cycle, cooling of the panels was performed under pressure (inside the press) by active cooling of the press plates for the next 400 s. With increasing WF content from 75 to 83 and 88 % the specific pressure were determined to be about 1, 2 and 3 N/mm² to reach the target panel thickness (10 mm), respectively.

### 3.3.3 Panel Properties

For foam core panel characterization, cross-sectional density profiles were measured using gamma-ray densitometry (Raytest GmbH, Trivolt PK60, Germany) and images from the core layer are taken by FE-SEM (Quanta FEG 250, USA).

For the mechanical properties (Publication I, II, IV and V), bending strength by three point test method, internal bond (IB), face/edge screw withdrawal resistance (SWR), surface soundness (SS) and planar shear test were determined. The physical behavior (Publication III) of the panels was characterized by dimensional stability and measuring thickness swelling (TS) and water absorption (WA) after water soaking (20 °C) in different time intervals. Reaction to fire (Publication VII and VIII) was also measured to evaluate fire performances of foam core panels. A list of property tests and the applied standards is presented in Table 3.

Planar shear properties of the foam core panels produced with different processing parameters were determined according to the pre-standard of prCEN/TS 00112189:2011.2, using universal testing machine (Zwick-Roell, Ulm, Germany). Three samples of 225*100*19 mm³ from each of four panel repetitions (n=12) were prepared and glued on the two piece of wooden support. A low temperature two components epoxy resin was used for bonding of the test samples to the wooden plates. All the samples were sanded prior to bonding for a better connectivity between the samples and the supports. Planer shear strength and planer shear modulus of rigidity were determined as the test results.

Table 3 Sample specifications for physical and mechanical tests

| Property | Standard | Sample size (mm) | Tested sample |
|---|---|---|---|
| Differential scanning calormetry | ASTM E 1356-08 | - | 1 |
| Particle size analysis | DIN 66165 | - | 50 gr |
| Density profile | EN 323 | 50*50*19 | 4 |
| Moisture content | EN 322 | 50*50*19 | 4 |
| Surface soundness | EN 311 | 50*50*19 | 12 |
| Bending strength | EN 310 | 430*50*19 | 12 |
| Internal bond | EN 319 | 50*50*19 | 12 |
| Screw withdrawal | EN 13446/EN 320 | 50*50*19 | 12 |
| Planar shear test | prCEN/TS 00112189 | 225*100*19 | 12 |
| Charpy impact strength | EN 179-1 | 80*10*10 | 30 |
| Thickness swelling | EN 317 | 50*50*19 | 12 |
| Water absorption | EN 317 | 50*50*19 | 12 |
| Dimensional stability | EN 318 | 300*50*19 | 12 |
| Reaction to fire | ISO 5660-1 | 100*100*19 | 3 |

With WPC panels (Publication VI), physical properties were characterized by density and moisture content measurement, as well as thickness swelling and water absorption after 2 h and 24 h and prolonged to 672 hours (periodically measured). Modulus of elasticity (MOE), modulus of rupture (MOR) and charpy impact strength (CIS) were determined as mechanical properties.

From each panel variation in this thesis four replicates were manufactured. Three samples of each replicates (n=12) were randomly selected and tested. Prior to testing all samples were conditioned in a climate chamber at 65 % relative humidity and a temperature of 20˚C until constant mass was reached. The samples were prepared as shown in Table 3. The physical tests were conducted on unsanded samples. Conventional particleboards supplied from the market were also tested for comparison purposes.

## 3.4 DATA ANALYZING

All the data analysis throughout this thesis was performed using statistical package for the social science (SPSS software, IBM). Scatter plot, histogram, and Kolmogorov-Smirnov tests were used for checking the assumption of normality. After the data normality check, a Leven test for checking the homogeneity of variances was applied. Thereafter, parametric ANOVA tests to evaluate possible significant differences between the mechanical and physical properties of produced panels using different processing parameters were performed. Statistical differences between variations were evaluated by multiple comparisons using either LSD or Dunnett3 test depending on variance status. The P-value level of statistical significance was set at $P<0.05$.

# 4 Results and Discussion

As the first analysis, produced foam core panels with two different core layer material (MS & EPS) are tested and compared by some important properties like density profile, bending strength (MOR), internal bond (IB), physical properties by means of thickness swelling and water absorption after 2 and 24 hours (Publication I).

For further analysis in this thesis, only foam core panels using EPS as core layer material were produced with different processing parameters and tested for a complete set of structural properties (i.e., field emission scanning electron microscopy (FESEM), Tg, density profile, surface soundness), mechanical properties (i.e., MOR, IB, screw withdrawal resistance, planner shear test) and physical properties (i.e., TS, WA, linear expansion and contraction). In addition, fire performances of untreated and treated samples and also recycling option for foam core particleboard residues were analyzed.

## 4.1 CHARACTERIZATION OF CORE LAYER MATERIALS

### 4.1.1 Pros and Cons of Microspheres and EPS

One of the important characteristics for the core layer material is that it has to be easy to scatter. Microspheres (MS) have a powder shape with a size in the micron range. To ease the handling and optimize the mat forming of the core layer, the microspheres should be mixed with wood particles (Luedtke 2011). This mixing of microspheres slightly diminishes the aim for achieving maximum weight reduction or reaching the lowest level of core layer density. The EPS beads are approximately 0.3 - 0.8 mm in diameter, which is about the size of sugar granules. With this granulate size the mixing of EPS with wood particles is not necessary for mat forming.

The first generation of Expancel microspheres was developed by companies KemaNord and Stora Kopparberg in 1973 (Anonymous 2008). Fourth generation of microspheres (the type used by Luedtke 2008) was introduced on the market in 2005. There exist only two producers for microspheres worldwide. Due to this the market for microspheres can be called monopolistic. Due to their relatively high price microspheres have are only applied in niche markets for special applications. But the EPS beads are not a new material which was patented by BASF in 1949. There are already several companies and manufacturers who are producing EPS materials all over the world. Hence, the availability of EPS beads are more than that of the MS.

Another important distinguished difference between EPS and MS is the price. According to the statement of EPS and MS producers, it can be said that the EPS

materials are much cheaper compared to MS (price relation MS:EPS ≈ 10:1). Expancel microsphere has a monopolistic market while for the EPS there exists a very competitive market. This leads to the decreasing price of EPS. On the other hand, the price of polymer ingredients of EPS itself (polystyrene monomer) is much lower compared to that of MS (a copolymer made of acrylonitrile, methacrylate and acrylates).

The glass transition temperature (Tg) measured by differential scanning calorimetry (DSC) for EPS (103 °C) is nearly 20 °C higher in comparison with the MS (85 °C). In this context, two important features should be discussed. A product containing thermoplastic foam can withstand temperatures below the Tg of the polymer. In other words, higher Tg means that the panel is more thermally stable. Additionally, since both EPS and MS are made of thermoplastic polymers, the cooling stage during processing is necessary to stabilize the foam cells after its expansion. The cooling of the polymer should be done to below its Tg. It should be also considered that the cooling has an important influence on the time the panel has to stay on the continuous press. For a given press length the cooling time needed will strongly affect production capacity and production costs. The higher the Tg, the less cooling is needed and, accordingly, higher productivity and lower cost are achieved (compared to a polymer foam with low Tg). The best solution would be a thermosetting expandable polymer because it would not need any cooling. But, a thermosetting expandable polymer which meets the entire requirement listed in chapter 2.1 has not yet been found.

A hydrocarbon as blowing agent is trapped in microspheres (isobutene) and dispersed in polystyrene (pentane). A flammable blowing agent air mixture may be generated during storage and processing of the EPS and MS. As mentioned earlier, the amount of isobutene in the microspheres is about 27 % by weight while for EPS it is 5.7 % by weight. Isobutene is trapped inside the shell of MS polymer and will be extracted from the shell if the breaking or crushing of the cells happens during expansion (foaming stage). This decreases the risk of generating flammable atmosphere during the storage and processing of MS. On the other hand, the high amount of isobutene as blowing agent which remains trapped inside the MS makes it flammable and therefore implies limitations with respect to certain applications. It should be mentioned that the dispersed pentane in polystyrene is extracted easier/faster compared to the isobutene in MS during both storage and processing stage. Due to the low initial amount of pentane (5.7 % by weight) in the EPS, the risk of generating flammable pentane-air mixtures will be decreased with adequate ventilation. Additionally, it should be mentioned that not all of the initial pentane (5.7 % by weight) will be extracted during the processing. About 2 % of pentane will remain inside the polystyrene after expansion which can be only extracted with EPS pyrolysis. This has a positive influence on the generation of explosive air mixtures

and therefore leads to a risk reduction. The lower and upper explosion limits (LEL and UEL) for pentane is 1.3 % and 7.8 % (vol/vol) and for isobutene 1.9 % and 8.5 % (vol/vol), respectively. Adequate ventilation can keep the levels of both isobutene and pentane below the lower explosive limit.

### 4.1.2 Physiomechanical Properties

A detailed comparison of mechanical properties between the panels having MS and EPS as core layer is presented in Publication I. As a summary, it can be said that the EPS panels with 3 and 4 mm facing have superior bending strength and internal bond values in comparison with the MS panels. The mechanical properties of EPS panels with 5 mm facing is inferior compared to the corresponding one with MS. This was due to the nearly 45 % higher MS core density in this types of panels what lead to the enhancing effect on bending strength and internal bond values.

Thickness swelling of 19 mm foam core particleboards using MS and EPS as core layer is shown in Figure 5. It is well explained in Publication III that the thickness swelling of foam core particleboards is a function of surface layer thickness. In the other words, foam core layer has no effect on the TS values due to the inherent hydrophobic properties of the polymeric foams. The thicker the surface layer, the higher a TS is achieved for all the soaking times. MS panels with a surface layer thickness of 3 and 4 mm have significantly higher TS compared to that of the corresponding EPS panels. In panels with 5 mm facing the differences are low and not significant. These higher TS in MS panels can be attributed to the un-resinated particles mixed with MS in the core layer.

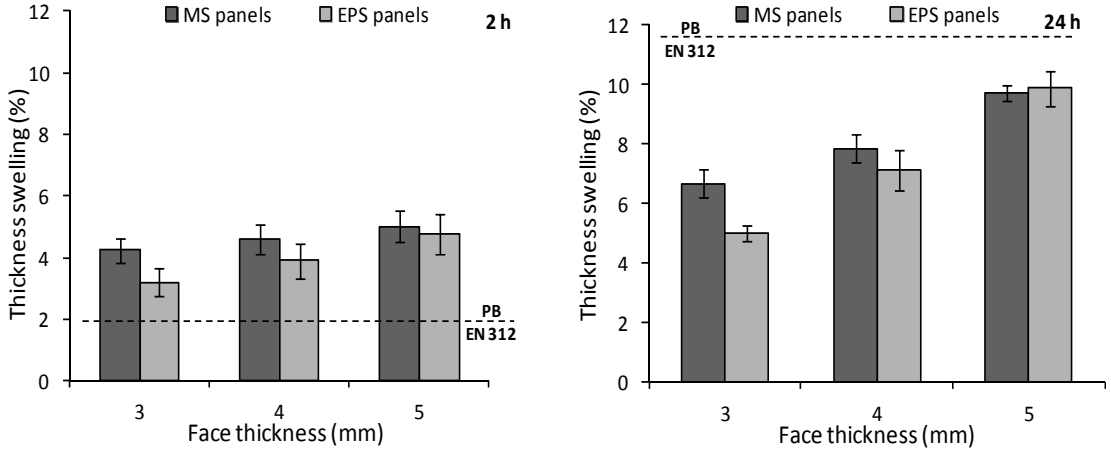


Figure 5: Thickness swelling of foam core particleboards after 2 (left) and 24 (right) hours soaking

TS of foam core panels in short term soaking (2 h) are significantly higher than those of conventional particleboards. With elevation of soaking time to 24 hours, it is seen that the foam core panels have lower TS compared with the conventional

particleboard. Further details regarding TS of foam core panels are discussed in Publication III.

Water absorption (WA) values of foam core panels using MS and EPS as core layer after 2 and 24 hours soaking are presented in Figure 6. Elevation of surface layer thickness (from 3 to 5 mm) shows two different trends for the WA values: 1. increasing of WA values for the EPS panels and 2. declining of WA values in the MS panels. The differences between the MS panels are reduced at longer soaking times.

It is also visible from the Figure 6 that the MS panels compared to the EPS panels have relatively higher WA values due to the un-resinated particles used in the core layer. Foam core particleboards have significantly higher WA values compared to the conventional particleboard (EN 312/P2).

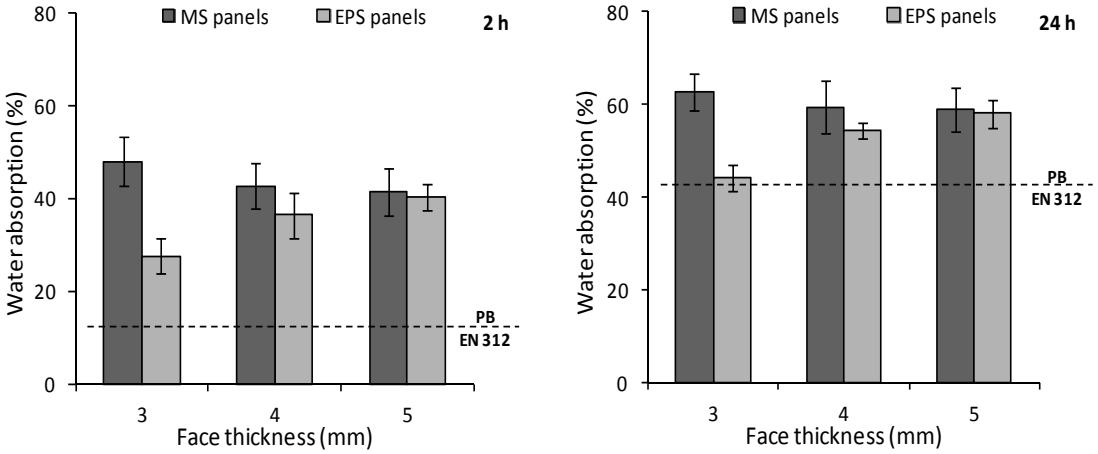


Figure 6: Water absorption of foam core particleboards after 2 (left) and 24 (right) hours soaking

As a result, this study showed that the EPS panels show a promising potential to substitute conventional particleboards in the furniture industry. EPS is more ideal to be used in the core layer of foam core particleboards due to the easy scattering, better availability and accordingly lower price, better technological characteristics (e.g. Tg) and superior physical and mechanical properties.

## 4.2 INFLUENCE OF PROCESSING PARAMETERS

### 4.2.1 Determination of Opening Time of the Pressing Steel Belt for Foaming

The pressing time needed for the compaction and curing (100 °C) of the surface layers determined by the experimental work in the lab is shown in Figure 7 as a function of press temperature and different surface layer thicknesses. The graph also shows the appropriate time for the opening of the pressing steel belt (press plates)

to allow core expansion during the second stage of the foam core process. It is clear that with increasing press temperature from 130 to 220 °C the pressing time during the first stage is dramatically decreased. The higher the press temperature, the faster is the resin curing of the face layers and accordingly less time is needed for the core layer material to reach the activation temperature. This indicates that with increasing press temperature the pressing steel belt should be opened after a shorter elapsed time because of the more intense heat flux to the core layer material.

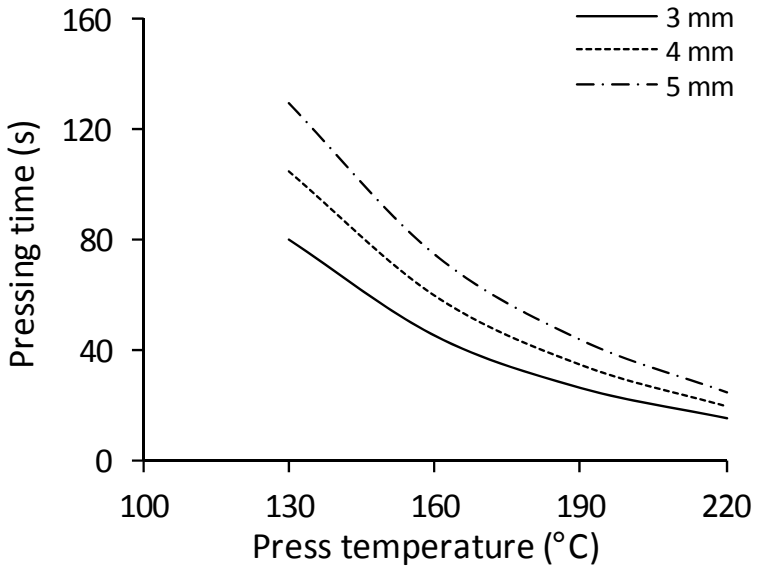


Figure 7: The pressing times to reach 100 °C in the face-core interface needed for compaction and initial curing of the surface layers obtained by experimental work

The Press Factor can be determined based on the experimental results shown in Figure 7. Table 4 shows the exponential functions and regression coefficients derived from the Press Factor data plotted with corresponding press temperatures. Y means Press Factor during the first stage of the pressing scheme and X is the press temperature.

Table 4 Exponential functions of Press Factor determined by experiment

| Face thickness | Function | Regression Coeff. |
|---|---|---|
| 3 mm | $Y= 148e^{-0.019X}$ | 0.99 |
| 4 mm | $Y = 143e^{-0.018X}$ | 0.99 |
| 5 mm | $Y= 140e^{-0.018X}$ | 0.99 |

The above mentioned experimentally results for determination of opening time of the press plates and Press Factor are based on a constant mat moisture content of 8 %. Increasing the mat moisture content causes an increment of heat flux towards the core layer and shortening the time needed for pressing steel belt opening. To see

the effect of increasing mat moisture content from 8 to 12 % on the opening time of the pressing steel belt have been done by computer simulation using Virtual Hot Press (VHP). Pressing conditions (e.g. density, pressing time, mat sizes, and specific pressure) resembling the laboratory production of the foam core panels were kept constant during the computer simulation using VHP. The VHP software predicts that pressing times needed before the press belt can be opened, show a reduction range between 7 to 17 % when the moisture content is raised from 8 % to 12 %. The time (in seconds) needed to reach 100 °C (equivalent with the opening time of the pressing steel belt) in the core layer materials during the first stage of press schedule as predicted by VHP is presented in Table 5.

It can be also seen from the Table 5 that the most important factors determining the opening time of the press belt is the face layer thicknesses, followed by the press temperature and MC of the face layers.

Table 5 Time (s) needed to reach 100 °C in the core layer materials (computer simulation with VHP)

| Press Temperature (°C) | Face Thickness (mm) | Time (8 % MC) | Time (12 % MC) | Reduction in % (8 to 12 %) |
|---|---|---|---|---|
| 130 °C | 3 | 36 | 30 | 16.7 |
| | 4 | 54 | 45 | 16.7 |
| | 5 | 78 | 65 | 16.7 |
| 160 °C | 3 | 25 | 22 | 12 |
| | 4 | 37 | 32 | 13.5 |
| | 5 | 52 | 44 | 15.4 |
| 190 °C | 3 | 20 | 18.5 | 7.5 |
| | 4 | 30 | 26 | 13.3 |
| | 5 | 40 | 35 | 12.5 |
| 220 °C | 3 | 17 | 15.5 | 8.8 |
| | 4 | 24 | 21 | 12.5 |
| | 5 | 34 | 29 | 14.7 |

### 4.2.2 Process Parameters and Properties

Different foam core particleboards can be produced by varying panel features (e.g. face layer thickness and foam core density) and press parameters (e.g. press temperature, pressing and foaming time). A series of experiments (Publications II, III, IV and V) have been conducted to verify the influence of process parameters on the resulting foam structures and accordingly panel properties.

### 4.2.2.1 Panel parameters

There are two major panel parameters in foam core particleboards which have an important influence on the panel properties as well as on the final panel cost; a) surface layer thickness and b) foam core layer density. For panels with a nominal thickness of 19 mm the effect of three different surface layer thicknesses (3, 4 and 5 mm) and foam core densities (80, 100, 120 kg/m³) on foam structure and panel properties have been investigated. The experiments (Publication II and III) show that an increment of the face layer thickness from 3 to 5 mm has a positive effect on the foam cell structure (finer and more cell size) due to the higher amount of water vapor which is generated from the wood particles and transported into the core layer material. It was also observed that thicker surface layers results in increasing bending strength, face screw withdrawal resistance (FSWR), thickness swelling and water absorption values. The thicker the surface layer, the higher is the panel density what is directly influenced the above mentioned properties. Furthermore, the increment of face layer causes more hygroscopic materials to swell more by water absorption. Internal bond shows an inverse trend with thicker face layers. The thicker the face, the lower are the achieved IB values. This is mainly attributed to the increment of low compacted face particles at the face-core layer interface (Publication II and III).

Increasing foam core density from 80 to 120 kg/m$^3$ (50 %) shows different trends on the physiomechanical properties of foam core panels (Publication IV and V). It does not affect the bending strength and TS, while it significantly increases both the face and the edge screw withdrawal resistance (SWR). Surface layer thickness in foam core particleboards has the superior influence on the bending strength and TS, due to the higher rigidity of wood (compared to the polymeric materials) and inherently hydrophobic property of the EPS core materials, respectively. Raising core density also shows two contrary trends on the internal bond values: an increase in case of the 1-EPS$_{130\,°C}$ panels and a reduction in case of the 2-EPS$_{160\,°C}$ panels. Most probably, the face-core layer interface quality is the reason for such trends. The results (Publication IV and V) also confirm that raising core density by 50 % leads to an increment of the foam cells numbers, what reduces the small voids between the cells and accordingly decreases the ability to absorb water.

### 4.2.2.2 Press parameters

Varying press parameters, like press temperature, pressing and foaming times, which are key parameters for process optimization, have caused different foam structures, surface layer quality and face-core layers interface characteristics. Each of these features has a strong effect on the different physical and mechanical properties of the panels. A denser surface layer is achieved by a low press temperature and the resulting longer pressing time (1-EPS$_{130\,°C}$ panels). An undesired

increment of the surface layer thickness (beyond the target value) in the 2-EPS$_{160\,°C}$ panels is a result of the short pressing time (nearly half of 1-EPS$_{130\,°C}$ panels). This, accordingly, leads to the ca. 10 % unwanted increase of foam core density (Publication III). Surface layer quality has an effect on surface soundness, bending strength and thickness swelling. A more rigid facing positively influences the surface soundness and bending strength values. Additionally, the thickness swelling values in long term soaking decline, due to the lower accessibility of the wood hydroxyl groups for the water molecules. Different surface layer quality is evident by observing the density profiles of the panels. Figure 8 shows a comparison of the density profiles of the 1-EPS$_{130\,°C}$ and the 2-EPS$_{160\,°C}$ panels, both with a surface layer thickness of 5 mm. The same graphical comparison for the panels with 3 mm surface layer thickness is presented in Figure 3 in Publication IV. It shows that the 1-EPS$_{130\,°C}$ have a more homogenous compaction zone in the surface layer due to the longer pressing time.

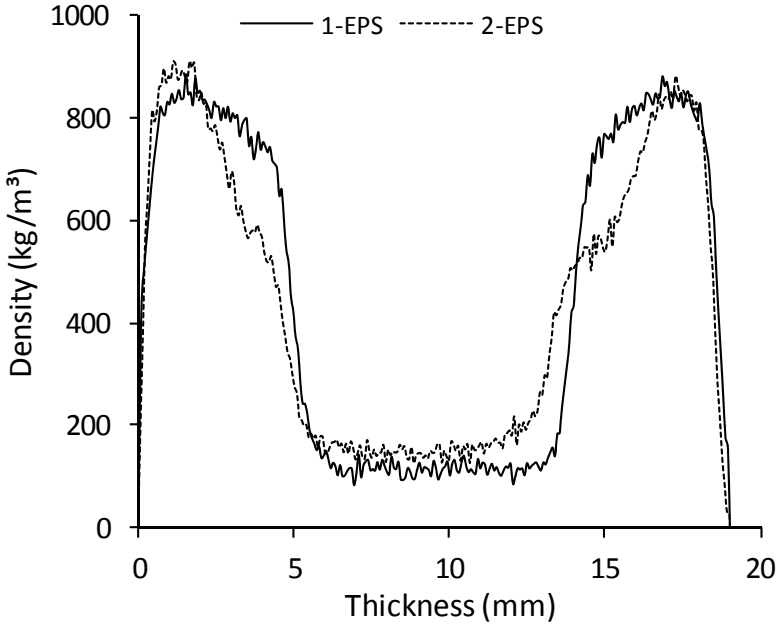


Figure 8: Comparison of density profiles for the 1-EPS$_{130\,°C}$ and the 2-EPS$_{160\,°C}$ panels

An improved interface between face and core layer materials is achieved in the 1-EPS$_{130\,°C}$ panels compared to the 2-EPS$_{160\,°C}$ panels. A chemical linkage between the wood particles in the face layers and polymeric core layer is not possible due to the inherent polar property of the wood particles and non-polar property of the EPS core materials. Longer pressing and foaming times in the 1-EPS$_{130\,°C}$ panels give more possibility to the semi-viscous EPS for penetration into the face layers particles and leads to a better mechanical interlocking between the wood particles and the foam cells. Figure 9 shows an example of EPS foam interlocked between the wood particles of the 1-EPS$_{130\,°C}$ panels.

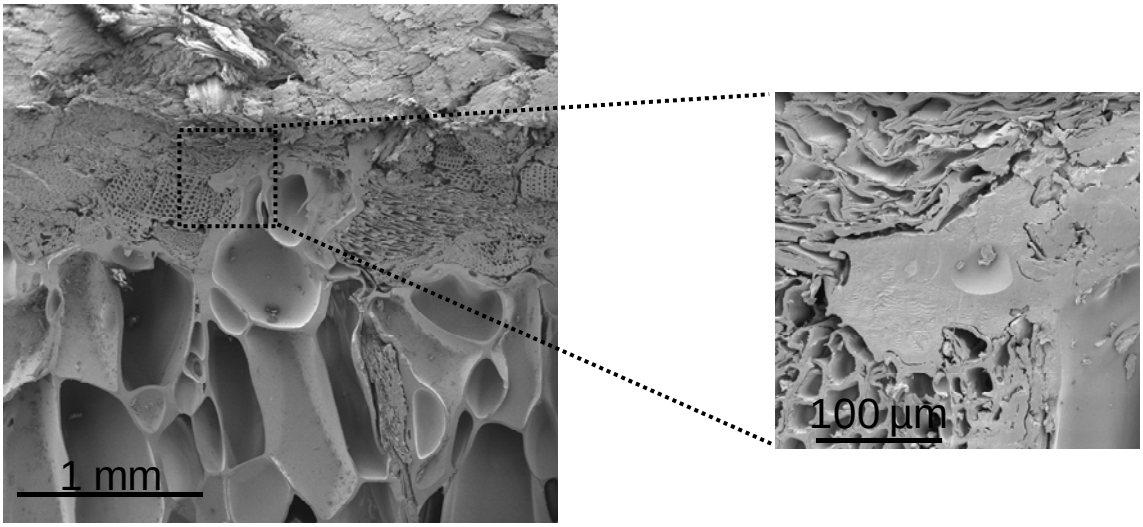


Figure 9: Penetrated of EPS foam into the face layer of the 1-$EPS_{130\,°C}$ panels

The interface between face and core layer plays an important role on the development of the internal bond values (Publication II and IV). Due to the strong interface the 1-$EPS_{130\,°C}$ panels have tremendously high IB values compared to those determined for the 2-$EPS_{160\,°C}$ panels. During the IB test, the failure of the 1-$EPS_{130\,°C}$ samples was observed in the foam core layer stating that the strength between EPS cells is lower than the strength of the face-core interface. For the 2-$EPS_{160\,°C}$ panels the failure always occurred in the interface. It is worth mentioning that, due to the better foam characteristics (smaller and more uniform foam cells) the IB values of the 2-$EPS_{160\,°C}$ would be even higher than those of the 1-$EPS_{130\,°C}$ panels, if the interface would have been stronger (Publication II and IV).

The foam structure achieved with the 2-$EPS_{160\,°C}$ panels strongly influences the edge screw withdrawal resistance (ESWR) and water absorption values (Publication II). Observation of the microstructure pictures of the EPS foam (Publication II and IV) shows that the panels produced with higher press temperature and shorter foaming time (2-$EPS_{160\,°C}$ panels) have better foam cell configurations (more and finer cells) than the panels produced with lower pressing temperature. The ESWR is nearly doubled in the 2-$EPS_{160\,°C}$ panels compared with the 1-$EPS_{130\,°C}$ panels due to the more and finer foam cells. The better foam structure in the latter is also reflected by the lower water absorption during soaking test in comparison to the 1-$EPS_{130\,°C}$ samples. It can be expected that controlling foam cell size could act as a compensating factor for maintaining mechanical properties in a desirable range while foam core density is reduced for future optimization steps.

Affirmation of the enhanced interface between face and core layer in the 1-$EPS_{130\,°C}$ panels and better foam cell configuration in the 2-$EPS_{160\,°C}$ panels is also documented by the planar shear test. The ability to prevent internal slipping of one layer upon another within the panel is detected by planar shear or inter-laminar

shear failure. This is an indicator for qualification of the glue line or bonding performance inside or between the test materials (Forest Product Laboratory 2010), because the planar shear often takes place where stresses have to be transferred between components through an adhesive joint. The result of planar shear strength of 19 mm foam core particleboards is shown in Figure 10. Planner shear strength in the 1-EPS$_{130\,°C}$ panels increases from 0.64 N/mm² for the 3 mm facing to 0.85 N/mm² for the 5 mm facing, whereas the values for the 2-EPS$_{160\,°C}$ panels are declined from 1.0 N/mm² for the 3 mm facing to 0.57 N/mm² for the 5 mm facing.

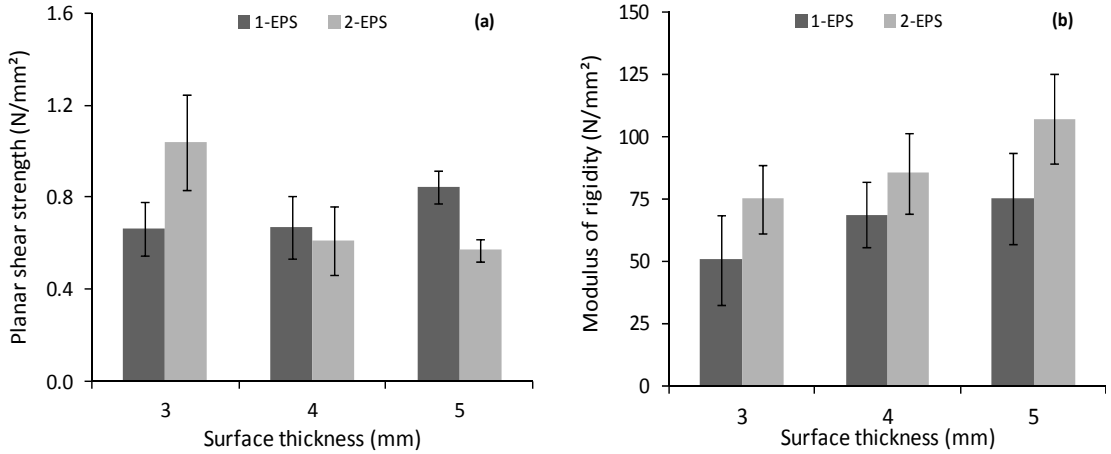


Figure 10: Planner shear strength and modulus of rigidity of foam core particleboards

It is shown that an increment of surface layer thickness leads to two different trends for the planar shear strength; a) increment in case of the 1-EPS$_{130\,°C}$ panels and b) decline in the case of the 2-EPS$_{160\,°C}$ panels. The reason for this can be derived from the failure modes observed for the tested samples, which are illustrated in Figure 11. The 1-EPS$_{130\,°C}$ samples failed in the middle of foam core layer while in the 2-EPS$_{160\,°C}$ samples the slippage occurs in the interface of face-core layers. It was demonstrated earlier (Figure 2 in Publication II) that the 1-EPS$_{130\,°C}$ panels have an enhanced interface compared to the 2-EPS$_{160\,°C}$ panels. In other words, in the case of the 1-EPS$_{130\,°C}$ samples the planar shear strength of the face-core interface is higher than the shear strength of foam cells. Due to the enhanced foam cell configuration in the 2-EPS$_{160\,°C}$ panels on the one hand and the weak face-core interface on the other hand, the shear failure occurred in the interface. It is supposed that the 2-EPS$_{160\,°C}$ panels with a better face-core interface would maintain much higher planner shear strength in the core layer, as it was observed for the 2-EPS$_{160\,°C}$ sample with 3 mm surface layer thickness where the interface was slightly better than the others (facing with 4 and 5 mm).


Figure 11: Failure made in tested foam core particleboards for planar shear test

The modulus of rigidity or shear modulus describes the resistance to deflection of a member caused by shear stresses. Figure 10b shows the modulus of rigidity of foam core particleboards produced with different processing parameters. The value for the 1-$EPS_{130\,°C}$ increases from 50 N/mm² for 3 mm facing to 75 N/mm² for 5 mm facing, and for the 2-$EPS_{160\,°C}$ from 75 N/mm² for 3 mm facing to 107 N/mm² for 5 mm facing. Enlarging the face layer thickness (from 3 to 5 mm) leads to the declining of foam core layer thickness (from 13 to 9 mm) and accordingly the modulus of rigidity for both panel types was significantly elevated. This is due to the fact that wood is stiffer and stronger than the polymer core material (Clemons 2008). The modulus of rigidity for the 2-$EPS_{160\,°C}$ panels is also significantly higher than the corresponding values for the 1-$EPS_{130\,°C}$ panels. This is attributed to the stronger foam cell configurations as a consequence of more and finer foam cells in the 2-$EPS_{160\,°C}$ panels (Figure 2 and Figure 9 in Publication II). This finding also confirms the results presented in Figure 5 in Publication II.

## 4.3 RECYCLABILITY OF FOAM CORE PARTICLEBOARD RESIDUES

Flat pressed WPC panels made of milled residues of foam core particleboards as raw material were characterized by physical and mechanical tests (Publication VI). Size distribution of milled powder from foam core particleboard indicated that the bigger particles belong to the EPS core layer and fine particles resulted from wood material in the surface layers. Density comparison of WPC panels showed that with elevating wood flour content (WF) from 75 to 88 % and adding of coupling agent (CA) the conditioned and dried densities were raised nearly 13 % in both panel types made of dry blend and pre-compound material. Panels made of pre-compound material have higher density in comparison to those made of dry blend material. Pre-compounding of raw material and adding of CA lead to declined equilibrium moisture content (EMC) values.

Thickness swelling (TS) and water absorption (WA) in different time intervals (2, 24 and 674 hours) significantly increased with raising WF content and soaking time. The results (Publication VI) showed that pre-compounding of waste-raw materials has a negative influence on TS and WA values due to more wood breakage and degradation in waste materials (Balasuriya et al. 2001). Additionally, CA improved TS and WA when it was added during pre-compounding process of raw materials due to the enhanced bonding between wood and polymer (Adhikary et al. 2008). But due to the insufficient distribution and placement of the CA in the dry blend samples, it leads to elevation of both TS and WA (Benthien and Thoemen 2012).

Bending properties (MOE and MOR) of flat pressed WPC decline with higher WF content (from 75 to 88 %), which is presented in Figure 7 in Publication VI. This can be attributed to the reduced binding between wood flour as a consequence of declining EPS polymer content as binder (Chaharmahali et al. 2008, Sanadi et al. 2001). The additional process of pre-compounding has negatively influenced the bending properties. Furthermore, CA acts as plasticizer in dry blend samples and reduces the bending properties (Poletto et al. 2011). But, subjoining of CA in pre-compounding materials has improved both the MOE and MOR. The trend observed for bending properties was determined for the charpy impact strength of WPC test samples. Elevation of WF decreases the CIS due to the weakening of the interface between wood flour and polymer (Butylina et al. 2011). Dry blend samples showed superior values of CIS compared to the pre-compounded samples. Although subjoining of CA improved the CIS, dry blend samples without CA still have higher CIS.

This study (Publication VI) showed that durable and water resistant WPC panels can be easily produced by using milled foam core particleboards. Costly treatments like adding CA and further compounding of raw materials (extruder mixing) have no positive effect on the panel properties. The superior panel properties were obtained with dry blend material which can be easily prepared.

The type of raw materials, mixing/compounding techniques and processing technologies for making the commercial WPC products lead to the wide range of variations and properties for the WPC products. Due to that the physical and mechanical properties of flat pressed WPC determined in this study has not been compared with any commercially available WPS panels.

## 4.4 FIRE PERFORMANCES

### 4.4.1 Fire Behaviour of Untreated Foam Core Particleboard

A summary of the values for all characteristic fire parameters of foam core particleboards is given in Table 2 and Table 3 in Publication VII. It is found that the time to sustained ignition (TSI) is a function of surface layer thickness and surface layer density. The thicker and denser the surface layer, the higher the TSI is.

The graphs of heat release rate (HRR) for foam core particleboards are illustrated and interpreted in Figure 3 in Publication VII. Overall, the whole combustion period of foam core particleboards is nearly half of that for the conventional particleboard. High first peak of HRR of foam core panels is a consequence of the protective effect of the foam core underneath the wood surface layer. The second peak of HRR refers to the pyrolysis front acceleration into the core layer and volatilization of combustible materials of the back side of the board. Although, elevating of surface layer thickness (from 3 to 5 mm) has positively reduced the peak of HRR, but an increase of core density (from 80 to 120 kg/m³) displayed no significant effect on the peak of HRR.

A 10 to 20 % lower amount of total heat released (THR) was achieved for the foam core panels in comparison with the conventional particleboard due to the substituting of high amount of coarse particles in particleboard with small amount of EPS. Figure 6 in Publication VII shows the flashover propensity and THR of the foam core panels. This also indicates that the surface layer thickness has an important effect on the ignition speed. The thinner the face layer, the faster the ignition is.

Average effective heat of combustion (EHOC) is calculated as the ratio of THR to total mass loss (Publication VII). Surface layer increase from 3 to 5 mm reduced significantly EHOC due to the corresponding decrease of EPS foam core layer thickness (from 13 to 9 mm). The 2-$EPS_{160\,°C}$ panels showed a higher average EHOC as a result of different foaming condition and accordingly also a higher total heat released (THR). Mass loss rate (MLR) is a function of HRR. The higher the HRR, the higher is the MLR. This is attributed to the more complete pyrolysis and volatilization of the combustible materials.

Average specific extinction area (ASEA) of foam core particleboards presented in Publication VII shows that the surface layer thickness and foam core density significantly influences the ASEA. Increasing surface layer thickness (from 3 to 5 mm) and decreasing core layer density (from 120 to 80 kg/m³) have declined ASEA. Foam core panels generally have much higher ASEA in comparison with the conventional particleboards due to the foam core component.

### 4.4.2 Cone Calorimeter Analysis of Treated and Untreated Panels

Flammability properties of foam core particleboards without and with fire retardant improvements have been analyzed by the advanced cone calorimetry techniques (Publication VIII). Improved heat release rate calculations were also designed. The physical state of the EPS foam core (softening, melting, decomposition, and ignition) have been observed by inserting four thermocouples attached to the various depths of the specimen (middle of both surfaces and two face-core interfaces). A state-of-art gas analysis procedure was designed to determine composition features of panel pyrolysis, which resulted in validating the calculations of empirical composition of the volatiles as Y/X and Z/X, and of carbon loading and oxygen mass to fuel mass ratio. These various analytical procedures were used to evaluate sandwich panels that had a) surface layer without veneer, b) surface layer with beech veneer, and c) surface layer with beech veneer-intumescent paper.

For all these three variations of foam core particleboards good agreement of the fuel mass rate from gas analysis with the load cell time derivative is obtained. Only in panels treated with beech veneer-intumescent paper good improvement in flammability properties have been observed, because more of the pyrolysis is occurring after 600 seconds, thereby effectively reducing the HRR contributing to the ASTM E84 test environment (Publication VIII). Temperature profiles showed that the EPS degradation is occurred at times around 100 and 150 seconds for the panels without and with veneer, respectively. EPS remained below the degradation temperature of 350 °C at times up to 600 seconds in panels treated with veneer-intumescent paper. Generally, the cone calorimeter tests at 50 $kW/m^2$ show that the veneer-intumescent paper composite protected the core EPS foam from degrading, as well as seal and dilute wood volatiles in the early stages of pyrolysis, to where it may be possible to achieve a Class A flame spread rating (Publication VIII).

# 5 Conclusions and Outlook

Wood based panel manufacturers are recently faced to reduce panel density due to the decreased raw material availability (competition with the energy sector) and accordingly increased price for raw materials. Moreover, new design and ease of handling are arguments for the panel and furniture producers to reduce weight and increase lightness of furniture elements. Investigations in this thesis showed that producing lightweight foam core particleboards with an one-step process consisting of three consecutive stages derived from the conventional production line of particleboard can offer a alternative for certain applications in the furniture industry.

The first study of this thesis shows that the using of expandable polystyrene (EPS) is more ideal to be used in the core layer of foam core particleboards in comparison to the expancel microspheres (MS). The main reasons for the better performance of EPS are easy scattering, better availability and accordingly lower price, better technological characteristics (e.g. Tg) and superior physical and mechanical properties. Hence, other research conducted in this thesis was focused on the panels produced with EPS as core layer material.

Final performance of foam core particleboards is significantly dependent on the quality of surface layers, face-core interface and foam cells configurations. Each of these features has affected the physical and mechanical properties of foam core particleboard. Varying of the both panel (e.g. surface layer thickness, core layer density) and press (e.g. press temperature, pressing and foaming times) parameters lead to the different quality of these features. Surface layer quality is influenced the density profile, surface soundness, bending strength and thickness swelling. Internal bond and planar shear strength/modulus are significantly affected by the face-core interface of the foam core particleboards. Foam cell configuration is also impressed the water absorption values and the edge screw withdrawal resistance.

It is understood from this thesis that the opening time of the pressing steel belt (plates) for foaming significantly changes the aforementioned panel features and accordingly final panel performances. The most important factors determining the opening time of the press belt for foaming is the face layer thicknesses, followed by the press temperature and moisture content of the face layers, regardless of the type of core layer material. Press belt was opened for foaming in the panels produced with low press temperature (1-$EPS_{130\,°C}$) after a longer time (nearly double) compared to the panels produced with high press temperature (2-$EPS_{160\,°C}$). Heat transfer towards the core layer in the 1-$EPS_{130\,°C}$ panels reaching the EPS activation temperature is slower than those in the 2-$EPS_{160\,°C}$ panels. This leads to the longer compaction of the surface layers in the 1-$EPS_{130\,°C}$ panels and, accordingly, longer time for interlocking of the EPS core layer material with the wood particles close to

the face-core interface. These are the reasons for better surface layer quality and enhanced face-core interface in the 1-$EPS_{130\,°C}$ panels. It should be pointed out that the increasing of pressing time in the 2-$EPS_{160\,°C}$ panels more than the specified values to have better surface layer quality like the 1-$EPS_{130\,°C}$ panels cause more blowing agent extraction (pantene) during pressing stage and, accordingly, foaming power is decreased and uneven surface layers will be achieved.

The most significant findings to be revealed from the experiments (Publication II, III, IV and V) are that the panel properties can be varied in wide ranges to obtain panels which fulfill minimum requirements set by industrial users. Suitable process parameters can be designed to produce foam core panels that meet physiomechanical requirements comparable to conventional particleboard.

The focus of the sixth study (Publication VI) was for the trimming waste and rejected foam core panels during industrial production line, whereas this recycling option may also be implemented for the panels after their service life. It should be considered that foam core particleboards after their service life would be supposed to have higher amount of contaminations. Due to the costly procedure and difficulties for separation of impurities, it is proposed to burn foam core panels after their service life. Trimming waste and rejected panels have clean and well composition for making flat pressed WPC with the same production line for foam core panels. Since both of these products (foam core panels and WPC) should be produced with a flat press having a cooling zone integrated with the pressing zone, the recycling option can be done once a week/two weeks with the same production line. As the study showed, extrusion process and using of coupling agent is not recommended for producing WPC of these residues.

To confirm and support general advantages of lightweight foam core particleboards, the possible restriction due to fire performance was examined (Publication VII & VIII) with cone calorimetry tests (ASTM E 1354-11a) and compared with conventional particleboard. In comparison to the reference particleboard the foam core panels generally had much higher heat release what reduced their burning times approximately in half. They also show higher heat of combustion and smoke production due to the EPS component of foam core panels. However, as the surface layer thickness was increased from 3 to 5 mm, the flammability properties began to improve and approached, as expected, those of the reference particleboard. Gas analysis of the treated and untreated foam core particleboards to reveal their decomposition behavior show the veneer-intumescent paper composite protected the core EPS foam from degrading, as well as seal and dilute wood volatiles in the early stages of pyrolysis, to where it may be possible to achieve a Class A flame spread rating.

As a final conclusion, it can be said that lightweight foam core particleboard can in the future increasingly be used to replace conventional wood-based particleboards in the furniture industry. With a proper design, structural constructions made of lightweight panels can achieve weight reductions of up to 50 % compared to conventional particleboards, while still maintaining comparable strengths. Further developments in materials design processes will lead to even lighter components with strength and stiffness properties that can be optimally adapted to suit the requirements.

There are still a lot of research topics regarding foam core particleboards for further investigation. As an outlook, it is assumed that increasing press temperature more than 160 °C would result in a better quality of panel features (surface layer, face-core interface and foam cell configuration) which leads to the outstanding physical and mechanical properties of foam core panels. Further research can be conducted in the area of improving the quality of face-core interface, especially in panels produced with high press temperature (> 200 °C), and detailed study of foam cells topology (e.g. cell density, cell sizes and etc.).

One of the most interesting outlooks for further research would be the development of other foam materials, especially expandable thermosetting foam which fulfills the requirements of core layer materials detailed in section 2.1. This is very important condition for industrialization of foam core particleboard. To produce foam core panels in industrial scale with already exiting production line the cooling of the core layer should be removed by using of thermosetting polymers. Although using of bio-based polymers as core layer like poly lactic acid (PLA) can give a great ecological advantage, but this has to be also considered that the PLA is a thermoplastic polymer which needs cooling for stabilization stage. Developing a thermosetting bio-based polymer to be used in foam core panels would be of high interest.

Research surveying the environmental impact of foam core particleboards by doing life cycle assessment (LCA) and comparison with the conventional wood based panels would be another interesting research.

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# Peer Reviewed Publications

# I

# Comparison of foam core materials in innovative light weight wood-based panels

**Ali Shalbafan**
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DOI 10.1007/s00107-011-0552-0

ORIGINALS ORIGINALARBEITEN

# Comparison of foam core materials in innovative lightweight wood-based panels

**A. Shalbafan · J. Luedtke · J. Welling · H. Thoemen**

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**Abstract** In the present paper, lightweight wood-based foam core panels were produced in a novel continuous process. Expandable microspheres (MS) and expandable polystyrene (EPS) were used as core materials. The influence of surface thickness and core materials on bending strength, internal bond and specific strength of the produced panel were investigated.

With increasing the surface thickness, bending strength was increased in both core types of panels. The internal bond value of the panels with expandable microspheres was steadily raised while the surface thickness was increased. The internal bond for the expandable polystyrene with increasing face thickness was reduced. In comparison with conventional particleboards, the specific bending strength and internal bond were increased. In addition, FE-SEM-microscopy and gamma-ray densitometry were used to characterize the panels.

**Vergleich von Schaumkernmaterialien in innovativen leichtgewichtigen Holzwerkstoffplatten**

**Zusammenfassung** Leichte Schaumkernplatten wurden in einem neuartigen einstufigen Verfahren hergestellt. In zwei Plattenvarianten wurden als Mittellagenmaterialien expandierbare Mikrosphären (MS) und expandierbares Polystyrol (EPS) eingesetzt. Der Einfluss der Decklagendicke und des Kernmaterials auf Biegefestigkeit, Querzugfestigkeit und die korrespondierenden spezifischen Festigkeiten wurde untersucht.

Es konnte ein deutlicher Einfluss der Decklagendicke auf die Biegefestigkeiten beider Plattenvarianten und eine steigende Querzugfestigkeit der Platten mit MS-Mittellagen nachgewiesen werden. Die Querzugeigenschaften der Platten mit MS-Mittellagen reduzierten sich mit steigender Decklagendicke. Im Vergleich zu konventionellen Spanplatten konnte eine Erhöhung der spezifischen Biege- und Querzugfestigkeiten festgestellt werden. Die Analyse der Ergebnisse erfolgte mit Hilfe von FE-SEM-Mikroskopie und Gammastrahlen-Densitometrie.

## 1 Introduction

A wood-composite sandwich panel comprises two identical face sheets which are separated by a thick and light core material. The faces are bonded to the core material to obtain a load transfer between the components (Allen 1969; Vinson 1999). Actually, sandwich panels are no new products, since they have been used and show widely growth mainly in construction, aerospace and furniture industries in recent decades (Karlsson and Aström 1997). Numerous approaches have been made to save weight, since the costs for raw materials and energy have been rapidly increasing recently. Using of low density species were the preliminary tests for reducing the density of conventional particleboard and MDF to provide strength and lightweight panels. In addition, sustaining the mechanical properties of the produced

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panels in a desirable range for certain usages is a critical aspect (Wang et al. 2008).

The use of plywood, thin particleboard and MDF as faces and different types of honeycombs, end-grain balsa wood and expanded foams as core layers in multi-stage process were the subsequent trials to achieve low density panels in sandwich constructions. The variety of wood-based sandwich panels basically depends upon the configuration of the different type of core material (irrespective of the face material constituents). Developing core materials also has continued from the 1940s through to today in an effort to reduce the weight of sandwich panels (Gibson and Ashby 1997; Zenkert 1997; May-Pat et al. 2010). The main benefits of the lightweight wood-based foam core panels for furniture applications are a high strength to density ratio, lighter and easier transporting and handling and also lower transportation costs (Michanickl 2006).

Doroudiani and Kortschot (2004) investigated the relationships between processing, structure and mechanical properties of wood fiber polystyrene composites produced by a batch foaming technique. Since most of the manufacturers are not willing to use a production process that is related to changes in their major technology, foam core panels produced in a one-stage process have become important arguments for the production of lightweight panels.

In the current study, the panels were manufactured in a continuous process from a three layered mat without additional gluing between the face and core layers Luedtke et al. (2008a). This study was performed to obtain information on the mechanical properties of multi–layered lightweight panels using expandable microspheres (MS) and expandable polystyrene (EPS) as core materials. The objectives of the study were to evaluate the bending strength, internal bond and specific strength of the panels produced in a simulated continuous process.

## 2 Materials and methods

### 2.1 Facing materials

For each type of produced panels, resinated wood particles (>90% softwood) from a particleboard mill were used for the surface layers. The urea formaldehyde resin (BASF) content was 12% based on oven dry mass of wood. 1% hardener (Ammonium sulfate) based on solid content of resin was added. The wood particles were resinated by using a rotating drum-type blender. The target density was calculated as 750 kg/m$^3$ for the surface layers.

### 2.2 Core materials

Two different types of expandable materials were used for the cores. Expandable microspheres (MS) were supplied by AkzoNobel. The microspheres are small spherical particles comprising a polymer shell encapsulating liquid isobutane as blowing agent. When the microspheres are heated up to a certain temperature, gas pressure inside the shell increases while the shell softens which results in a volume increase of the microspheres. The activation temperature for the microspheres used in this study is 85°C. Since the microspheres are very fine (∼15 µm), the powder type material was mixed with unresinated particles for a better mat forming. The amount of unresinated particles was 450 g/m$^2$ in each type of panel. Earlier studies revealed that this amount of unresinated particles has only minor-influence on the panel properties (Luedtke et al. 2008b).

The second type of core material used was expandable polystyrene granulate (Sunpor). The trapped blowing agent is pentane. With increasing temperature, the expandable polystyrene turns into a softened state and the pentane changes state from liquid to gaseous state. The heat-softened polystyrene granulates expand to reach the desired thickness. During expansion, the connectivity between the expanded beads and between the bead and the particles in the faces is achieved. The activation range for EPS lies within 95–115°C. Granulate diameter of EPS particles was 0.3–0.8 mm. Because of the granulate size the EPS materials can easily be spread evenly and therefore did not have to be mixed with unresinated particles.

It should be mentioned that both isobutane (microspheres) and pentane (EPS) as blowing agents might form an explosive gaseous mixture with air in a manufacturing process. The lower and upper explosion concentration limits (LEL and UEL) for pentane are 1.3% and 7.8% (vol/vol) and for isobutane 1.9% and 8.5% (v/v), respectively. Adequate ventilation can keep the levels of isobutane and pentane below the lower explosive limit. Quantification of gas emissions (during the process and also from produced panels) as well as possible measures to reduce the danger of explosion is dealt with by ongoing research projects at University of Hamburg.

### 2.3 Production of the panels

The 19 mm panels are manufactured from a three layered mat without additional gluing between the face and core layers. The surface layers are comprised of resinated wood particles and the core is formed from an expandable material. Such a mat is then processed in a lab-scale single opening hot-press Siempelkamp (press plate size: $800 * 600$ mm$^2$). The temperature of the press plates was 160°C. The press cycle is divided into three phases. The resinated particles in the surface layers are compacted and cured in the first phase. When the temperature of the thermo-sensitive core materials reaches the activation point, the press opens to the predefined distance (final thickness of the panel) to allow core

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**Table 1** Composition of variables of the produced panels
**Tab. 1** Variationsmatrix der hergestellten Platten

| No | Surface thickness | Core material | Target density kg/m$^3$ | Core density kg/m$^3$ |
|---|---|---|---|---|
| 1 | 3 | MS+ wood particles[a] | 300 | 120 |
| 2 | 4 | MS+ wood particles[a] | 400 | 150 |
| 3 | 5 | MS+ wood particles[a] | 500 | 180 |
| 4 | 3 | EPS[b] | 320 | 124 |
| 5 | 4 | EPS[b] | 390 | 124 |
| 6 | 5 | EPS[b] | 460 | 124 |

[a]MS: Expancel Microspheres 031 DUX40

[b]EPS: Sunpor expandable polystyrene Terrapor 4

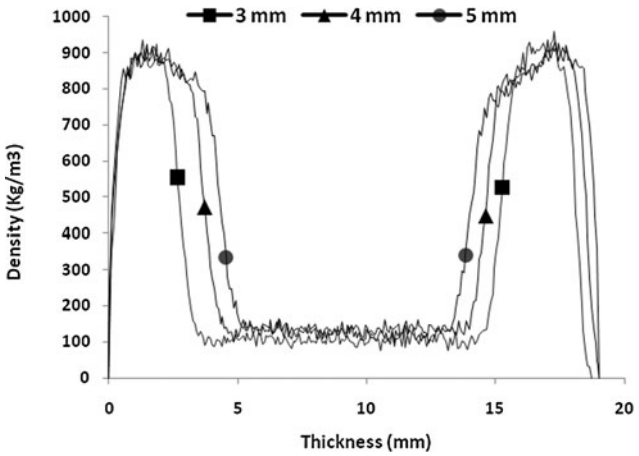


**Fig. 1** Density profiles for different surface thicknesses of the EPS panels
**Abb. 1** Dichteprofile der geprüften EPS-Platten mit unterschiedlichen Decklagendicken

expansion. At this time, the pressing distance is kept constant until the expansion is finished (Luedtke et al. 2008a). The press program allows simulating the pressing condition in a continuous hot press with a cooling zone.

The panels were produced with varying surface thicknesses 3, 4 and 5 mm. Four repetitions from each type of variation in the panel were produced using the two different core materials. Table 1 shows the composition of the variables.

### 2.4 Preparation of samples

For a better understanding of the panel formation, determination of the cross sectional density profile was conducted using gamma-ray densitometry with measuring steps of 75 µm. Figure 1 shows the three density profiles of the panels with different surface thickness. The graphs show a highly symmetric density profile. It is clearly shown that with increasing facing thickness, the core thickness is equally decreased.

The bending strength tests were performed with a universal testing machine (Zwick-Roell) and the samples were tested at a constant cross head displacement of 8 mm/min. For the three point bending test, the samples and tests were conducted according to EN310. Three samples of $430 * 50 * 19$ mm$^3$ for each repetition ($n = 12$) were prepared and the modulus of rupture (MOR) was determined.

The internal bond strength tests were accomplished according to EN319 using a universal testing device (Losenhausenwerk). According to the standard, three samples of $50 \times 50 \times 19$ mm$^3$ were prepared from each panel ($n = 12$). All specimens were allowed to condition for two weeks at 20°C and 65% relative humidity before testing.

For characterizing the structure of interfaces between surface and core layers using a Field-Emission Scanning Electron Microscope (Quanta FEG 250) at an acceleration voltage of 5 kV the samples were first glued on stubs and then the surfaces were sputtered with gold prior to the microscopy work.

## 3 Results and discussion

In order to investigate the mechanical behaviour of the produced panels, mechanical tests were performed. The influence of panel parameters on the properties with varying surface thicknesses and core materials is reported below.

### 3.1 Foam characterization

Figures 2 and 3 show the typical microstructure of the interfaces between foam core and particle surface layers. With increasing surface thickness, low compacted particles were observed between core and surface layer in the EPS-core panels. In the density profiles (Fig. 1) this is expressed by the less steep decrease of density in the interface between surface and core layer. Visual observations revealed a high compaction density of particles in the panels with a thinner surface thickness near-by the interface.

Comparisons of Figs. 2 and 3 showed that both types of the produced foams in the panels consist of closed cells. The cell sizes of the MS foam in comparison with the EPS cells are smaller. Consequently, the numbers of foam cells in the MS foam are higher than in EPS foam which results in a thicker cell wall in the EPS foam. This can be due to higher granulate size of the EPS bead than that of the microspheres. The properties of the cell wall are the major factors affecting mechanical properties of foams (Gibson and Ashby 1982).

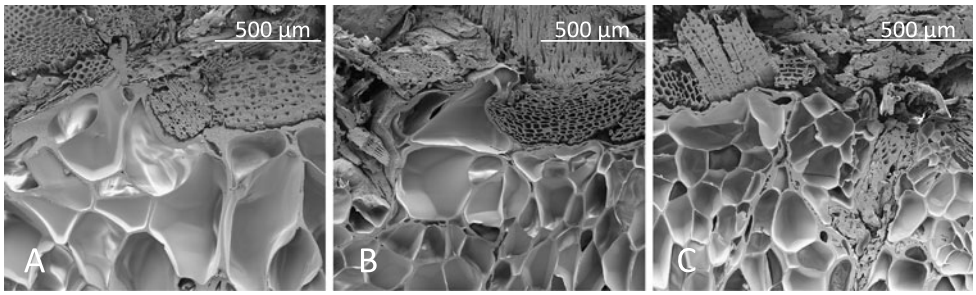


**Fig. 2** Microstructure of the EPS-panel interface zones with different surface thicknesses: **A**: 3 mm, **B**: 4 mm, **C**: 5 mm
**Abb. 2** Mikrostruktur der EPS-Proben mit unterschiedlichen Decklagendicken, **A**: 3 mm, **B**: 4 mm, **C**: 5 mm

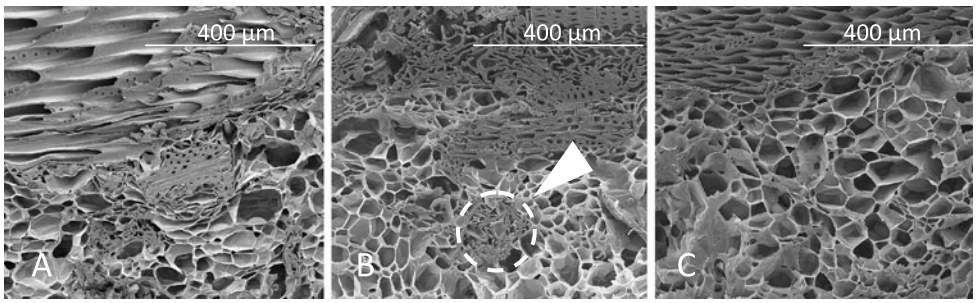


**Fig. 3** Microstructure of the MS-panel interface zones with different surface thicknesses: **A**: 3 mm, **B**: 4 mm, **C**: 5 mm
**Abb. 3** Mikrostruktur der MS-Proben mit unterschiedlichen Decklagendicken, **A**: 3 mm, **B**: 4 mm, **C**: 5 mm

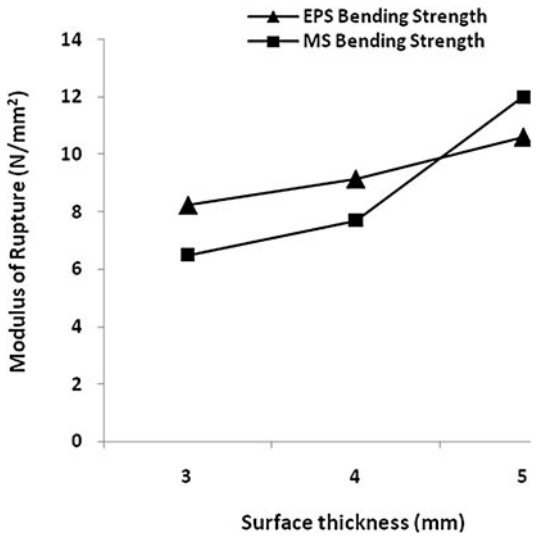


**Fig. 4** Bending strengths and standard deviations of the panels with different core materials
**Abb. 4** Biegefestigkeiten und Standardabweichungen der Platten mit unterschiedlichen Mittellagenmaterialien

| Standard deviation of MOR (n=12) | | |
|---|---|---|
| Face Thickness (mm) | EPS | MS |
| 3 | 1.1 | 1.17 |
| 4 | 1.24 | 1.03 |
| 5 | 0.92 | 1.47 |

### 3.2 Bending properties

Three point bending experiments were performed. The measured bending strength is shown in Fig. 4. It can be seen that with increasing surface thickness, the bending strength is steadily raising 6.5 N/mm$^2$ for 3 mm to 12 N/mm$^2$ for 5 mm surface thickness of MS-core sandwich panels and from 8.3 N/mm$^2$ for 3 mm to 10.9 N/mm$^2$ for 5 mm surface thickness for EPS-core sandwich panels, respectively.

The results revealed that the bending strength in the panels with polystyrene foam core with 3 mm and 4 mm surface thickness is 27% and 19% higher than that with microspheres core, respectively. Bending strength of 5 mm MS panels is 13% more than that of the corresponding panel with EPS core. This can be due to a higher density of the MS panel (11%) and higher core density (45%) at this variable (5 mm MS panels) when compared to the corresponding EPS samples. Since the core density in the MS panels increased, unresinated particles acted as localized agents that cause a stronger link between the foam cells and accordingly lead to a higher bending strength. It can be observed from Fig. 3-B (specified with an arrow) that unresinated particles in MS-core panels are linked to the cell foam.

Since EPS foams are quite rigid and the bond between the core and faces is strong, most of the EPS samples failed because the tensile stress in the lower face exceeds the maximum allowable stress. Only in some samples with 5 mm face thickness, the crack formation was observed at the interface between foam and facing which is due to the observed lower

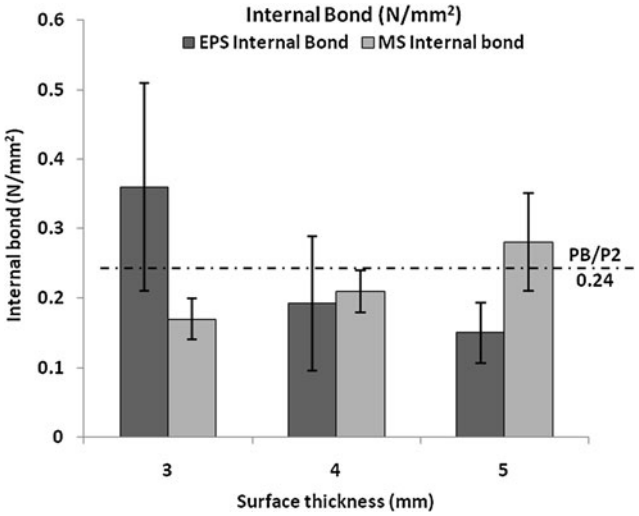


**Fig. 5** Results of the internal bonding tests with different core materials
**Abb. 5** Querzugfestigkeiten der Platten mit unterschiedlichen Mittellagenmaterialien

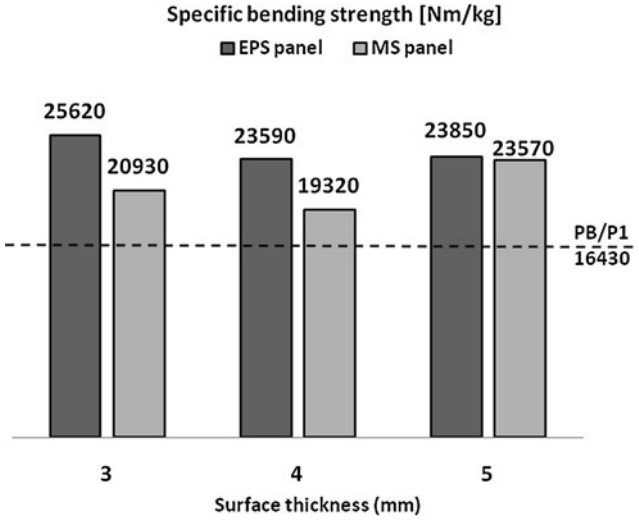


**Fig. 6** Specific bending strength with different core materials and surface thickness
**Abb. 6** Spezifische Biegefestigkeiten der Platten mit unterschiedlichen Mittellagenmaterialien und Decklagendicken

compacted particles in the interface region. On the contrary, with increasing surface thickness in the samples with microspheres, the failure mode varied from shear failure at the upper interface to tensile failure in the lower face. According to EN312 (PB/P2), the minimum requirement for a 19 mm standard particleboard is 11.5 N/mm$^2$ MOR.

### 3.3 Internal Bond (IB)

The results of the Internal Bond tests are shown in Fig. 5. The average values for MS-core panels with 3, 4 and 5 mm surfaces are 0.17, 0.21 and 0.28 N/mm$^2$, respectively. As can be seen, with increased surface thickness the internal bond for MS panels raised about 60% from 3 to 5 mm surfaces. With increased face layer thickness in the case of MS-type panels, the density of the core increases which results in a higher foaming pressure during the expansion phase. An increasing internal pressure causes a better interface connection between foam and particles and also higher internal bond values (Fig. 5).

The values of internal bonding for EPS-type panels declined about 40% from 3 to 5 mm surfaces. These values reached from 0.36 N/mm$^2$ to 0.15 N/mm$^2$ as the surface thickness increased from 3 to 5 mm. This is attributed mainly to the weaker interface of EPS samples when the surface thickness is increased (Fig. 2). Enhanced interface connectivity between particles and polystyrene with 3 mm surface thickness was observed, which is believed to play an important role on internal bond values. The IB requirement is 0.24 N/mm$^2$ for general-purpose 19 mm particleboards according to EN312.

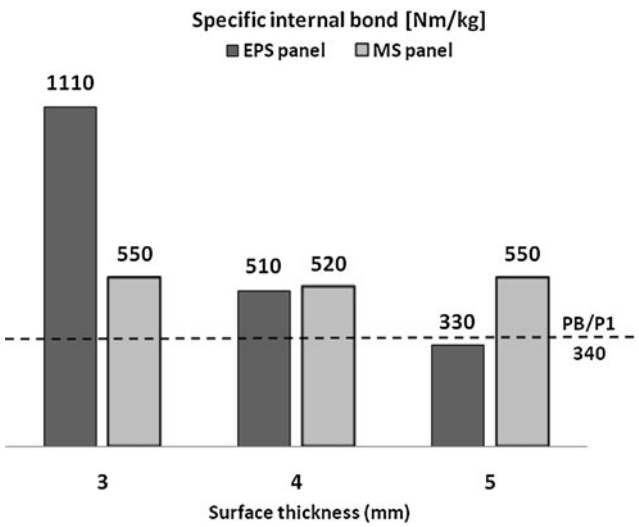


**Fig. 7** Specific internal bond with different core materials and surface thickness
**Abb. 7** Spezifische Querzugfestigkeiten der Platten mit unterschiedlichen Mittellagenmaterialien und Decklagendicken

### 3.4 Specific strength

One of the most important reasons to use lightweight wood-based foam core panels is that they provide a high strength to *mean* density ratio. Values listed in Figs. 6 and 7 clearly demonstrate that high specific bending strength and high specific internal bond of foam core panels can be achieved when compared to normal particleboards with the same thickness.

A comparison of corresponding specific strengths for EPS and MS-type sandwich panel was performed. The re-

sults show that there is a noticeably increase in the specific strength for EPS panels in comparison with MS panels. As can be observed, the highest amounts of specific bending strength and specific internal bond are related to the EPS panels with 3 mm facing thickness. The relationships between these parameters were explained more clearly by comparing the microstructure. An improved interface was observed in EPS-panels with 3 mm face thickness. Since the specific strength of foam core panels is higher than that of conventional particleboards, while saving a large amount of mass, the use of this promising type of lightweight panel in certain applications seems possible.

## 4 Conclusion

Sandwich panels with different types of foam cores can be produced in a one-step process. Expandable microspheres (MS) and polystyrene (EPS) were used as core materials. Significant improvement was observed in both bending strength and internal bond of EPS panels compared to MS panels. Additionally, the price for polystyrene is much lower than that for expandable microspheres which makes it economically more feasible to use EPS for the production of lightweight foam core panels. It was also found that the specific strength of this type of panels, especially in 3 mm face thickness, is more than that for conventional particleboard. Accordingly, the use of these novel lightweight panels can offer an alternative for certain applications in the furniture industry.

As a result of further innovation, multi-layered lightweight foam-core panels can in the future increasingly be used to replace conventional wood-based particleboards in the furniture industry. With a proper design, structural constructions made of lightweight panels can achieve weight reductions of up to 50% compared to conventional particleboards, while still maintaining comparable strengths. Further developments in materials design processes will lead to even lighter components with strength and stiffness properties that can be optimally adapted to suit the requirements.

**Acknowledgements** Sincere thanks are expressed to the "Ministry of Science, Research and Technology of Iran" for granting Ali Shalbafan a doctoral scholarship. The authors would also like to thank the companies Sunpor, AkzoNobel and BASF for providing materials.

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# II

# Effect of processing parameters on mechanical properties of lightweight foam core sandwich panels

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**ORIGINAL ARTICLE**

# Effect of processing parameters on mechanical properties of lightweight foam core sandwich panels

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**Abstract**
Sandwich-like lightweight wood-based panels were produced in an integrated one-stage process using resinated wood particles as faces and expandable polystyrene (EPS) as the core layer. Two different press temperatures (130 and 160°C) were applied to reach different foam structures in the core. The results showed that there is a significant correlation between the foam structure and the mechanical properties of the panels. The bending strength of the panels prepared at 130°C was nearly 10% higher compared to the panels prepared at 160°C. A significant lower internal bond (IB) was observed for samples produced at the higher pressing temperature. The specific bending strength and IB fulfilled the calculated requirement values of conventional particleboard. Statistical analyses did not confirm significant differences for face screw withdrawal resistance (SWR) of the panels prepared at the two different pressing temperatures. It was found that the edge SWR for the 160°C pressing temperature is significantly higher than for the 130°C pressing temperature.

**Keywords:** *Lightweight, sandwich, EPS, foam, polystyrene, wood-based panels.*

## Introduction

Four strategies for reducing the density of wood-based panels can be identified; (1) Wood and annual or perennial plants with low density like poplar, maize, sunflower, hemp can be used to reduce the overall density of the boards by substituting heavier raw materials; (2) Foamed adhesives which create low-density spaces between the particles while maintaining the inter-particle connection; (3) Heavy core material replaced by hollow sections like tubes and paper or plastic honeycombs with cells in a variety of shapes and sizes, generally filled with air; and (4) Foam core sandwich panels in which heavy core material is replaced by a homogeneous lightweight layer (Allen 1969, Gibson and Ashby 1997, Thomsen *et al*. 2005). The light panels have a high potential for substitution of "heavy" wood-based panels where the high strength is not needed. However, the production of light panels is still not a routine business in industrial scale.

The major methods for manufacturing sandwich panels are either a batch process where the prefabricated layers are combined and glued together or a process where a foaming liquid to form the core material is injected between prefabricated facings in continuous processes (Karlsson and Åström 1996, Zenkert 1997). The disadvantages for these processes are the lack of simultaneous production of all layers together and also some restrictions regarding the production techniques. Luedtke *et al.* (2008) presented a novel approach allowing the continuous production of foam core sandwich panels in an one-stage process in already existing production lines for particleboard.

Shalbafan *et al.* (2010) reported on mechanical properties of panels that had been produced in an one-stage process using different types of foam core materials. They showed that the panels produced with EPS have better mechanical properties than those in expandable microspheres. The production process parameters determine different foam structures (Klempner and Frisch 1991). Michaeli *et al.* (2008) showed that, in spite of similar foam types, the properties of the foam structures depend upon

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the cell structure produced in the foaming process. Doroudiani and Kortschot (2003) investigated the relationship between structure and properties of EPS foam using $CO_2$ as a blowing agent in a three-stage batch foaming process. They showed that foaming time is the most important factor which affects foam density.

In this study, foam core sandwich panels were produced in an one-stage process using EPS as core material. A constant foam density (124 kg/m$^3$) was used to investigate effect of process parameters on foam performance and resulting panels properties. The panels were produced using two different press plate temperatures (130°C and 160°C). The objective of this study was to examine the relation between the obtained cell structure in the foam core and the mechanical properties of the produced panels.

## Materials and methods

*Face and core materials*

For the face layers fine softwood-particles mainly spruce and pine ($\leq$2 mm) were supplied from a particleboard mill. The particles were mixed with 12% urea formaldehyde resin (Kaurit 350, BASF, Germany) based on oven dry mass of the wood particles. One percent ammonium sulphate based on solid content of the resin was added as hardener. The adhesive was sprayed onto the particle furnish tumbling in a rotating drum-type blender by using a compressed air spray head. The target density for the surface layers was 750 kg/m$^3$.

The heat-sensitive material for the core layer was Terrapor 4 which is an EPS granulate supplied by Sunpor Kunststoff GmbH, Austria. The activation temperature interval for the EPS was 95–115°C. The granulate diameter of the EPS particles was 0.3– 0.8 mm. Because the granulate size of EPS was similar to the wood particles, manual scattering could be done in the same way. The target density of the foam core was 124 kg/m$^3$.

*Production of the panels*

Panels (19 mm thick) were manufactured from a three-layered mat without additional gluing between the face and core layers. After blending, the resinated wood particles for the faces were felted by hand using a 600 $\times$ 550 mm$^2$ forming box. The EPS 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 opening hot press (Siempelkamp, Germany). The temperature of the press plates was set to either 130°C (1-EPS) **or** 160°C (2-EPS). To simulate a continuous hot press with a cooling zone for stabilization of the core layer the pressing schedule was controlled by initiating the cooling of the press plates after approximately 1/3 of the pressing cycle.

The press cycle was performed as follows: (1) the specific pressure was increased from 0 to 3 MPa (0–435 psi) during the first 10 seconds and maintained for the compaction and curing of the faces until the core materials reached the activation temperature; (2) the specific pressure was then decreased from 3 to 0 MPa (435–0 psi) with opening of the press to the final panel thickness (19 mm) to allow core expansion; (3) for stabilization of the panel the press temperature was decreased to allow cooling until the temperature of the EPS material reached the glass transition temperature. For each press temperature and the corresponding program, three surface thicknesses (3, 4 and 5 mm) and four panel replicates were produced. Table I shows the composition of the variables.

*Foaming conditions*

Heating the core layer of a panel was achieved by the influx of steam generated by evaporation of the water contained in the surface layers of the mat (Thoemen 2000). Due to the combined process of conduction and convection the core temperature will rise to the level needed to start the expansion of the core material. As can be seen in Table I, different pressing

Table I. Composition of the panel variables.

| No | Face thickness (mm) | Press temperature (°C) | Target density (kg/m$^3$) | Pressing time (s) | Foaming time (s) | Stabilization time (s) | Panel replicates |
|---|---|---|---|---|---|---|---|
| *1-EPS* | | | | | | | |
| A | 3 | 130 | 320 | 80 | 45 | 130 | 4 |
| B | 4 | 130 | 390 | 105 | 45 | 140 | 4 |
| C | 5 | 130 | 460 | 130 | 45 | 150 | 4 |
| *2-EPS* | | | | | | | |
| D | 3 | 160 | 320 | 45 | 10 | 140 | 4 |
| E | 4 | 160 | 390 | 55 | 10 | 170 | 4 |
| F | 5 | 160 | 460 | 65 | 10 | 200 | 4 |

times were attained due to the initial pressing temperatures and surface thicknesses. The foaming condition was affected by the pressing and foaming times. For each press temperature a different foaming time was achieved. At low press plate temperature (130°C) the foaming time was longer (45 s) than at the higher press temperature (160°C).

During the pressing time at 130°C press temperature, the EPS beads were transformed to a semi-viscous state. When the press opened to the predefined distance (19 mm), the semi-viscous polystyrene slowly started to expand with a low expansion rate. The resulting foam shape of this foaming was like melted plastic and formed a glassy state.

At the 160°C press temperature, the EPS beads transfigured into a softened state while the temperature increased and the blowing agent (pentane) gasified. With opening of the press, the softened polystyrene granulates quickly expanded due to the high gas pressure of the blowing agent until the face layers were pressed against the pressing plates. The expansion of the beads took place in a few seconds (<10 seconds). During expansion two types of bonding must be achieved; (1) bonding between the expanding EPS beads, (2) bonding between the expanding EPS beads and the wood particles in the face layer. With 160°C the texture of the foam resembled EPS foams for packaging applications. Figure 1 shows example panels produced in the one-stage process with different surface layer thicknesses.

*Sample preparation and testing procedures*

All samples were conditioned at 65% relative humidity and a temperature of 20°C for two weeks prior to testing until equilibrium moisture content was achieved. For characterization of the panels, microstructure of the foams, glass transition temperature, bending properties by three-point bending strength modulus of rupture (MOR) and stiffness (deflection at 100 N), IB and screw withdrawal (SW) tests at both face and edge of the samples were carried out.


Figure 1. Varieties of lightweight foam core panels; 1-EPS (130°C: A, B, C) and 2-EPS (160°C: D, E, F).

Micrographs of the micro-morphology of the face and core layers were studied with a field-emission scanning electron microscope (FESEM, Quanta FEG 250, USA) at an acceleration voltage of 5 kV. After sampling by microtome and gluing them on stubs, the surfaces were coated with gold prior to the microscopy characterization.

The glass transition temperature (Tg) of EPS was measured using differential scanning calorimetry according to ASTM E 1356-08. The analysis revealed a glass transition temperature of EPS of approximately 103°C.

Bending properties in three-point bending were determined according to EN 310 using an universal testing machine (Zwick-Roell, Ulm, Germany) with a constant cross head displacement of 8 mm/min for each sample. Three samples of $430 \times 50$ mm$^2$ for each panel replicate ($n = 12$) were prepared and the MOR and stiffness by measuring deflection at 100 N force for all samples were determined.

The IB according to EN 319 and SW properties according to EN 13446 of the boards was determined using a universal testing device (Losenhausenwerk, Düsseldorf, Germany). Three square-test pieces of $50 \times 50$ mm$^2$ for IB and SW were prepared from each of the four panel replicates ($n = 12$). For the SWs tests steel screws with a nominal size of 4.2 mm diameter and 38 mm length according to EN 320 were used. SWR was conducted on both the face and the edge of the samples.

Data analysis was performed using statistical package for the social science (SPSS). Scatter plot, histogram, and Kolmogorov-Smirnov tests were used for checking the assumption of normality. After the data normality check, a Levene test for checking the homogeneity of variances was applied. Thereafter, a parametric ANOVA tests to evaluate possible significant differences between the mechanical properties of produced panels using different pressing temperatures were performed. Statistical differences between variations were evaluated by multiple comparisons using either LSD or Dunnet T3 test depending on variance status. The $P$-value level of statistical significance was set at $P < 0.05$.

## Results and discussion

*Morphological characterization of foam cells*

Figure 2 shows typical micrographs of the EPS samples of panels with different surface layer thick-

ness using the FESEM. An important feature in this case is the interface between face particles and foam cells which may affect the mechanical properties of the panels. By a visual comparison a more intact interface is observed in 1-EPS panels compared with the interface in the 2-EPS panels.

By the increased press plate temperature in the 2-EPS the number of foam cells increased, also resulting in smaller cells. The reason for this is related to the more intense and therefore shorter foaming and higher expanding rate of this type of panel (Doroudiani and Kortschot 2003). Higher foaming pressure during foam expansion causes smaller cell size. In addition, with increasing panel surface thicknesses from 3 to 5 mm the cell sizes decreased in both 1-EPS and 2-EPS samples, respectively. EPS beads are normally expanded in a hot vapour atmosphere. Compared to a thin surface layer a thick wood particle layer generates more vapour during hot pressing which penetrates into the core layer consisting of EPS beads. The higher the amount of vapour in the core layer the smaller will be the cell size of the EPS foam. Visual comparison of the cell shapes revealed that the cells in the 2-EPS panels have pentagonal or hexagonal shapes while lengthy or spherical cells were achieved in the 1-EPS panels.

*Bending strength (MOR)*

Figure 3 displays the average MOR of samples of the 1-EPS and 2-EPS panels. An increased surface layer thickness increased the MOR for both types of panels. The bending strength significantly increased from 9 N/mm$^2$ (3 mm) to 11.5 N/mm$^2$ (5 mm) with 1-EPS panels and from 8.2 N/mm$^2$ (3 mm) to 10.6 N/mm$^2$ (5 mm) with 2-EPS panels, respectively. Hence, this indicated that the average MOR of 1-EPS samples was approximately 10% higher than that of 2-EPS samples. The mechanical properties of foam are affected by the cell wall properties as well as the cell structure (Gibson and Ashby 1982, Gendorn 2005). The increased foam cell sizes in 1-EPS compared to 2-EPS panels resulted in thicker cell walls in 1-EPS (since the target density for the core layer was kept constant).

To get a better understanding of the mechanical performance of the lightweight sandwich panels it may be useful to relate the mechanical properties to the samples mean density. The resulting specific bending strength (Nm/kg) is depicted in Figure 4. The values for both types of the panels declined with increasing surface layer thickness. In 1-EPS panels specific bending strength ranged from 28,200 Nm/kg for 3 mm facing to 25,000 Nm/kg for 5 mm facings and for 2-EPS from 25,700 Nm/kg for 3 mm to 23,000 Nm/kg for 5 mm facings, respectively. Accordingly, the average specific values for 1-EPS were approximately 10% higher than the corresponding values for 2-EPS panels.

The Figure 4 shows that the specific values for all types of 1-EPS and 2-EPS panels fulfill the calculated specific value for conventional particleboard with a density of 700 kg/m$^3$ (16,400 Nm/kg). In accordance to EN 312/P2 the minimum requirement of bending strength for conventional particleboard is 11.5 N/mm$^2$.

To get estimation of the panels' stiffness, the deflection at 100 N force during the three-point bending test was determined for all samples (Stokes *et al.* 1988). Figure 5 shows the results of this

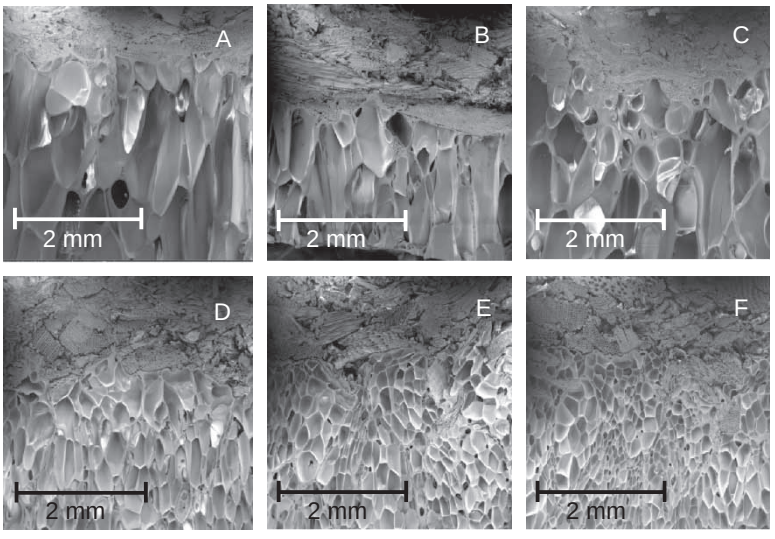
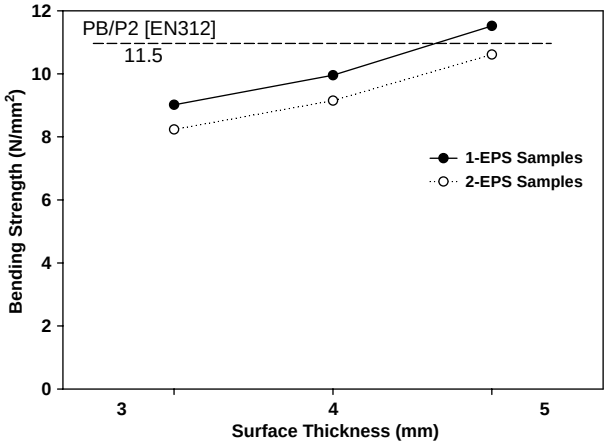



Figure 2. Micrographs of EPS foam in panels produced by different press temperature; 1-EPS (130°C; A, B, C) and 2-EPS (160°C; D, E, F).




| Standard deviation of MOR (n=12) | | |
|---|---|---|
| Face Thickness (mm) | 1-EPS | 2-EPS |
| 3 | 0.9 | 1.1 |
| 4 | 1.1 | 1.2 |
| 5 | 0.8 | 0.9 |

Figure 3. Average values of bending strength in 1-EPS and 2-EPS panels.

deflection test. It can be noticed that the stiffness increased significantly with the increased thickness of the facings from 3 to 5 mm. This is due to the fact that wood is stiffer and stronger than the polymer core material. The moment of inertia is improved by increasing the surface thicknesses. Statistical assessment confirmed no significant differences of stiffness between the panels pressed at the two different temperatures.

*Internal bond (IB)*

To determine the foam quality and the interfacial bonding of the produced panels, IB test was applied.

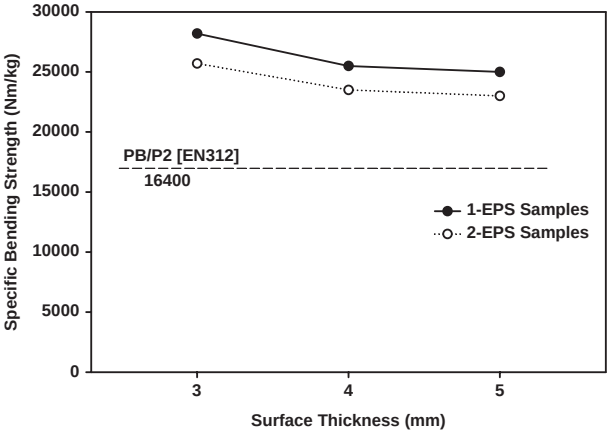



Figure 4. Average values of specific bending strength in 1-EPS and 2-EPS panels.

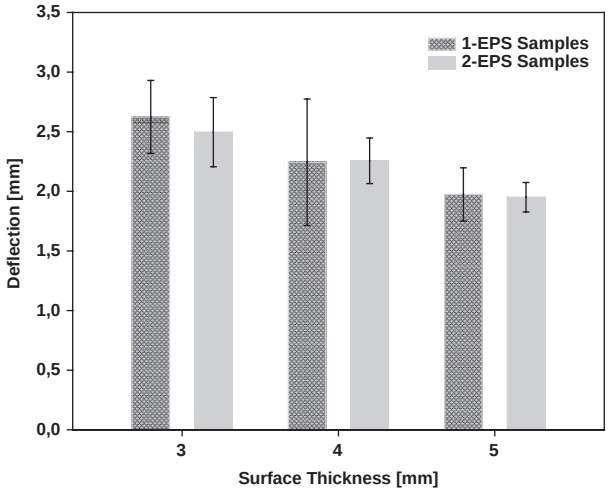



Figure 5. Average values of deflection in 1-EPS and 2-EPS panels.

Figure 6 shows the results for IB in both panels. The values of IB for 1-EPS samples are 1.9 N/mm$^2$ (3 mm), 1.74 N/mm$^2$ (4 mm) and 1.6 N/mm$^2$ (5 mm), respectively. The mean values for the 2-EPS range from 0.36 N/mm$^2$ (3 mm), 0.2 N/mm$^2$ (4 mm), and 0.15 N/mm$^2$ (5 mm), respectively. Significant increase of IB values confirmed between the 1-EPS and the 2-EPS panels when IB data are compared for the panels with 3, 4, and 5 mm surface thicknesses. Examinations of the tested samples revealed that the fractures in 1-EPS samples were located in the core layer. This indicates that the interface between face and foam core in 1-EPS samples was stronger than the foam cells. Most of the 2-EPS samples broke at the face-foam core interfaces indicating that this was the weakest line in the 2-EPS panels.

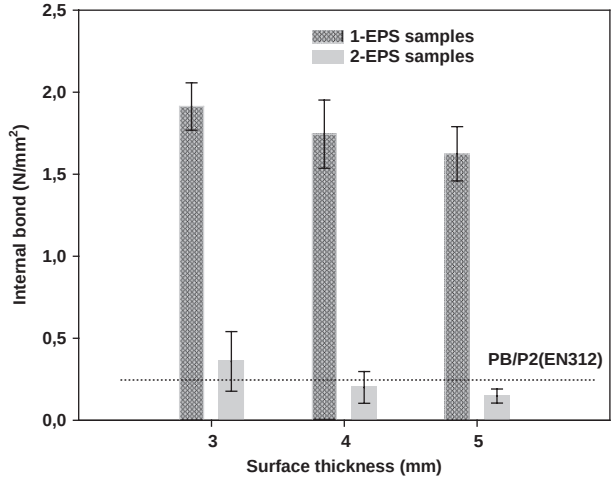



Figure 6. Average values of internal bond in 1-EPS and 2-EPS panels.

As can be seen in Figure 6 the IB values for 1-EPS panels were extraordinarily higher than those for 2-EPS. Most probably, the different foaming times during the pressing are the reason for this difference. For the 1-EPS samples, the foaming time was 45 seconds which is nearly 4 times longer than that for the 2-EPS samples (10 s). With a longer foaming time a better configuration of cell structure in the interface was achieved (Figure 2) and the junction between semi-viscous polystyrene and wood particles in the surface layer can be improved. Another feature displayed in Figure 6 is the decreased internal bonding values when the surface layer thickness was increased from 3 mm to 5 mm. This may be attributed to weak glue bonds between face particles adjacent to the interface resulting from poorly compacted particles when the surface layer thickness was increased (Shalbafan *et al.* 2012).

The specific IB (Nm/kg) is an important property for lightweight sandwich panels as depicted in Figure 7. As can be seen, the specific IB values of the EPS samples were higher than the ones of conventional particleboards, except in the 2-EPS samples with 5 mm facing. The decreasing values of specific IB with rising surface layer thickness are due to the increasing mean density. With increased surface thickness the values for specific IB in 1-EPS and 2-EPS samples declined about 40 and 70% based on the values for 3 mm facing, respectively. The specific IB values of the 1-EPS (A, B, C) panels were significantly higher than those of the 2-EPS (D, E, F) panels. According to EN 312 the minimum IB for conventional particleboard (density of 700 kg/m$^3$) is 0.24 N/mm$^2$ resulting in a derived specific IB of 340 Nm/kg. Both types of foam core panels, 1-EPS and 2-EPS, exceeded this value (except the 2-EPS panels with 5 mm facing).

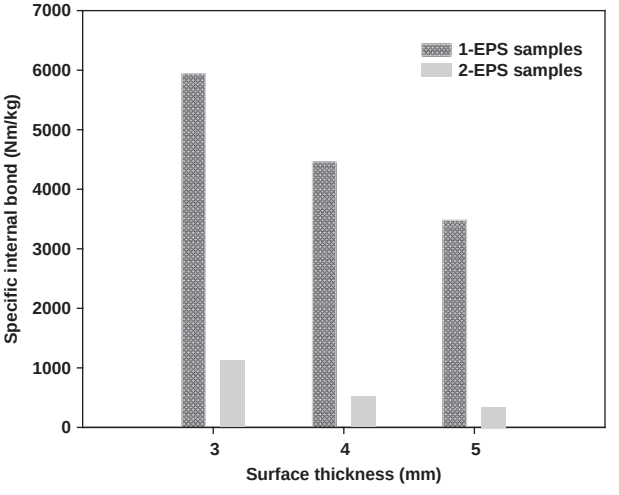



Figure 7. Average values of specific internal bond in 1-EPS and 2-EPS panels.

*Screw withdrawal resistance (SWR)*

A poor Srew withdrawal resistance could be obstructing the wider adoption of lightweight panels by the furniture industry. The bar chart in Figure 8 shows the face SWR of panels with different face thicknesses.

The withdrawal resistance increased from 385 N to 630 N when the face thickness was increased from 3 to 5 mm. The corresponding values were 360 N to 580 N for the 2-EPS panels. The results display that the added resistance of the face SW was significant while the surface layer thickness was increased in both the 1-EPS and the 2-EPS samples. This can also be related to the increased panel density from 320 to 460 kg/m$^3$ when increasing the surface thickness from 3 to 5 mm. In the case of wood-based panels, it has been found that panel density has a strong effect on the withdrawal resistance of screws (Eckelman 1975). The results also point out that there are no notable differences between the corresponding samples of 1-EPS and 2-EPS samples with a similar mean density. Statistical analysis confirmed that no significant differences between different pressing temperatures existed. The SWR values for the 1-EPS samples were slightly higher than the values for the 2-EPS values which may be explained by the possible stronger interface in the 1-EPS samples.

Figure 9 shows obtained the edge SWR values of the panels. The edge screw resistance of the 2-EPS panels was superior to that of the 1-EPS panels. For the 1-EPS panels the SWR at the edge varied from 132 N (3 mm) to 153 N (5 mm) and the corresponding values for the 2-EPS from 235 N (3 mm) to 280 N (5 mm). Statistical analyses showed significant differences between the two pressing

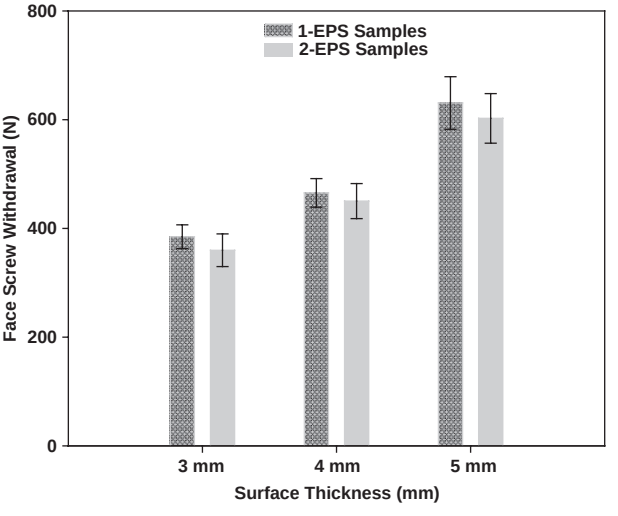



Figure 8. Screw withdrawal resistance at the face of samples in different face layer thickness.

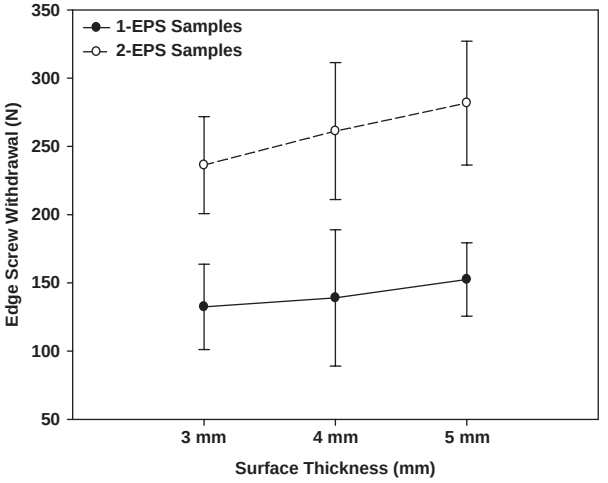



Figure 9. Screw withdrawal resistance at the edge of samples in different face layer thickness.

schemes. At similar core densities the superior values for the 2-EPS panels is attributed to finer cell sizes. A higher press plate temperature results in a faster foaming in the 2-EPS panels which results in more and smaller foam cells. No significant differences were observed for the edge SWR between the samples with different surface layers thickness.

## Conclusion

The study shows that the interface between the foam core and the surface layer has a considerable effect on the mechanical properties of the panels, especially on the IB values. An improved interface can be established by the lower pressing temperature (130°C) as well as by a longer foaming time. Increasing surface layer thickness results in significantly increased face SW in both types of the panels. Different press temperatures have no significant effect on the face SW of the corresponding samples in the 1-EPS and the 2-EPS. A better and finer foam cell configuration can be achieved by higher pressing temperature (160°C) and shorter pressing time. The finer cell configuration significantly affects the edge SW.

The results indicated that the foaming conditions (press temperature, press and foaming times) are crucial parameters influencing the properties of the foam core panels. The most significant findings to be revealed from the experiments are that controlling the foam structure in foam core panels produced in a one-stage process is possible by adjusting the pressing schedule. Panel properties can be varied in wide ranges to obtain panels which fulfill minimum requirements set by industrial users. With the proper selection of process variables suitable press parameters to produce panels that meet specific customer requirements can be designed.

## Acknowledgements

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# III

# Effect of processing parameters on physical and structural properties of lightweight foam core sandwich panels

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**ORIGINAL ARTICLE**

# Effect of processing parameters on physical and structural properties of lightweight foam core sandwich panels

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**Abstract**
Weight reduction is becoming an important topic for the wood-based panels industry. Recent development for foam core particleboard in an integrated process has a great potential to replace heavy conventional particleboards. For further progress of these new types of panels, exploring the physical properties is of high interest. In this study, the effect of two different sets of process parameters (press temperature, pressing and foaming times) on the physical properties and dimensional stability of foam core panels was examined. Panels produced by a lower press temperature (130°C) have a better surface quality. Thickness swelling of panels in short- (2 h) and long-term (24 h, 14 days) immersion shows different trends due to the different attained foam structures. Small inter cellular voids between the foam cells formed during the *in situ* foaming process play an important role for the water absorption values, especially in short-term immersion. Different process parameters caused different fusion of the beads in the core layer. With increasing panel density, the dimensional stability is significantly decreased because of the increased wood particles in the face layer. With proper selection of process parameters, foam core panels with higher dimensional stability than conventional particleboards can be produced.

**Keywords:** *Physical properties, foam, lightweight, dimensional stability, wood-based panels.*

## Introduction

Recent approaches to reduce the weight of wood-based panels take advantage of minimising the core density for example by introducing polymer beads or starch-based granulates to replace part of the wooden particles in the core (Kharazipour *et al*. 2011). This is an indication for an on-going specialisation of wood-based panels for certain applications and towards multi-component and multi-layered materials. In this context, the use of wood-based sandwich panels supports the trend towards lightness of materials and helps to relieve the increasingly tightening competition between the material and energetic use of wood on the other hand (Rivela *et al*. 2006, Watt 2010).

Sandwich panels offer a structural concept which makes it possible to save material because of its three-layered composition comprising two thin and stiff facings which are separated by a lightweight core. This multi-layered design generates properties comparable to conventional panels with a significant density reduction. A new technology presented by Luedtke *et al*. (2008) allows producing wood-based foam core panels in a one-step process in three consecutive stages for the first time. During the first stage, the wood-based surfaces are compacted and hardened before the foam expands *in situ*. In the second stage, the press opens to the final panel thickness to allow core expansion when the expandable core materials reach the activation temperature. Third, the panel is stabilised in the press by cooling the press plates.

The companion paper of this article surveyed the relation of processing parameters (press temperature, pressing and foaming times) on the mechanical properties of foam core sandwich panels (Shalbafan *et al*. 2012b). It was shown that the foam cell configuration and the interface between foam and surface layer are the most important factors determining the mechanical properties of foam core panels. Controlling the foam structure by adjusting the pressing parameters was also possible.

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One of the most important parameters for design purposes is dimensional stability. With changing relative humidity in the surrounding air swelling and shrinkage take place in wood-based panels. The maximum allowable changes in dimension for wood-based panels are defined in ANSI 208.1-2009 Particleboard Standard. These should be considered for eliminating possible problems with the product during further processing and use phase (e.g. buckling, pushing out of the fasteners). Research determining physical properties of particleboard has been extensively conducted. Halligan (1970) reviewed the literature on thickness swelling of particleboard. He mentioned that the all process variables have a similar effect for both thickness swelling and equilibrium moisture content. Vital *et al.* (1980) and Suzuki and Miyamoto (1998) surveyed the dimensional stability of particleboard. They concluded that the panel density has an important effect on the dimensional stability. Suchsland (1972) found out that one of the most important factors determining linear expansion (LE) of particleboard is particle geometry.

Only a few studies have been done to investigate the physical properties of expanded polystyrene (EPS) foam. Gnip *et al.* (2006) studied the water absorption of expanded polystyrene boards in different periods of time for predicting the long-term water absorption. Duskov (1997) also investigated the mechanical and physical properties of EPS foam with two different densities (15 and 20 kg/m$^3$). He concluded that the diffusion is the dominant transport mechanism for water absorption. Within the development of a novel one-step process for foam core panels, information regarding physical characteristics of the produced panels is a precondition for further progress. The aim of this article is to explore the effect of processing parameters on the physical and structural properties of the foam core particleboard.

## Materials and methods

### *Production of the panels*

In the present study, 19-mm thick foam core panels were manufactured from a three-layered mat without additional gluing between the face and core layers. The surface layers comprise resinated wood particles (urea formaldehyde; Kaurit 350, BASF, Germany) and the core is formed from expandable polystyrene (EPS; Terrapor 4, Sunpor, Austria). The hot pressing process of such a three-layered mat is divided into three consecutive stages. The resinated particles in the surface layers are compacted and cured in the first stage. When the temperature of the thermosensitive core materials reaches the activation point for foaming, the press opens to the predefined distance (final panel thickness) to allow core expansion. During this stage, the pressing distance is kept constant under low press pressure until the expansion is finished. For the last stage, the stabilisation of the panels takes place in the press by cooling the press plates. For the present study, the temperature of the press plates was set to 130°C (1-EPS; A, B, C panels) and 160°C (2-EPS; D, E, F panels), respectively. The panels were produced with varying surface layer thicknesses of 3, 4 and 5 mm for each press temperature. For each surface layer thickness four panel replicates were produced. Table I shows the composition of the variables.

More details regarding the materials, production process of the panels and foaming conditions were described in companion paper of this article (Shalbafan *et al.* 2012b).

### *Sample preparation and testing procedures*

All samples were kept in a conditioning chamber at 65% relative humidity (RH) and temperature of 20°C for approximately two weeks prior to testing. Density profiles, surface soundness, physical properties by using thickness swelling and water absorption criteria (2 h, 24 h and two weeks immersion) and dimensional stability by calculating LE/contraction and thickness swelling/shrinkage after storage in a wet and dry condition chamber were determined.

The vertical density profile was investigated to get information about the panel formation. Gamma-ray densitometry (Raytest GmbH, Trivolt PK60, Germany) with measuring steps of 75 μm was used.

Surface soundness (SS) was measured with a universal testing machine (Losenhausenwerk, Düsseldorf, Germany) according to the EN 311. All top surface layers of samples were sanded before testing for a good connection between round jig and surface. Three samples were cut from each panel replicates ($n = 12$).

The examination of physical properties was carried out by means of thickness swelling (TS) and water absorption (WA) after submerging the samples in distilled water at 20°C. Three samples with dimensions of 50 by 50 by 19 mm from each panel replicates ($n = 12$) were prepared according to EN 317. After different time intervals (2, 24-hours and two weeks) the samples were removed from the water. Excess water on the samples was removed. The thickness in the middle of each sample and weight of each test piece was measured with a precision of 0.01 mm and 0.001 g, respectively.

Table I. Composition of the panel variables.

| No | | Face thickness (mm) | Press temperature (°C) | Target density (kg/m$^3$) | Pressing time (s) | Foaming time (s) | Stabilisation time (s) |
|---|---|---|---|---|---|---|---|
| A | | 3 | 130 | 320 | 80 | 45 | 130 |
| B | 1-EPS | 4 | 130 | 390 | 105 | 45 | 140 |
| C | | 5 | 130 | 460 | 130 | 45 | 150 |
| D | | 3 | 160 | 320 | 45 | 10 | 140 |
| E | 2-EPS | 4 | 160 | 390 | 55 | 10 | 170 |
| F | | 5 | 160 | 460 | 65 | 10 | 200 |

The swelling in thickness (TS) of each sample as a percentage of the initial thickness was calculated according to the following formula:

$$\mathrm{TS}(\%) = ((T_t - T_I)/T_I)^{*}100 \quad (1)$$

where TS is the thickness swelling after time $t$, and $T_t$ and $T_I$ are the thicknesses of the samples at time $t$ and initial thickness of the samples, respectively.

Accordingly, the WA of all the samples was calculated according to the equation:

$$\mathrm{WA}(\%) = ((W_t - W_I)/W_I)^{*}100 \quad (2)$$

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 $t$ and initial weight of the samples, respectively.

Conditioned samples (20°C, 65% RH) were transferred in another chamber with different climate to evaluate dimensional stability following the EN 318. From each panel, three samples of 300 by 50 by 19 mm were tested. LE, linear contraction (LC), thickness swelling ($TS_w$) and thickness shrinkage ($TS_d$) of test pieces was determined at 20°C in wet and dry conditions with RH of 85 and 35%, respectively. Determining the LE, LC, $TS_w$ and $TS_d$ of the samples has been done by calculating on the basis of initial dimension. These parameters are calculated by following equations in Table II.

It should be noted that all the physical tests were done on unsanded samples. For comparison purposes of TS and WA percentages, industrial particleboard was purchased and tested.

The statistical data analysis was performed using parametric ANOVA tests with Statistical Package for the Social Science (SPSS software, IBM) to evaluate the physical and structural properties of panels using different pressing parameters. Due to the homogeneity of variances, statistical differences between variations were done by multiple comparisons using a least significant difference (LSD) test. The $p$-value level of statistical significance was set at $p < 0.05$.

## Results and discussion

### *Structural properties*

*Density profile*. The vertical density profile reflects changes in density over the panel thickness. Figure 1 shows six density profiles of panels with different surface layer thicknesses, which were produced by varying pressing parameters.

As presented in the companion paper (Shalbafan *et al*. 2012b), the bending strength of the corresponding 1-EPS and the 2-EPS samples of a same mean density was different. Shen and Carroll (1970) found that with the same mean density but including different density profiles bending strength can change by up to 80% in wood-based panels. The establishment of a density gradient over the cross-section of panels during hot pressing influences most mechanical and physical properties like bending strength, screw withdrawal resistance and dimensional stability (Plath and Schnitzler 1974, Geimer *et al*. 1975, Kelly 1977, Wong *et al*. 1999, Ganev 2002).

The graphs show a highly symmetric density profile for each panel. A closer examination reveals that the density gradient from the surface to core layer in the samples D, E and F (160°C pressing temperature; 2-EPS) is more pronounced as compared to samples A, B and C (130°C pressing temperature; 1-EPS). This effect is also observed in the interface when surface layer thickness is increased from 3 to 5 mm, especially in samples A, B and C. Our studies indicated that density gradient of foam core panels has important influence on the panel properties.

*Surface soundness (SS)*. The SS values as an indicator of the surface quality of the boards are summarised in Figure 2. It is obvious that the SS values in the 1-EPS panels are significantly higher than those in the 2-EPS. This can be explained by longer pressing times (nearly two times) for the 1-EPS panels than those in the 2-EPS panels. With the longer pressing time more compacted surface layers are achieved.

The SS values are significantly raised for the 1-EPS panels with increasing surface thickness

Table II. Equations for calculating dimensional stability.

| No | Equations | Description |
|---|---|---|
| 1 | $LE\ (\%) = ((L_{85\text{-final}} - L_{65\text{-initial}})/L_{65\text{-initial}})*100$ | LE: linear expansion (%)<br>$L_{85\text{-final}}$: length after conditioning in RH 85%<br>$L_{65\text{-initial}}$: initial length after conditioning in RH 65% |
| 2 | $LC\ (\%) = ((L_{65\text{-initial}} - L_{35\text{-final}})/L_{65\text{-initial}})*100$ | LC: linear contraction (%)<br>$L_{35\text{-final}}$: length after conditioning in RH 35% |
| 3 | $TS_w\ (\%) = ((T_{85\text{-final}} - T_{65\text{-initial}})/T_{65\text{-initial}})*100$ | $TS_w$: thickness swelling (%) in wet climate<br>$T_{85\text{-final}}$: thickness of the samples in RH 85%<br>$T_{65\text{-initial}}$: initial thickness of the samples in RH 65% |
| 4 | $TS_d\ (\%) = ((T_{65\text{-initial}} - T_{35\text{-final}})/T_{65\text{-initial}})*100$ | $TS_d$: thickness shrinkage (%) in dry climate<br>$T_{35\text{-initial}}$: thickness after conditioning in RH 35%. |

from 3 to 5 mm. This can be explained by denser face layer resulting from longer pressing time (from 80 (3 mm) to 130 seconds (5 mm)). Closer comparison of the density profiles (Figure 1) also shows that the high density zone is broader in the 1-EPS panels when surface thickness is increased. For the 2-EPS panels the opposite trends are observed. The SS is significantly reduced with thickening the surface layer. This could be caused by increased amount of low compacted particles in the inner layers of surface when face thickness is increased (Shalbafan *et al.* 2012a). According to EN 312, the minimum requirement of SS for conventional particleboard (type P2) is 0.8 N/mm2. Both types of foam core panels, the 1-EPS and the 2-EPS panels, exceed this value.

*Physical properties*

*Thickness swelling (TS)*. The values for TS after submersion for 2, 24 hours and 14 days are summarised in Figure 3 and Appendix 1. With increasing the surface layer thickness from 3 to 5 mm, TS significantly raises. This is due to the increasing number of water attractive hydroxyl groups (OH) in the thicker surface layers of the panels (Halligan and Schniewind 1972). This increase in TS is more evident in the 2-EPS panels (D, E, F panels) in comparison with the 1-EPS panels (A, B, C panels). This can be explained by the less compacted particles in the face layers in the 2-EPS panels. These less compacted particles result in a better accessibility of OH groups to the surrounding water. The EPS foam is made of polystyrene monomer which is a hydrophobic polymer itself. This means that in this type of foam core panels the core layer has no effect on the TS value (van Dorp 1988).

A corresponding comparison of TS after 2 h water soaking shows that there is no significant difference between the samples with the same face layer thickness produced with different press temperature (Figure 3). The corresponding differences of TS are statistically significant for longer immersion times (24 h and 14 days), while surface layer thickness is increased from 3 to 5 mm in panels produced with both pressing temperatures.

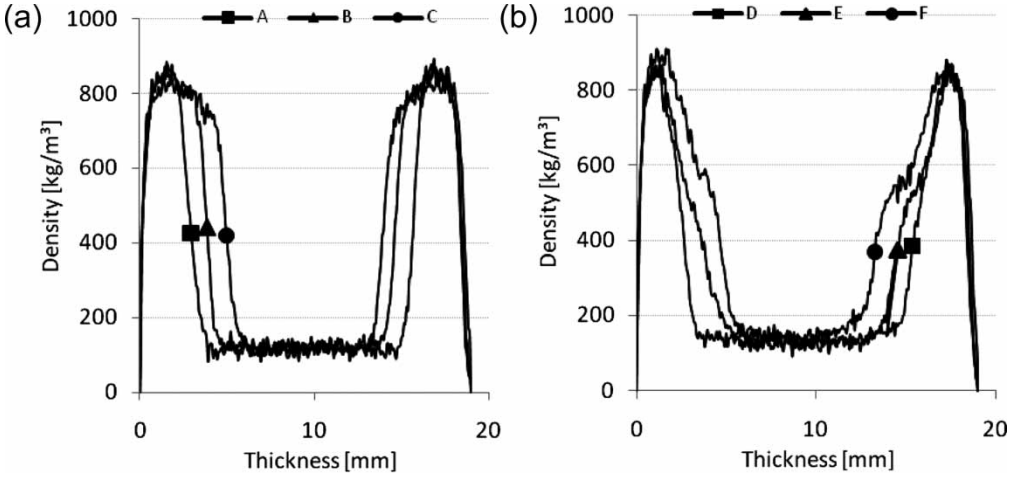


Figure 1. Density profile from the EPS-panels produced with different surface layer thickness and press temperature, (a) press temperature of 130°C, (b) press temperature of 160°C.

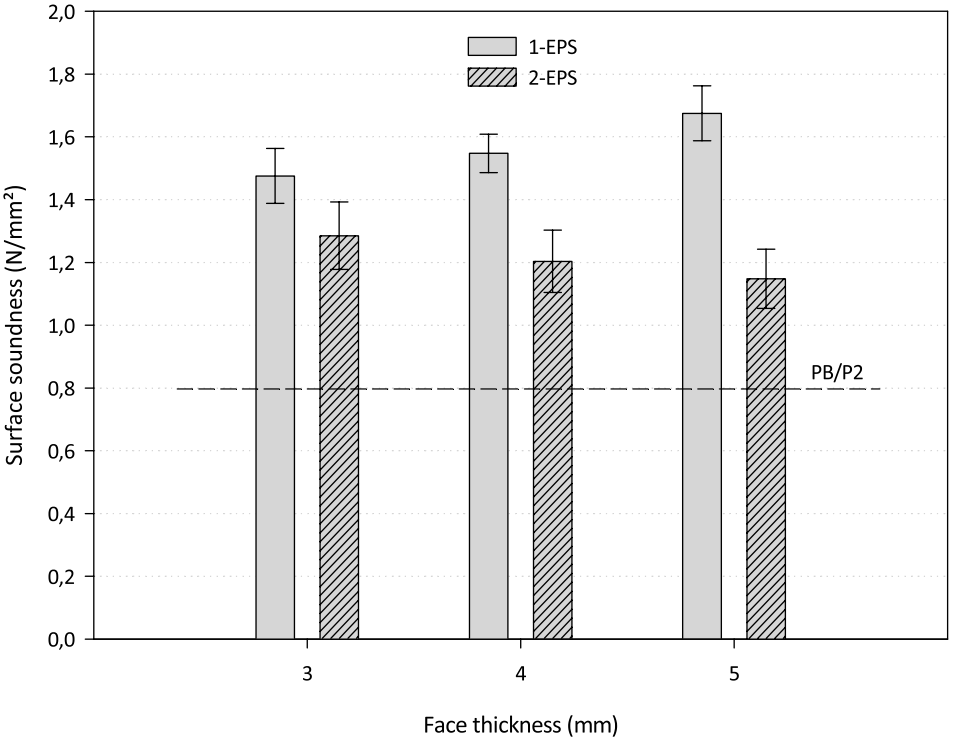


Figure 2. Surface soundness of foam core panels produced with different press temperature of 130°C (1-EPS) and 160°C (2-EPS).

The TS in the 1-EPS panels after 2 h submersion is still slightly higher than those in the 2-EPS panels, while at longer water soaking times (24 h and 14 days) this trend is reversed. This can be explained by higher compacted surface layers in the 1-EPS panels in comparison with the 2-EPS panels. The pressing times for the 1-EPS panels are about twice as long than the corresponding ones for the 2-EPS panels. The longer the pressing time in the 1-EPS, the more compacted surface layers and the more compression stresses are achieved in the 1-EPS panels. Figure 1 illustrates the high density zone ($\sim$850 kg/m$^3$) in the 1-EPS is broader in comparison with the corresponding panels in the 2-EPS. We believe that the TS value in particleboard results from the sum of two major components; swelling of wood materials and springback as a result of relieved compression stress from pressing operation (Gatchell *et al.* 1966). The reason for slightly higher TS value in the 1-EPS after 2 h immersion can be explained by higher springback resulting from release of compression stresses. With increasing immersion time to 24 h and 14 days, the prevailing process for TS in this type of panels is swelling of wood materials and accessibility to the OH groups. The less the compaction of the surface layers in the 2-EPS panels, the higher the accessibilities of the hydroxyl group can be assumed.

The TS after 2 h water soaking for the reference particleboard was measured to be 2% as illustrated in Figure 3. This value jumps to 11.5 and 22.5% after 24h and 14 days submersion, respectively. The foam core panels have higher TS value at the short-term immersion (2 h) in comparison to an industrial particleboard. But with increasing immersion time to 24 h and 14 days the TS value of the reference panels is significantly higher than those of foam core panels. Lower TS at the short-term submersion in particleboard can be explained by the using of hydrophobic agents like wax in industrial scale production. It is well understood that the hydrophobic agents have only short-term effect on the water resistance of panels (Heebink and Hann 1959). This explains the tremendously increased TS in conventional particleboard after long-term immersion (24 h and 14 days).

*Water absorption (WA).* The WA values after immersion for 2, 24 hours and 14 days are illustrated in Figure 4 and Appendix 1. For WA a similar trend as with TS is visible. The higher the surface layer thickness, the higher is the WA in the short- and long-term immersion in both the 1-EPS and the 2-EPS panels. The significant increase of WA with increasing surface layer thickness can be explained by the greater number of wood particles in surface layer. In short-term immersion (2 h), the WA values in the 1-EPS (A, B, C panels) are higher than those in the 2-EPS panels (D, E, F panels). But with increasing immersion time to 24 h and 14 days the

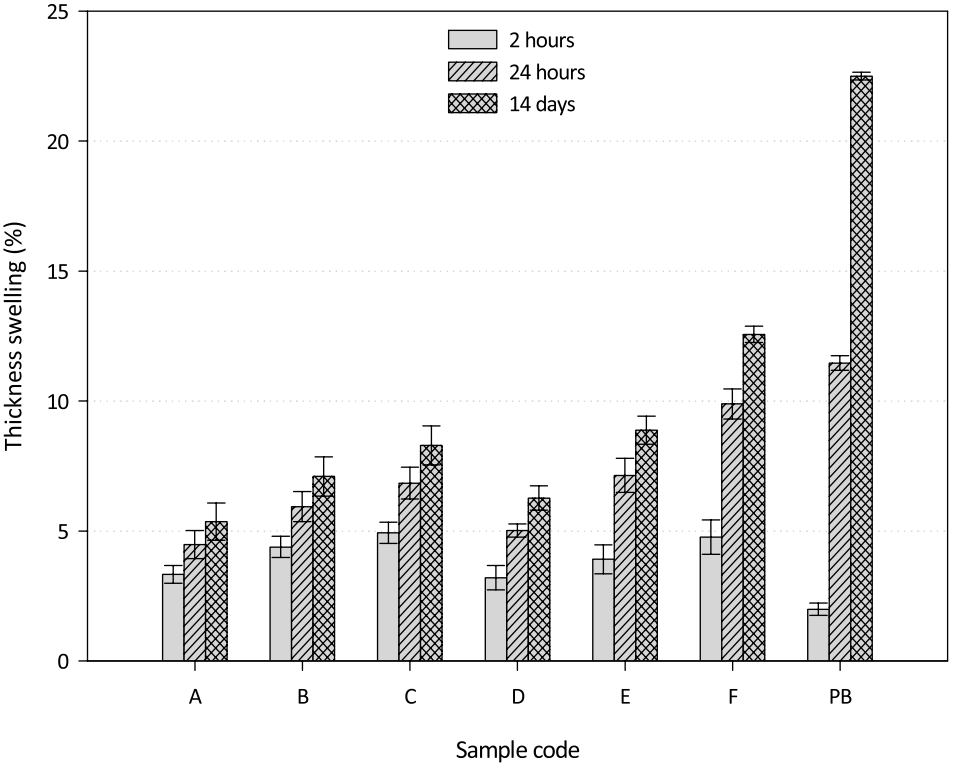


Figure 3. Thickness swelling after immersion in water (2 h, 24 h and 14 days) in the 1-EPS (A, B, C), the 2-EPS panels (D, E, F) and conventional particleboard (PB).

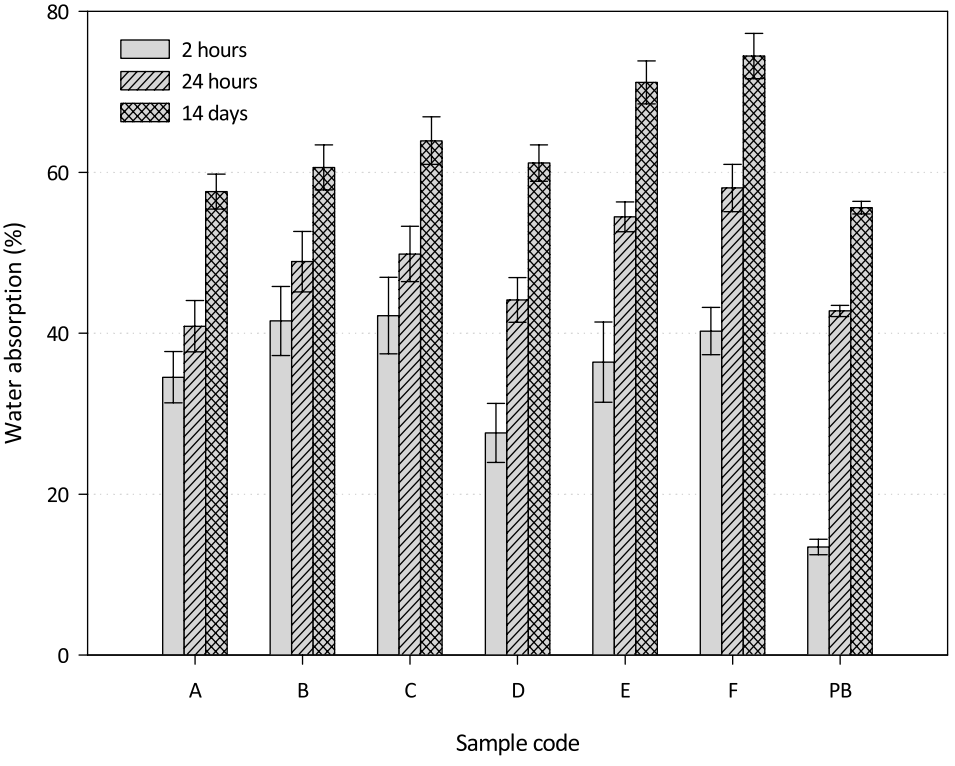


Figure 4. Water absorption after immersion in water (2 h, 24 h and 14 days) in the 1-EPS (A, B, C), the 2-EPS panels (D, E, F) and conventional particleboard (PB).

WA in the 2-EPS panels increases significantly in comparison with the 1-EPS panels.

Even though increasing wood particles have a significant role on the WA values in foam core panels, the effect of core layer also has to be considered. It was mentioned earlier that the EPS material is generally non-hydroscopic. The closed cell structure of the EPS after foaming prevents the absorption of water into the expanded polystyrene beads. However, water can just enter through the small voids between the fused polystyrene beads. Horvath (1994) mentioned that the most important factor determining the water resistance of the EPS is bead fusion during the foaming process. The results revealed that there are more small voids available for absorbing water in the 1-EPS panels than in the 2-EPS panels. This can clarify the reason for higher WA in the 1-EPS at the short-term submersion (2 h) in comparison with the 2-EPS panels.

The ratio of water absorbed during 2 hours soaking related to the water absorbed after 24 hours and 14 days shown in Figure 5. It is obvious that in the 1-EPS panels more than 80 and 60% of the total absorbed water during 24 hours and 14 days were already absorbed after the first 2 hours immersion, respectively. It can be found for the 2-EPS panels that nearly 60 and 45% of the total WA during 24 hours and 14 days were absorbed after the first 2 hours submersion, respectively. These results also stated that the amount of absorbed water after 2 hours in the 1-EPS is higher than that in the 2-EPS panels due to the more small voids between the EPS foam cells. According to these findings, it can be said that the core layer is the dominant factor for the short-term WA values, while the effect of face layer thicknesses has more influenced the WA values for the long-term immersion.

Comparison of the results with reference particleboard showed that foam core panels have significantly higher WA values in all the submersion times. Even though particleboard has a higher number of hydroxyl groups for absorbing water, the WA values of foam core panels are significantly higher due to the more voids in the EPS of core layer. As a result, it can be argued that the process parameters (foaming temperature, foaming and pressing times) have a significant effect on the fusion and consequently on the resulting small voids between the EPS beads. A better EPS cell fusion with lower void volume between the cells can be achieved by increasing press temperature from 130 to 160°C or even higher.

*Dimensional stability.* The values for LE and LC percentage of samples in wet (85 % RH) and dry (35% RH) conditions with 20°C are summarised in Figure 6 and Appendix 1. Both LE and LC significantly increase with increasing surface layer thicknesses. This effect on the dimensional stability can be

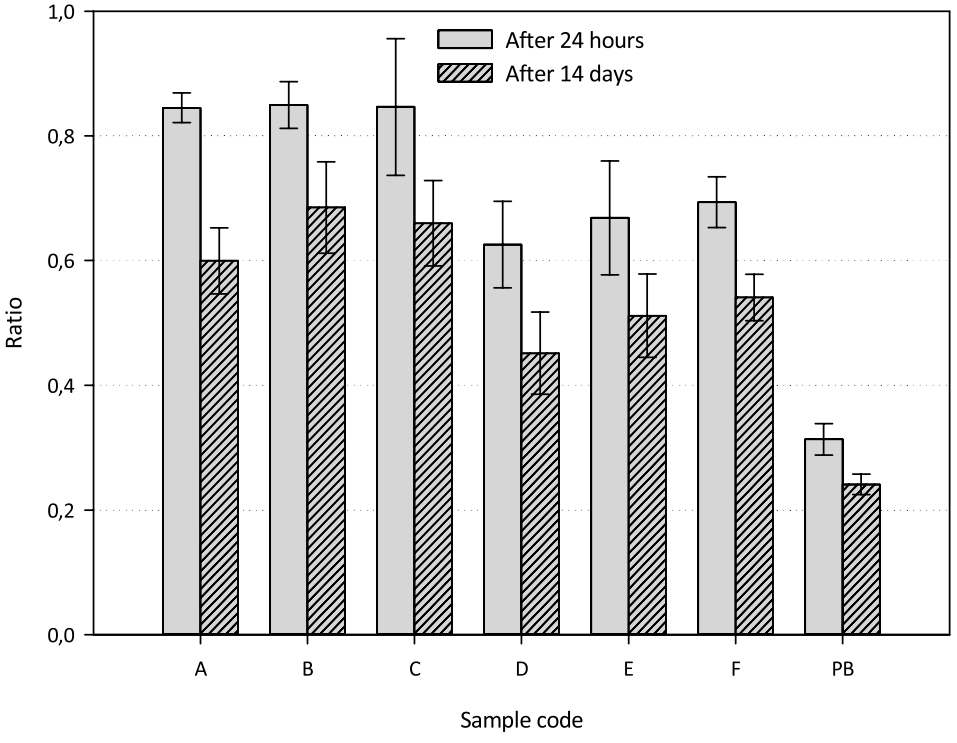


Figure 5. Ratio of water uptake after 2 hours soaking to long-term water uptake (24 hours and 14 days) in the 1-EPS (A, B, C), the 2-EPS panels (D, E, F) and conventional particleboard (PB).

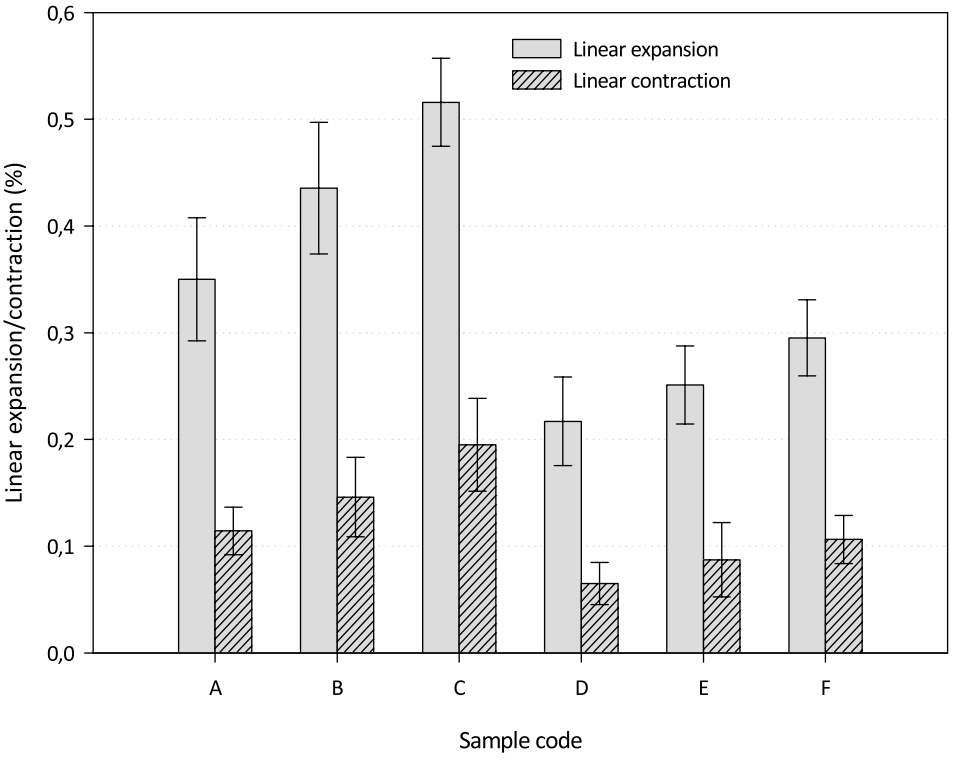


Figure 6. Linear expansion/contraction of foam core panels at 20°C in wet (85% RH) and dry (35% RH) condition in the 1-EPS (A, B, C) and the 2-EPS panels (D, E, F).

due to the increased panel density by the higher amount of hygroscopic material (Vital *et al.* 1980, Suzuki and Miyamoto 1998, Ayrilmis 2007). As discussed about the EPS properties earlier, the core layer has no direct effect on LE and LC percentage.

At the first glimpse, it is also obvious that the LE percentages are significantly higher than LC percentages. It is well known that the absorbed moisture in higher RH is never entirely released at lower RH (Suchsland 1972). A corresponding comparison revealed that the LE and LC in the 1-EPS panels (A, B, C panels) are higher than those in the 2-EPS panels (D, E, F panels). The reason can be the better foam characteristics (smaller and more cells) in the 2-EPS panels compared to the 1-EPS panels (Shalbafan *et al.* 2012b). A better foam cell configuration in the 2-EPS panels behaves like an internal restraining system underneath the hygroscopic face layers. Verifying both the behaviour of interface between face and core layers and changing of interparticle bonding in the 1-EPS and the 2-EPS panels when exposed to different climates are recommended topics for more investigations in this area. According to the ANSI-A208.1 (2009), the maximum allowable LE for conventional particleboard is 0.40%. This requirement is fulfilled for all the panels except panel B and C.

The thickness swelling ($TS_w$) and shrinkage ($TS_d$) of foam core panels in wet and dry conditions at 20°C and 85% and 35% RH are shown in Figure 7 and Appendix 1. The thickness changes in wet and dry conditions are raised by increasing the surface layer thickness in both panel types. High level of the $TS_w$ in comparison with the $TS_d$ can also be referred to the hysteresis phenomena (Suchsland 1972). It should be mentioned that the dimensional changes in response to changing environmental conditions were tremendously smaller than those of the immersion test.

Linear expansion and contraction percentage are based on the initial dimension of the samples before climate changing. For a better understanding, the LE and the LC percentage were recalculated on the basis of equilibrium moisture content changes (ΔEMC). Figure 8 shows the LE and the LC per unit change of moisture content (LE/ΔEMC and LC/ΔEMC (%/%)) of foam core panels in wet and dry conditions. In the 1-EPS panels, LE/ΔEMC is increased from 0.12 (3 mm) to 0.15 (5 mm) and for the 2-EPS from 0.07 (3 mm) to 0.085 (5 mm). The LC/ΔEMC for the 1-EPS ranges from 0.07 (3 mm) to 0.11 (5 mm) and also in the 2-EPS from 0.04 (3 mm) to 0.06 (5 mm). Due to the hysteresis phenomena, it is obvious that the amounts of the LE/ΔEMC are significantly higher than those in the LC/ΔEMC. This study showed that with changing the process parameters (press temperature, pressing and foaming time) in the production of lightweight foam core panels a better dimensional stability in

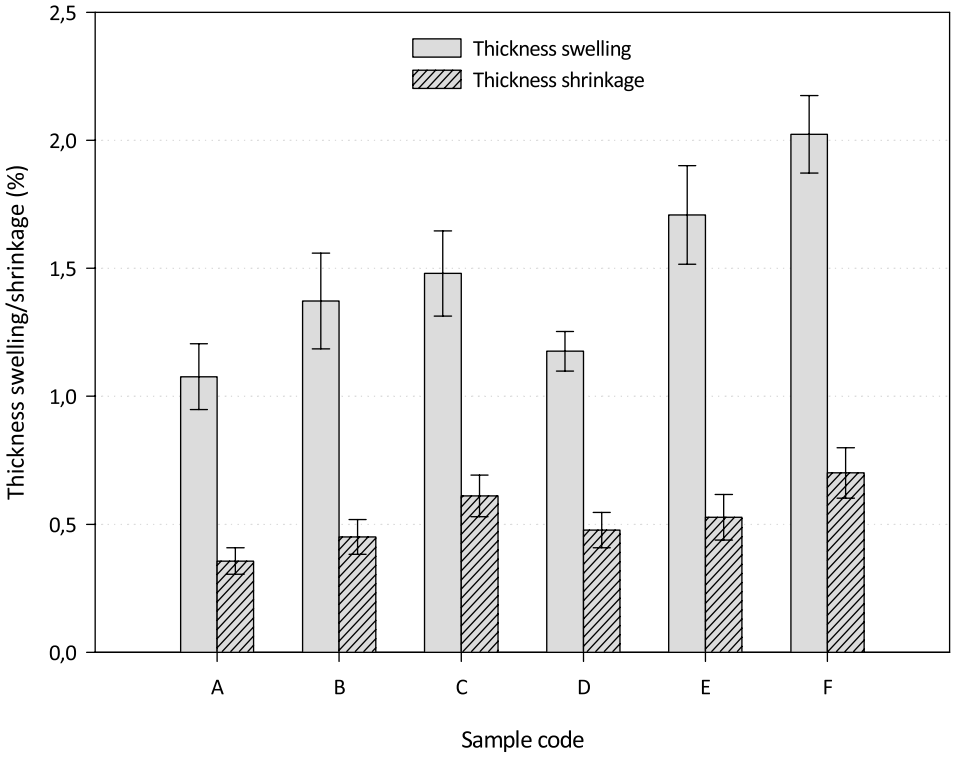


Figure 7. Thickness swelling/shrinkage of foam core panels at 20°C in wet (85% RH) and dry (35% RH) condition in the 1-EPS (A, B, C) and the 2-EPS panels (D, E, F).

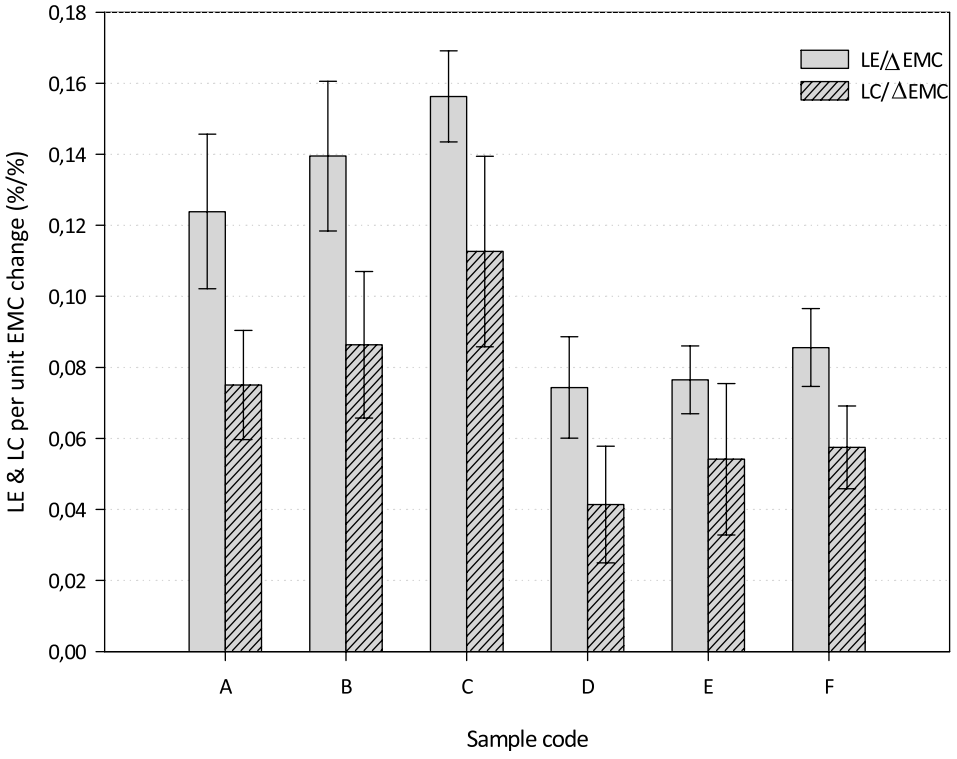


Figure 8. Linear expansion/contraction per unit equilibrium moisture content change of foam core panels at 20°C in wet (85% RH) and dry (35% RH) condition.

comparison with conventional particleboard would be possible. More stable panels under changing environmental conditions cause fewer defects at products in use.

## Conclusion

Foam core particleboards with EPS as core material have been produced in a one-step process with different pressing parameters. This study revealed that the foaming parameters (press temperature, press and foaming times) have a significant influence on the physical and dimensional properties.

A better surface layer with higher SS value and broader peak density plateau ($\sim 850\,kg/m^3$) are achieved in the panels with lower press temperature and longer pressing time. Surface quality plays an important role on both physical properties and dimensional stability. It can be assumed that the springback of the surface layer has an important role in the TS value in short-term immersion. The predominant phenomenon for TS in longer soaking conditions is the swelling of wood particles and accessibility to the OH groups. The more compacted the surface layer is, the less TS and WA are achieved in long-term immersion. The increment of wood particles in the surface layers causes significant effect on WA. The small voids between the EPS cells resulting from different foaming processes are also the critical parameters when the WA value is considered. Due to these voids in the EPS, the greatest part of absorbed water in long-term soaking is absorbed in the first 2 hours after immersion. The higher the press temperature is, smaller is the volume of the voids between the beads. As an outlook for further investigation, it is assumed that increasing press temperature more than 160°C would result in a better foam cell configuration and consequently better physical and dimensional properties.

It is revealed that due to the hysteresis phenomena, the LC and $TS_d$ are tremendously lower than the LE and $TS_w$, respectively. Using the LE/ΔEMC and LC/ΔEMC give a better understanding of dimensional stability in foam core panels. This study also figured out that with manipulating the process parameters producing lightweight foam core panels with a higher dimensional stability than particleboard would be possible. More stable panels with changing environmental condition cause fewer defects with products in use.

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Appendix 1. Physical properties (thickness swelling and water absorption) and dimensional stability of foam core particleboard.

| | Immersion test | | | | | | Conditioning chamber | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Thickness swelling (TS) | | | Water absorption (WA) | | | Wet chamber (85% RH) | | Dry chamber (65% RH) | |
| Number | 2 h | 24 h | 14 days | 2 h | 24 h | 14 days | $LE_{65–85(\%)}$ | $TS_w$ | $LC_{65\ to\ 35\ (\%)}$ | $TS_d$ |
| A | 3.3 (0.34) | 4.5 (0.54) | 5.4 (0.71) | 34.5 (3.20) | 40.9 (3.18) | 57.6 (2.17) | 0.35 (0.05) | 1.08 (0.13) | 0.11 (0.02) | 0.35 (0.05) |
| B | 4.4 (0.41) | 5.9 (0.57) | 7.1 (0.75) | 41.5 (4.30) | 48.9 (3.77) | 60.6 (2.78) | 0.43 (0.06) | 1.37 (0.19) | 0.15 (0.04) | 0.45 (0.07) |
| C | 4.9 (0.40) | 6.8 (0.62) | 8.3 (0.75) | 42.2 (4.76) | 49.8 (3.42) | 63.9 (2.96) | 0.52 (0.04) | 1.48 (0.17) | 0.19 (0.04) | 0.61 (0.08) |
| D | 3.2 (0.47) | 5.0 (0.25) | 6.3 (0.47) | 27.6 (3.68) | 44.1 (2.79) | 61.1 (2.27) | 0.22 (0.04) | 1.17 (0.08) | 0.06 (0.02) | 0.48 (0.07) |
| E | 3.9 (0.56) | 7.1 (0.65) | 8.9 (0.54) | 36.4 (4.98) | 54.5 (1.84) | 71.1 (2.67) | 0.25 (0.03) | 1.70 (0.19) | 0.09 (0.03) | 0.53 (0.09) |
| F | 4.8 (0.66) | 9.9 (0.58) | 12.6 (0.31) | 40.3 (2.92) | 58.1 (2.94) | 74.5 (2.80) | 0.29 (0.03) | 2.02 (0.15) | 0.10 (0.02) | 0.70 (0.10) |

LE, linear expansion in wet condition; $TS_w$, thickness swelling in wet condition; LC, linear contraction in dry condition; $TS_d$, thickness shrinkage in dry condition.
Numbers in parenthesis show the standard deviation.

# IV

# Physiomechanical properties of ultra-lightweight foam core particleboard: different core densities

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# Physiomechanical properties of ultra-lightweight foam core particleboard: different core densities

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## Abstract

Ultra-lightweight foam core particleboards have been produced in a novel one-step process with resinated wood particles for the faces and expandable polystyrene (EPS) as core layer material. The mechanical and physical properties of panels were investigated in terms of the different foam core densities and press parameters (temperature, pressing and foaming time). The bending strength properties of the panels were not significantly changed with increasing foam core density from 80 to 120 kg $m^{-3}$. Panels produced at a press temperature of 130°C (1-EPS) have an improved core-face interface and also a denser surface layer, which positively influences the internal bond and thickness swelling. The panels produced at a press temperature of 160°C (2-EPS) have smaller and more foam cells and an improved fusion of foam beads and properties, which have a positive influence on the edge screw withdrawal resistance and water absorption.

**Keywords:** EPS; foam core particleboard; one-stage process; sandwich; ultra-lightweight panel.

## Introduction

The idea of sandwich structures in construction can be traced back to Fairbairn (1849), while the first application of wooden sandwich type materials was in aviation during World War II (Mosquito bomber, see Zenkert 1997; Vinson 2005). In sandwich structures, the heavy core materials are replaced with lightweight ones. Their structural performance is comparable to that of conventional materials while saving weight (Allen 1969; Karlsson and Åström 1997).

The development of sandwich structures in the wood-based panel industry is rather slow, because the costs of core material and processing are high, and a specialized technology is needed. Challenges include the bonding of the separate layers, the edge processing, and integration of connectors. Recent developments with integrated process technology in focus have provided a new opportunity for enhancing the application of foam core sandwich panels in furniture production (Luedtke et al. 2008). This approach is derived from the conventional production principle of particleboards. Gluing of the separate layers is not needed, due to the *in situ* foaming and simultaneous production of all layers at once. Solid foam in the core layer (compared to the hollow sections of honeycomb panels) minimizes the difficulties of edge-processing and integration of connectors.

The mechanical properties of polymeric foams in the core are principally affected by density, morphology, and the molecular weight and polymer type in the foam (Sands and Shivkumar 2003). Gendron (2005) proposed that it might be possible to maintain the mechanical properties of polystyrene foam with a lower density, by decreasing the foam cell size. Doroudiani and Kortschot (2003) described a batch foaming process for investigating the 'process-structure relationships' in the expanded polystyrene and were able to produce foams with similar densities and different cell sizes, by controlling the foaming conditions. Shalbafan et al. (2012b) succeeded in producing different foam cell configurations, by changing pressing parameters in the foam core particleboards produced in a one-step process. They varied different pressing temperatures**,** which changed the pressing, foaming, and stabilization time in the press schemes. However, the study did not further discuss the optimum foam core density in the products. Minimizing the foam core density has a strong influence on the production cost.

In the current study, ultra-lightweight foam core particleboards are in focus, which were produced in a one-step process based on resinated wood particles for the faces and thermo-sensitive expandable polystyrene (EPS) granulate in the core. The pressing temperature of 130°C and 160°C will be applied to reach different foam structures. The aim of the study is to check the effect of foam core densities with 80, 100, and 120 kg $m^{-3}$ on the physiomechanical properties of panels produced in two different regimes of press temperature.

## Materials and methods

### Panel manufacturing

Three-layered panels with a nominal thickness of 19 mm were produced in an integrated process. Fine wood particles (≤2 mm) for the surface layers were resinated with 12% urea formaldehyde resin (BASF, Ludwigshafen, Germany). The target density of the surface layer was 750 kg $m^{-3}$. The core layer was produced from EPS granulates (EPS; Terrapor 4, diameter 0.3–0.8 mm) provided by Sunpor

Kunststoff GmbH (Pölten, Austria). The activation temperature was 95–115°C and the glass transition temperature 103°C. Target core densities of the panels were 80, 100, and 120 kg $m^{-3}$. The surface (3 mm) and core (13 mm) layer thicknesses were kept constant at all the parameter variations.

After forming the face and core materials into a three-layered mat (600×550 $mm^2$), the mat was pressed in three consecutive stages (pressing, foaming and stabilization stages) in a single opening lab hot-press, which was computer controlled and which was equipped with a cooling option (Siempelkamp, Krefeld, Germany). First, the faces were compacted until the urea formaldehyde resin was cured. The pressing time at this stage was 80 s for the panels produced at 130°C (1-EPS) and 45 s for the panels produced at 160°C (2-EPS). Second, the press was opened to the final panel thickness at the due time, to allow core expansion. In the third stage, the stabilization of the panel was done in the press by internal cooling of the press plates, in a controlled distance to consolidate the expanded core. The stabilization times for the 1-$EPS_{130°C}$ and the 2-$EPS_{160°C}$ panels were 130 and 140 s, respectively.

At a press plate temperature of 130°C, a longer foaming time (45 s) is needed than at 160°C (10 s), because of the less intense heat flow from the surface layer to the thermosensitive material in the core. Due to the different foaming conditions, the resulting foam in the 1-EPS panels looks glassy like, whereas the EPS foam in the 2-EPS panels resembles packaging materials. Four panels of each series as replicates were produced. Table 1 shows the experimental design for panel manufacturing.

Figure 1 shows the combined press schedules and protocols for the two panel types. Temperature measurement: by inserted thermocouples at three positions along the panel thickness. In the surface layer, the thermocouple was in a distance of ca. 0.5 mm from the interface between the foam core and the wood-particle layer. The temperatures at the interface and in the foam core layer were recorded individually. At the time of foaming (2nd pressing stage), the temperature of the EPS material in the core reached 100°C in the 1-EPS and 95°C in the 2-EPS panels. The cooling (by water circulation in the pressing plates) was started when the distance between press plates reached the final panel thickness (19 mm). Due to the unsophisticated cooling system, a time delay for cooling of the core layer was observed. When the cooling starts, the temperature of surface layers decreases much faster than that of the EPS core layer.

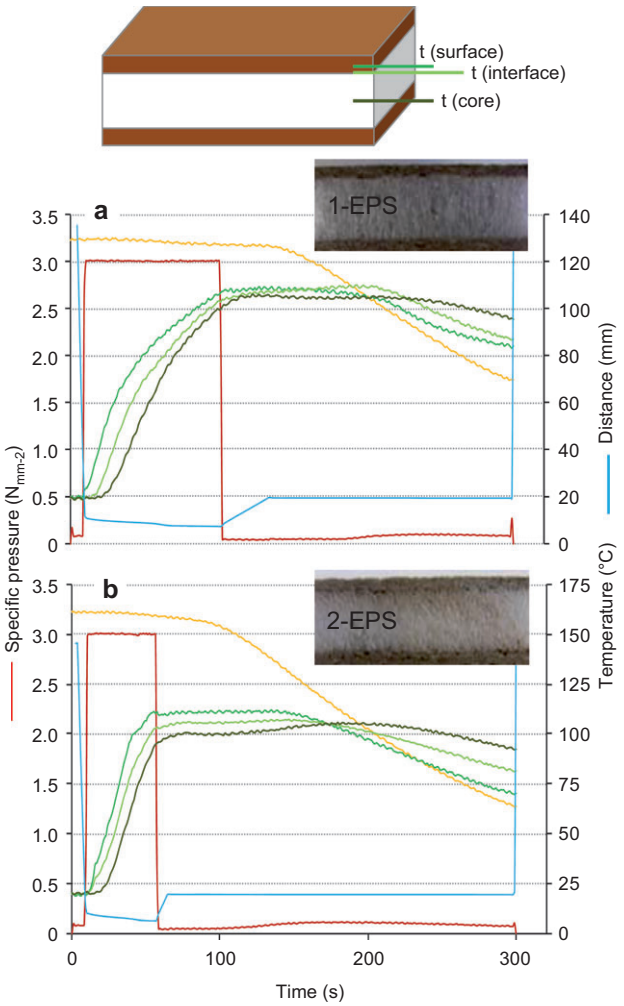


**Figure 1** Pressing schedule protocol of ultra-lightweight foam core panels – 1-EPS panels (130°C) and 2-EPS panels (160°C); t shows temperature and distance mean press plates distance.

## Sample preparation and testing procedures

For panel characterization, cross-sectional density profiles were measured by γ-ray densitometry (Raytest GmbH, Straubenhardt, Germany) and FE-SEM images from the core layer were taken by Quanta FEG 250, Oregon, USA.

Bending strength (EN 310), internal bond strength (EN 319) and face-edge screw withdrawal resistance (EN 13446) were determined. The physical behavior (EN 317) of the panels was characterized by measuring the thickness swelling and water absorption after 2 and 24 h water soaking at 20°C. From each panel variation, four replicates were manufactured. Three samples of each replicates ($n$=12) were randomly selected and tested. Prior to testing, all samples were

**Table 1** Experimental design for the 19 mm foam core particleboard with 3 mm face layer.

| Panels | Press temp. (°C) | Densities (kg $m^{-3}$) | | Time (s) for | | | Number of repetitions |
|---|---|---|---|---|---|---|---|
| | | Target core | Target panel | Pressing | Foaming | Stabilization | |
| 1-EPS | | | | | | | |
| A | 130 | 80 | 295 | 80 | 45 | 130 | 4 |
| B | 130 | 100 | 310 | 80 | 45 | 130 | 4 |
| C | 130 | 120 | 325 | 80 | 45 | 130 | 4 |
| 2-EPS | | | | | | | |
| D | 160 | 80 | 295 | 45 | 10 | 140 | 4 |
| E | 160 | 100 | 310 | 45 | 10 | 140 | 4 |
| F | 160 | 120 | 325 | 45 | 10 | 140 | 4 |

conditioned in a climate chamber at 65% relative humidity and 20°C, until constant mass was reached. The sample preparation is summarized in Table 2. All the physical and mechanical tests were conducted on unsanded samples.

A one-way analysis of variance (ANOVA) of the physiomechanical properties was performed with the Statistical Package for the Social Science (SPSS, New York, USA). Due to the homogeneity of variances, statistical differences between variations were evaluated by multiple comparisons based on a least significant difference (LSD) test. The statistical significance was set to $P<0.05$.

## Results and discussions

### Density profile

The density profiles of the panels in Figure 2 show three different levels of core densities in both panel types. A closer examination reveals that the panels 1-EPS$_{130°C}$ have a more homogenous compaction zone in the surface layer. This is due to the nearly doubled pressing time compared to the 2-EPS$_{160°C}$ panels. The average densities of the former (panels A, B and C) and the latter (panels D, E and F) in Figure 3 show the following: the lower compaction of the surface material in the 2-EPS$_{160°C}$ panels caused an undesired increase of the surface layer thickness beyond the target of 3 mm, and accordingly, reduced the core layer thickness (<13 mm). This led to an increase of foam core density of approximately 10% above the target density. It should be mentioned that there is no penetration of EPS into the surface layer close to the interface.

Average surface layer densities >600 kg m$^{-3}$ on both sides (upper and lower surfaces) in both panel types were calculated in the specified rectangular area indicated in Figure 3. The 1-EPS$_{130°C}$ panel (810 kg m$^{-3}$) in the specified area has a 40 kg m$^{-3}$ higher surface density than the 2-EPS$_{160°C}$ panels (770 kg m$^{-3}$).

### Foam characterization

Figure 4 with the microstructure of EPS foams demonstrates the closed cell structures. It is also visible that the foams produced at 130°C (panels A, B, C) have relatively bigger cells in comparison to those (panels D, E and F) produced at 160°C. A higher pressing temperature results in faster foaming and, accordingly, smaller and more uniform foam cells (Doroudiani and Kortschot 2003). The cell size decrement in the 2-EPS$_{160°C}$ panels compared with the 1-EPS$_{130°C}$ samples is also a result of the undesired decrease of core layer thicknesses (<13 mm), because less space is available for EPS expansion.

**Table 2** Sample specifications for physical and mechanical tests.

| Property | Standard | Sample size (mm) | Tested sample |
|---|---|---|---|
| Density profile | EN 323 | 50×50×19 | 4 |
| Bending strength | EN 310 | 430×50×19 | 12 |
| Internal bond | EN 319 | 50×50×19 | 12 |
| Screw withdrawal | EN 13446 | 50×50×19 | 12 |
| Thickness swelling | EN 317 | 50×50×19 | 12 |

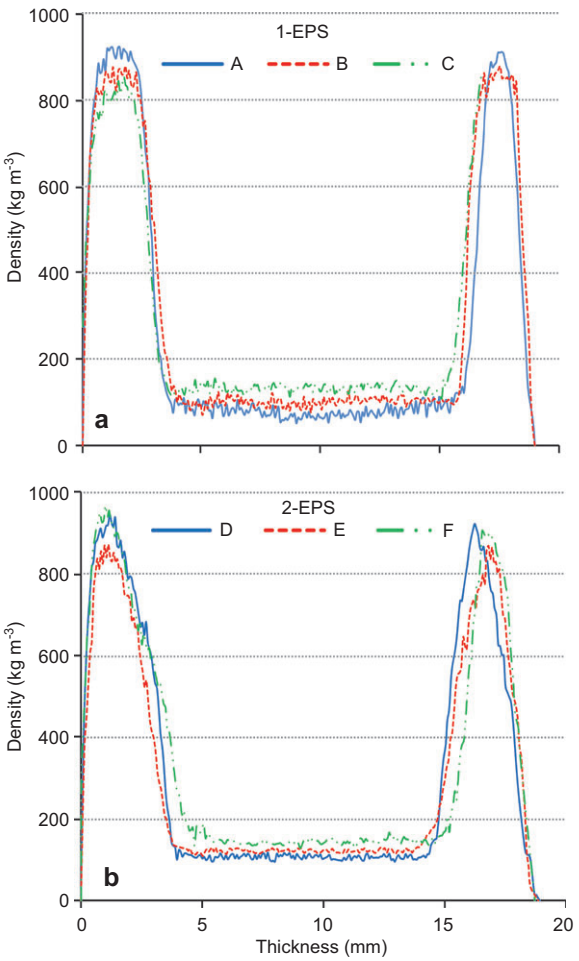


**Figure 2** Vertical density profile of panels produced with different core densities (A, and D: 80 kg m$^{-3}$, B and E: 100 kg m$^{-3}$, C and F: 120 kg m$^{-3}$) and press temperatures of 130°C (panels A, B, C) and 160°C (panels D, E, F).

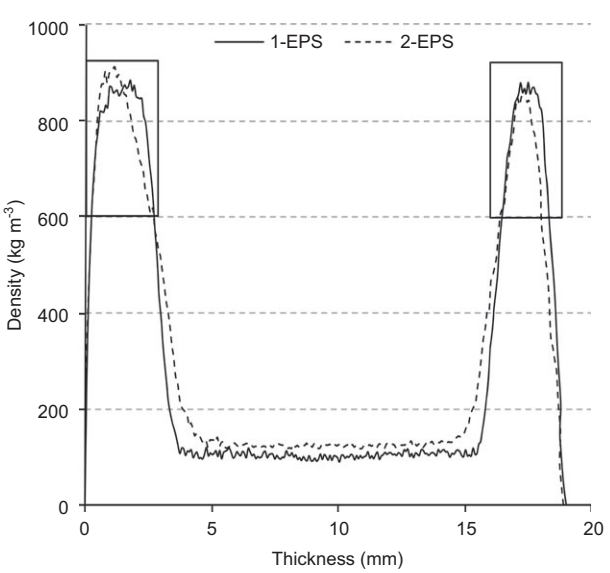


**Figure 3** Comparison of density profiles for the 1-EPS and 2-EPS panels.

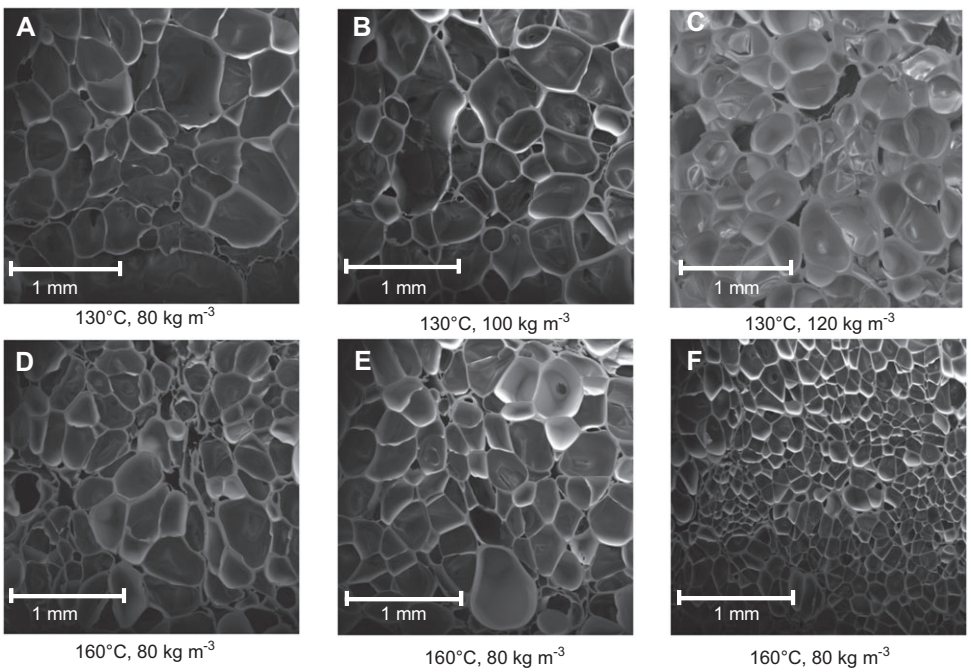


**Figure 4** Microstructure pictures of foam cells in 19 mm foam core particleboard: 1-EPS (panels A, B, C) and 2-EPS (panels D, E, F).

Both pressing schemes (at 130°C and 160°C) result in an increased number of foam cells per volume unit, and the foam density becomes higher. These factors entail, automatically, a cell size decrement. The smaller the cell size, the better are the mechanical properties of the foam. Bureau and Gendron (2003) and Gendron (2005) described this correlation. In summary, cell size control is one of the keys for process optimization.

### Bending strength (MOR)

The bending properties of sandwich structures with a soft core layer are different from the monolithic wood-based panels. In the latter case, the shear deformation does not significantly contribute to the bending properties in contrary to the situation in sandwich structures (Allen 1969; Luedtke 2011). Due to the layered buildup from different materials, the determination of a modulus of elasticity (MOE) is not appropriate in three-point bending. Thus, the bending properties are expressed by the modulus of rupture (MOR), which is defined here as failure stress measured in three-point bending tests.

Figure 5a illustrates the results of MOR tests. By increasing the core density from 80 to 120 kg $m^{-3}$, the MOR raised from 8.5 to 9 N $mm^{-2}$ in the 1-$EPS_{130°C}$ (panels A, B, C) and from 8 to 8.2 N $mm^{-2}$ in the 2-$EPS_{160°C}$ (panels D, E, F). The increase of either core density (from 80 to 120 kg $m^{-3}$) or pressing temperature (from 130 to 160°C) has no significant effect on the bending strength. Accordingly, the surface layer thickness in the foam core particleboard has a superior influence in this regard. The MOR values for the 1-$EPS_{130°C}$ panels are insignificantly higher than those of the 2-$EPS_{160°C}$ panels.

Obviously, the denser surface layers of the former influence the bending strength only slightly. In both panel types, the bending samples failed mostly due to collapsing the lower faces. Shear failure at the interface between foam and face layers was observed only in panel F.

According to Figure 5a, the minimum requirement of bending strength for a conventional particleboard according to EN 312/P2 (11.5 N $mm^{-2}$) is not fulfilled for foam core panels with 3 mm surface layer thickness. This fact should be related to the 50% lower density of an ultra-lightweight foam core particleboard. Moreover, the bending strength is sufficient for certain applications, where the requirement of EN 312/P2 has not to be fulfilled.

To make the panels with different densities comparable, the bending strength values were divided by the target panel density, resulting in specific strength values. These data are in the range of approximately 29 000 to 27 700 Nm $kg^{-1}$ (1-$EPS_{130°C}$ panels) and of 27 300 to 25 300 Nm $kg^{-1}$ (2-$EPS_{160°C}$ panels). While the foam core density is raised from 80 to 120 kg $m^{-3}$, the specific bending strength in both panel types slightly declines due to the raising mean panel density. The specific bending strength of 17 700 Nm $kg^{-1}$ of a conventional particleboard, with a density of 650 kg $m^{-3}$, is exceeded by all the lightweight panel variations. In some applications, where the weight saving is important, or for certain components of a piece of furniture, preserving the minimum requirements of strength would be possible. Hence, replacing conventional panels with lightweight foam core panels is reasonable, due to the higher specific strength.

### Internal bond strength (IB)

The values for IB are presented in Figure 5b, according to EN 319. Two significant trends are visible as a function of core density increment from 80 to 120 kg $m^{-3}$. First, for 1-$EPS_{130°C}$

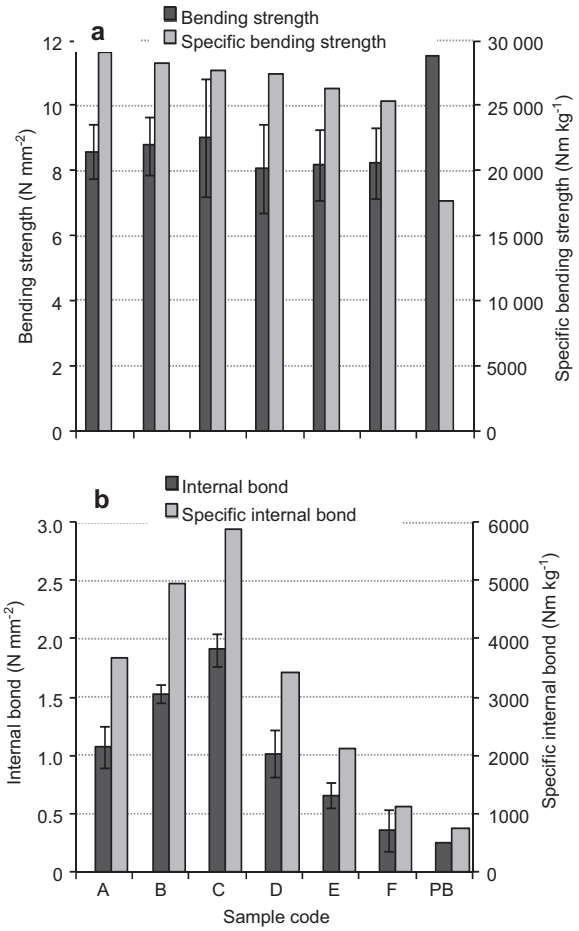


**Figure 5** Bending strength (a) and internal bond strength (b) values of 19 mm foam core particleboard: 1-EPS (panels A, B, C) and 2-EPS (panels D, E, F).

(panels A, B, C), the IB rises from 1.00 to 1.90 N mm$^{-2}$ and second, for 2-EPS$_{160°C}$ (panels D, E, F), the IB decreases from 1.00 to 0.36 N mm$^{-2}$. The significantly raised IB values in the first case can be explained by the increased number of foam cells as a result of enhanced density, which leads to a stronger foam (Klempner and Frisch 1991).

Two different failure modes were observed in the context of core density. The panels A, B, C failed in the core layer, while the fracture was monitored at the interface between the face and core in panels D, E, F. This indicates a better interface between foam cells and wood particles in panels pressed at 130°C. The pressing time for the 1-EPS$_{130°C}$ panels is nearly twice as long as that for the 2-EPS$_{160°C}$ panels, which facilitate a better connectivity between softened polystyrene beads and wood particles. The opposite is true for 2-EPS$_{160°C}$ panels. The small cell sizes, with their stronger foam cell structure in the latter case, were already pointed out. This is the reason why 2-EPS$_{160°C}$ fails in the interface. The role of the interface was also pointed out by Shalbafan et al. (2012a): the stronger the interface, the higher is the IB. All panels outperform the minimum requirement of 0.24 N mm$^{-2}$ for the IB of particleboards according to EN312/P2. In summary, increasing the foam core density leads to unnecessarily high IB values in the 1-EPS$_{130°C}$ panels and also to a decline in IB values in 2-EPS$_{160°C}$ panels.

The specific IB values in Figure 5b show the same trend as the absolute IB data. With elevation of the core density from 80 to 120 kg m$^{-3}$, the specific values raise from 3600 to 5900 Nm kg$^{-1}$ (1-EPS$_{130°C}$) and decline from 3400 to 1100 Nm kg$^{-1}$ (2-EPS$_{160°C}$). The calculated specific internal bond (370 Nm kg$^{-1}$) for a 650 kg m$^{-3}$ particleboard is fulfilled by all the panels.

### Screw withdrawal resistance (SWR)

Expectedly, the face screw withdrawal resistance (FSWR) (Figure 6a) significantly rises by increasing the core density in both panel types, as was described earlier (Johnson 1967). Elevation of core density from 80 to 120 kg m$^{-3}$ causes a 10% increase in the mean panel density (from 295 to 325 kg m$^{-3}$). FSWR in wood products changes with the square of its density (USDA 1999). More foam cells per volume unit and the accompanying smaller foam cell sizes contribute to the FSWR increment.

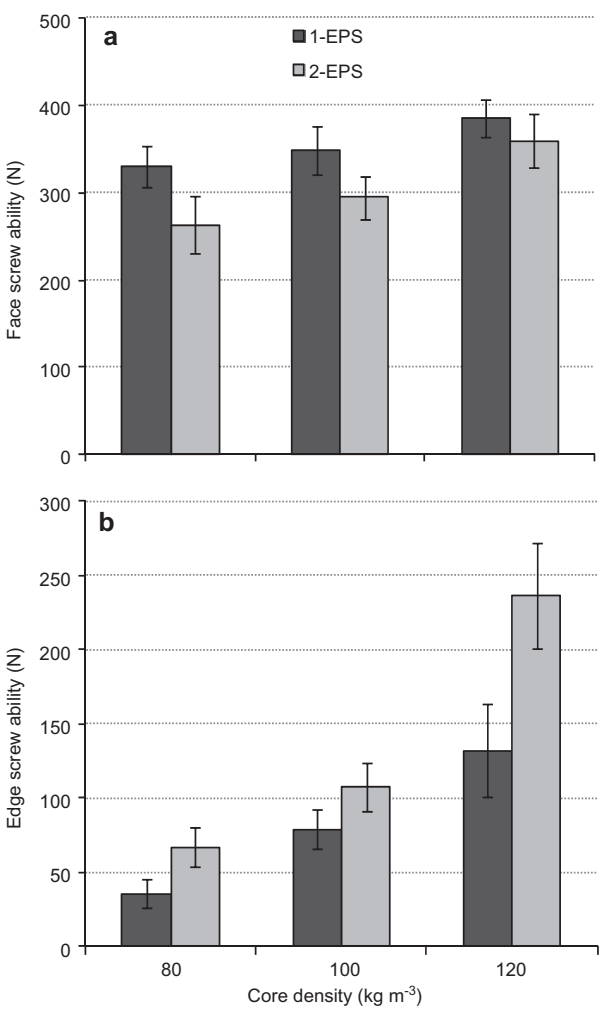


**Figure 6** Face screw (a) and edge screw (b) withdrawal resistance of 19 mm foam core particleboard: 1-EPS (130°C) and 2-EPS (160°C).

The performance of 1-EPS$_{130°C}$ panels was better in this regard than that of the 2-EPS$_{160°C}$ panels. This is related to the pressing time (Table 1), as it was nearly twice as long for the panels for the former than for the latter. As a consequence, the surface layer of the 1-EPS$_{130°C}$ panels is more compact (Figure 3) and this positively affects the FSWR.

The data of edge screw withdrawal resistance (ESWR) (Figure 6b) are also positively influenced by elevated core densities for both panel types. Interestingly, ESWR$_{2\text{-EPS}}$ are higher than ESWR$_{1\text{-EPS}}$, though the opposite was observed for the MOR, IB, and FSRW data. This effect can easily be explained by the better foam structure in the 2-EPS panels as has been outlined already.

### Physical properties

Thickness swelling (TS, Figure 7a) and water absorption (WA, Figure 7b) were determined after submersion in water for 2 and 24 h. TS does not change significantly as a function of core density because polystyrene foam (EPS) is hydrophobic, which neither shrinks nor swells in contact with water (Horvath 1994). Only the surface layer has influenced the TS, the quality of which was the same in both panel types. TS in short term immersion (2 h) in the 1-EPS$_{130°C}$ panels seems to be slightly higher than that of the 2-EPS$_{160°C}$ panels, but these differences are statistically not relevant. Prolongation of immersion time to 24 h, however, significantly raises the TS of 2-EPS$_{160°C}$ panels, which can be explained by the shorter pressing times. The pressing time in the 1-EPS$_{130°C}$ panels is nearly twice as long as in the 2-EPS$_{160°C}$ panels. The higher the pressing time, the higher is the compaction of the surface particles. Releasing the compression stress (springback) as a consequence of the longer pressing time has an important influence on the TS values in the short term soaking (slightly higher TS values in the 1-EPS panels). A more compacted surface layer (Figure 3) in the 1-EPS$_{130°C}$ panels also causes less accessibility to the hydroxyl groups in the surface layer (Kelly 1977). This leads to the lower amount of TS in the 1-EPS$_{130°C}$ compared with the 2-EPS$_{160°C}$ panels after 24 h of soaking.

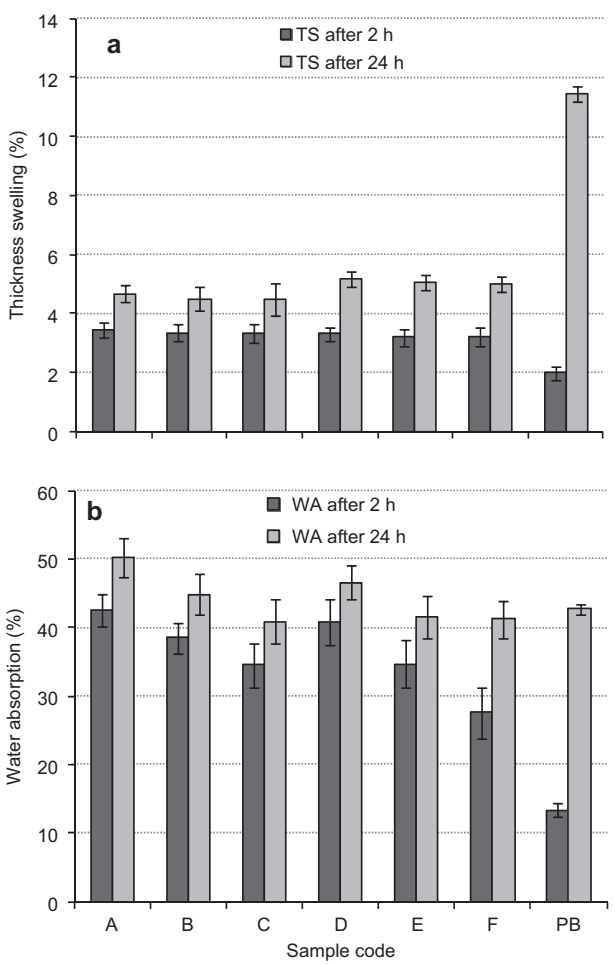


**Figure 7** Thickness swelling (a) and water absorption (b) values of 19 mm foam core particleboard after immersion (2 h, 24 h): 1-EPS (panels A, B, C) and 2-EPS (panels D, E, F).

The TS of the industrial particleboard is 2 and 11.5% after storage in water for 2 and 24 h, respectively. The better TS after 2 h is partly due to the wax treatment of conventional particleboards. Moreover, the pre-cured surface layers of the foam core particleboard were not removed by sanding prior to testing. This also elevates the TS (Cai et al. 2004). After 24 h soaking, the TS of the industrial particleboard is essentially higher than that of the foam core particleboards. The higher wood content of the latter is responsible for this, while the hydrophobic effect of wax vanishes during a long term water exposure.

Expectedly, the data of water absorption (WA, Figure 7b) are declining with increasing core densities, while WA$_{1\text{-EPS}}$>>WA$_{2\text{-EPS}}$ for short and long soaking times. WA for the industrial particleboard is 13% (2 h) and 43% (24 h). The good performance of foam core panels in the long time treatment falls below the WA values of industrial particleboard, except panel A and D. If the foam core densities are above 100 kg m$^{-3}$, the WA performance of ultra-lightweight foam core particleboards will be superior to that of conventional particleboards.

## Conclusions

Foam core particleboards 1-EPS$_{130°C}$ have a denser surface layer and improved foam-face interface than boards 2-EPS$_{160°C}$. This leads to a slightly increased bending strength and face screw withdrawal. The effect on TS is twofold: 1. there is higher compression stress release resulting from the pressing process (springback) and 2. there is less accessibility of moisture to the OH-groups in wood.

Processing at 160°C (2-EPS$_{160°C}$) leads to smaller and more uniform cells and to a better foam beads fusion. This positively influences the ESWR and WA. The smaller the foam cells are, the higher is the ESWR. Foam with fewer voids between the cells (obtained at higher press temperatures) is advantageous for the WA values. As a result, the physiomechanical properties of the panels are improved.

Increasing the foam core density has no effect on the bending strength and TS while it significantly increases both

the face and the ESWR. Higher core density entails higher $IB_{1\text{-}EPS}$ and lower $IB_{2\text{-}EPS}$. At foam core densities >100 kg $m^{-3}$, an ultra-lightweight foam core particleboard can be produced with lower WA compared with that of a conventional particleboard. It is possible to produce ultra-lightweight foam core particleboards with acceptable qualities.

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# V

# Physikalische und mechanische Eigenschaften von leichten Holzwerkstoffplatten mit in-situ geschäumtem Kern

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# Physikalische und mechanische Eigenschaften von leichten Holzwerkstoffplatten mit *in-situ* geschäumtem Kern

**Johannes Welling, Ali Shalbafan**

Für die Herstellung von leichten Holzwerkstoffen gibt es verschiedene Konzepte. Für Platten mit einem ähnlichen Eigenschaftsprofil, wie konventionelle Holzwerkstoffe bei gleichzeitig drastisch reduziertem Gewicht, eignet sich der Sandwichaufbau. Während konventionelle Sandwichplatten in der Regel in einem mehrstufigen Verfahren aus unabhängig voneinander hergestellten Komponenten hergestellt werden, ist es am Thünen-Institut (TI) für Holzforschung in enger Zusammenarbeit mit dem Zentrum Holzwirtschaft der Universität Hamburg gelungen, leichte Holzwerkstoffe mit Schaumkern in einem einzigen Prozessschritt zu erzeugen. Durch das Aufschäumen der Mittelschicht *in-situ* in der Heißpresse lassen sich Schaumkernplatten erzeugen, die bei etwa 50 % Gewichtseinsparung in ihren physikalischen und mechanischen Eigenschaften konventionellen Holzwerkstoffen weitgehend entsprechen. Die spezifischen, also auf die Dichte bezogenen, Eigenschaften dieser Platten liegen zum Teil weit oberhalb der spezifischen Eigenschaften der konventionellen Alternativen.

**Schlüsselwörter:** Leichtbau, Sandwichstruktur, Spanplatte, EPS, Schaumkern

## Einleitung

Die Dichte von Span- und Faserplatten liegt üblicherweise im Bereich zwischen etwa 600 kg/m³ und 800 kg/m³. Seit vielen Jahren wird vor allem seitens der Hersteller von Mitnahmemöbeln der Wunsch geäußert, das Gewicht von Holzwerkstoffen zu reduzieren, um das Gewicht der Verpackungseinheiten reduzieren und dem Kunden die Manipulation der Pakete erleichtern zu können. Durch die erhebliche Ausweitung der Holzverwendung im stofflichen und energetischen Bereich in den letzten zehn Jahren, hat sich die Konkurrenz um den Rohstoff Holz verschärft, was letztendlich zu einem Anstieg der Preise für den Rohstoff geführt hat. So ist es verständlich, dass sich die Hersteller von Holzwerkstoffen um eine Verbesserung der Rohstoffeffizienz bemühen.

Um Holzwerkstoffplatten leichter zu machen, bieten sich verschiedene Strategien an (*Lüdtke et al.,* 2008). Neben der Verwendung von leichten Rohstoffen (z. B. Pappel oder Küstentanne) lässt sich durch die Ausgestaltung des Rohdichteprofils sowie durch die gezielte Beimengung von leichten Zuschlagstoffen (Flachsschäben, expandiertes Polystyrol, etc.) eine gewisse Gewichtsreduktion erreichen. Je nach Plattendicke und Plattenaufbau können auf diesem Wege Dichten von 450-550 kg/m³ erreicht werden. Will man zusätzlich Gewicht einsparen, so bietet sich die Herstellung von Holzwerkstoffen nach dem Prinzip des Sandwichsystems an (*Allen,* 1996; *Kalson und Åström,* 1997). Bekanntestes Beispiel hierfür sind die bereits vor vielen Jahren mit Erfolg eingeführten Wabenplatten, bei denen durch die Kombination von dünnen hochverdichteten Decklagen und superleichten Papierwaben als Kernmaterial extrem leichte Plattenwerkstoffe hergestellt werden können (*Wagenführ et al.,* 2005).

Nachteilig bei diesem Typ von Sandwichplatten sind die Trennung der Produktion von Deck- und Mittellagen, das nachtägliche Zusammenfügen der Komponenten sowie das in der Regel erforderliche Einbringen von Stegen entweder vor dem Zusammenfügen der Komponenten an vorbestimmter Stelle oder aber nachträglich im Rahmen der Weiterverarbeitung. Beides ist mit hohem Aufwand verbunden.

Am Thünen-Institut (TI) für Holzforschung in Hamburg wird seit 2007 in enger Zusammenarbeit mit dem Zentrum Holzwirtschaft der Universität Hamburg ein neuartiges Verfahren für die kontinuierliche Herstellung von Holzwerkstoffplatten mit *in-situ* geschäumtem Kernmaterial entwickelt. Mit diesem Verfahren soll es in Zukunft möglich werden, extrem leichte Span- und Faserplatten auf konventionellen kontinuierlichen

 

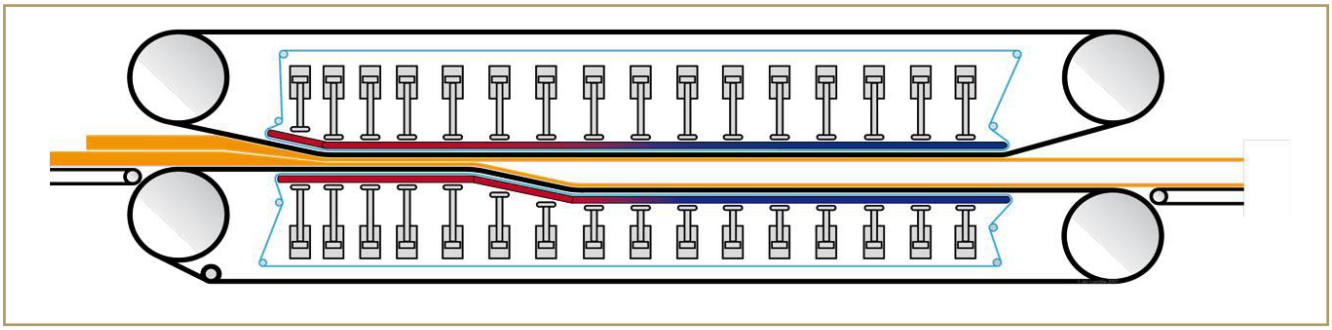

**Abb. 1: Herstellung von Spanplatten mit *in-situ* geschäumtem Kern auf Doppelbandpresse mit Kühlzone (*Lüdtke et al.*, 2008)**
*Fig. 1: Production of particleboard with in-situ foamed core on a double-bent press with cooling section (Lüdtke et al., 2008)*

Holzwerkstoffpressen in einem einzigen Pressvorgang herzustellen.

Das von *Lüdtke* (2007) entwickelte und von der Universität Hamburg zum Patent angemeldete Verfahren wurde bereits mehrfach in der Literatur beschrieben (*Lüdtke et al.*, 2008; *Lüdtke*, 2011). Die von Lüdtke im Rahmen der Verfahrensentwicklung verwendeten expandierbaren Mikrosphären wurden zwischenzeitlich von *Shalbafan et al.* (2012a) durch expandierbares Polystyrol (EPS) ersetzt.

Die nachfolgend beschriebenen physikalischen und mechanischen Eigenschaften wurden für Sandwichplatten mit Spandecklage und *in-situ* geschäumtem Kern aus EPS ermittelt.

## Charakterisierung der untersuchten Sandwichplatten

Die Eigenschaften von Sandwichplatten werden von einer Vielzahl von Faktoren bestimmt. Im Falle der hier untersuchten Spanplatten mit Schaumkern wurde als Beispiel aus einer Vielzahl möglicher Produkte eine 19 mm-Platte mit Spanplattendecklagen (Zieldicke jeweils 3 mm) und einer schaumförmigen Mittellage (Zieldicke 13 mm) untersucht. Variiert wurden der Einfluss der Presstemperatur (130 °C und 160 °C) sowie der Einfluss der Dichte des EPS-Schaumes in der Mittellage (Zieldichten: 80 kg/m³, 100 kg/m³ und 120 kg/m³).

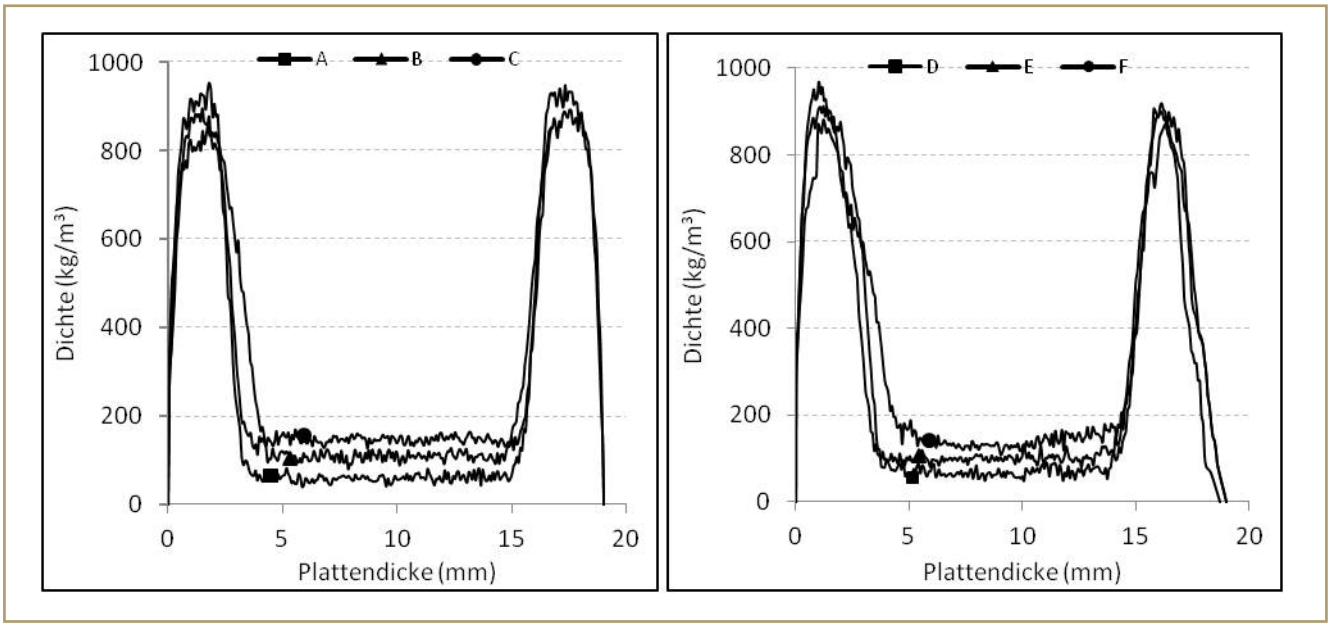


**Abb. 2: Dichteprofil in Schaumkernspanplatten mit 3-mm-Deckschichtdicke (Links: 130 °C Presstemperatur, Zielschaumdicken: A = 80 kg/m³, B = 100 kg/m³, C = 120 kg/m³; Rechts: 160 °C Presstemperatur, Zielschaumdicke: D = 80 kg/m³, E = 100 kg/m³, F = 120 kg/m³)**
*Fig. 2: Density profile of foam-core particleboard with 3 mm face layer thickness (Left: 130 °C press temperature, target foam density: A = 80 kg/m³, B = 100 kg/m³, C = 120 kg/m³; Right: 160 °C press temperature, target foam density: D = 80 kg/m³, E = 100 kg/m³, F = 120 kg/m³)*

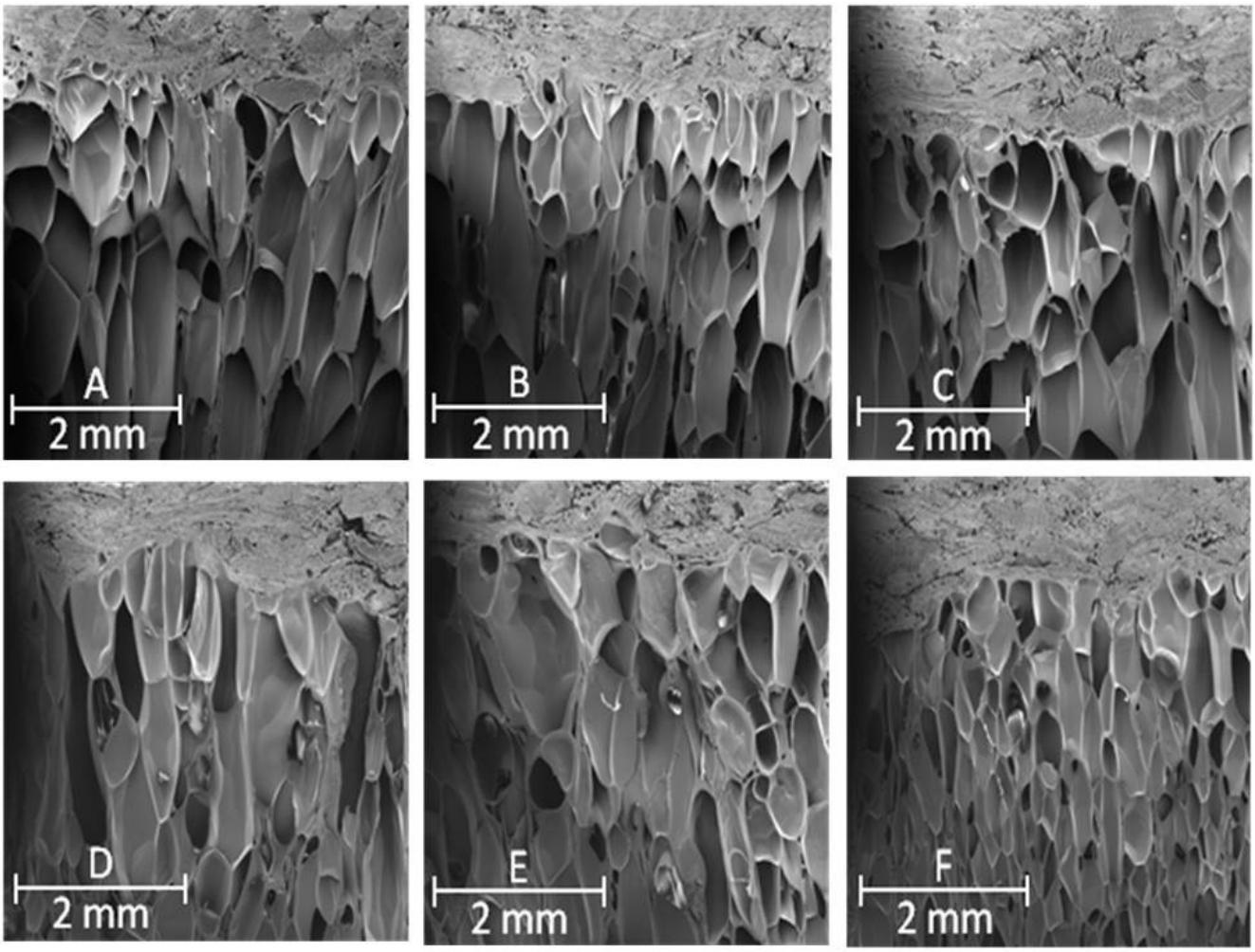


**Abb. 3: Übergangsbereich zwischen EPS-Schaum und Holzdecklage bei *in-situ* geschäumten Mittellagen von Schaumkernspanplatten (A, B und C hergestellt mit 130 °C; D, E und F hergestellt mit 160 °C)**

*Fig. 3: Interface between EPS foam and wooden face layer of in-situ foamed core material of foam-core particleboard (A, B and C produced at 130 °C; D, E and F produced at 160 °C)*

## Dichteprofil

Bei Span- und Faserplatten lassen sich aus dem Dichteprofil wichtige Charakteristika der späteren Performance ableiten. Während im Falle von Faserplatten meist ein möglichst flaches Dichteprofil mit geringen Unterschieden zwischen Plattenoberfläche und Plattenmitte erwünscht ist, bemüht man sich im Falle von Spanplatten normalerweise um eine möglichst hohe Dichte in der Decklage und technisch bedingt resultiert eine geringe Dichte in der Mittellage.

Bei konventionellen Spanplatten findet man nach dem Schleifen in den Decklagen Dichten mit Spitzenwerten zwischen 800 kg/m³ und 900 kg/m³. Bei den *in-situ* geschäumten 19 mm dicken Platten wurden bei einer Zieldicke für die Decklagen von 3 mm mittlere Dichten zwischen 650 kg/m³ und 700 kg/m³ erreicht, wobei die Spitzenwerte ebenfalls zwischen 850 kg/m³ und 900 kg/m³ lagen (Abb. 2). Die Dichte der Schaummittellage wurde in drei Stufen auf Zieldichten von 80 kg/m³, 100 kg/m³ und 120 kg/m³ variiert. Abhängig vom verwendeten Pressprogramm (130 °C und 160 °C) konnten charakteristische Unterschiede im Übergangsbereich zwischen den hochverdichteten Decklagen und der Schaummittellage festgestellt werden. Wie bereits von *Shalbafan et al.* (2012a und b) beschrieben, hat die Ausformung des Übergangsbereiches starken Einfluss auf bestimmte mechanische Eigenschaften. Durch die Variation der Pressbedingungen konnte gezeigt werden, dass die Eigenschaften der innovativen leichten Schaumkernplatten in weiten Grenzen gezielt beeinflusst werden können.

Mit beiden Pressprogrammen lassen sich bei geringen Schaumdichten in der Mittellage hohe Dichten in der Decklage und ein steiler Dichteabfall in der Übergangsschicht zwischen Decklage und Schaumkern erreichen.

## Charakterisierung des Mittellagenschaums

Bei den verwendeten EPS-Partikeln handelt es sich um marktübliche Polystyrol Beats, die werksseitig mit ca. 6 % Gewichtsanteil Propan beaufschlagt wurden. Während des Pressvorgangs erweicht das Polystyrol und die kugelförmigen Beats verfließen ineinander. Das im Polymer enthaltene Treibgas kann nur zu einem geringen Teil aus der sich in Plattenmitte befindlichen Polymerschmelze austreten, da einerseits

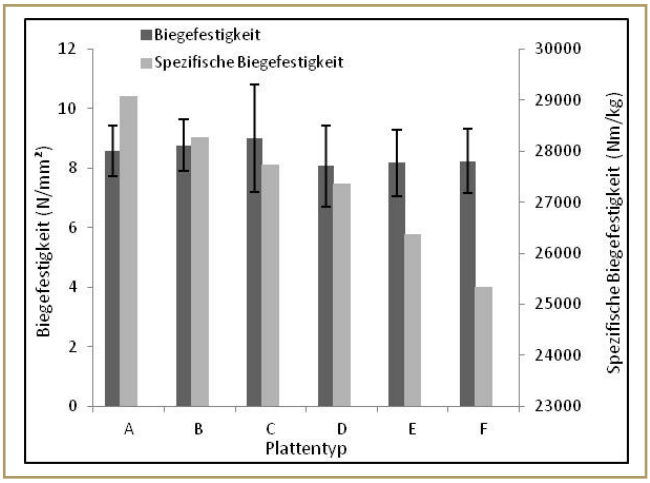


**Abb. 4: Biegefestigkeit von Spanplatten mit Schaumkern (Links: 130 °C Pressprogramm, Zielschaumdichte: A = 80 kg/m³, B = 100 kg/m³, C = 120 kg/m³; Rechts: 160 °C Pressprogramm, Zielschaumdichte: D = 80 kg/m³, E = 100 kg/m³, F = 120 kg/m³)**

*Fig. 4: Bending strength of foam-core particleboard (Left: 130 °C press temperature, target foam density: A = 80 kg/m³, B = 100 kg/m³, C = 120 kg/m³; Right: 160 °C press temperature, target foam density: D = 80 kg/m³, E = 100 kg/m³, F = 120 kg/m³)*

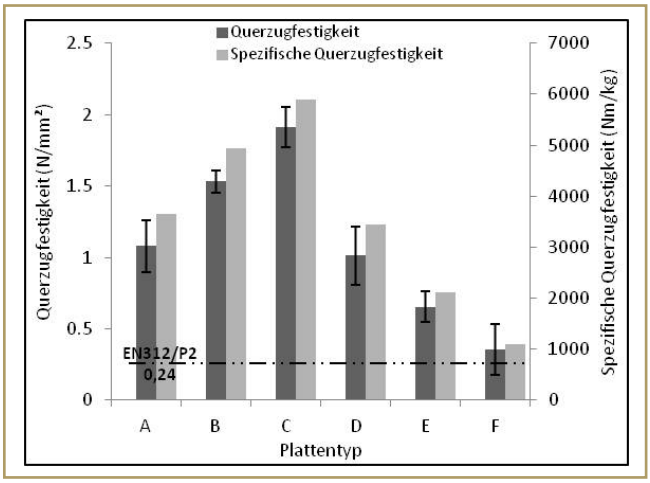


**Abb. 5: Querzugfestigkeit von Spanplatten mit Schaumkern (Links: 130 °C Pressprogramm, Zielschaumdichte: A = 80 kg/m³, B = 100 kg/m³, C = 120 kg/m³; Rechts: 160 °C Pressprogramm, Zielschaumdichte: D = 80 kg/m³, E = 100 kg/m³, F = 120 kg/m³)**

*Fig. 5: Internal bond of foam-core particleboard (Left: 130 °C press temperature, target foam density: A = 80 kg/m³, B = 100 kg/m³, C = 120 kg/m³; Right: 160 °C press temperature, target foam density: D = 80 kg/m³, E = 100 kg/m³, F = 120 kg/m³)*

durch den hohen anfänglichen Pressdruck die Decklagen aus Feinmaterial eine gute Abdichtung bewirken, andererseits das Treibgas – wenn überhaupt – nur seitlich aus dem Spanvlies austreten kann.

Wird nach der Aushärtung der Decklagen die Presse langsam bis zur Zieldicke der Platte unter leichtem Gegendruck geöffnet, so kommt es zur Expansion des Treibmittels und damit zum Aufschäumen des Mittellagenmaterials. Die Schaumstruktur und der Übergangsbereich zwischen Decklage und Schaum werden dabei von der Temperatur der aufgeschmolzenen Mittellage und der Öffnungsgeschwindigkeit der Presse beeinflusst. Beide Größen können über das Pressprogramm gezielt beeinflusst werden. Beispiele für die unterschiedlichen Schaumstrukturen sind in Abb. 3 dargestellt.

Ein niedriges Temperaturniveau von 130 °C führt bei langsamer Expansion des EPS-Schaumes zu relativ großen, dickwandigen Schaumzellen. Beim hohen Temperaturniveau von 160 °C entstehen dagegen bei rascher Expansion eher kleinere Zellen mit dünnen Wandungen. Rein optisch sind keine Unterschiede an der Grenze zwischen Schaum und Holz erkennbar.

## Mechanische Eigenschaften

Die folgenden mechanischen Eigenschaften wurden für die oben beschriebenen Parameterkombinationen untersucht: Biegefestigkeit, Querzugfestigkeit, Schaubenauszugwiderstand (senkrecht zur Plattenoberfläche sowie aus der Plattenschmalfläche).

### Biegefestigkeit

Die Biegefestigkeit (*DIN EN 310,* 1993) von Sandwichplatten wird entscheidend von der Zug- bzw. Druckfestigkeit des Decklagenmaterials in Plattenebene bestimmt. Bei den gewählten Parameterkombinationen unterschieden sich die Dicke und die Dichte des Decklagenmaterials nur unwesentlich. Im Vergleich der Biegefestigkeiten zwischen den Varianten sind deshalb auch nur marginale Unterschiede feststellbar.

Trotz der extrem niedrigen mittleren Dichten der untersuchten Platten zwischen 295 kg/m³ und 325 kg/m³ lagen die ermittelten Biegefestigkeiten (Abb. 4) nur knapp unterhalt der in *DIN EN 312* (2010) für P2-Spanplatten festgelegten Grenze von 11,5 N/mm² (*Welling et al.,* 2011). Errechnet man eine spezifische Biegefestigkeit (Nm/kg) durch Division der Biegefestigkeit durch die jeweilige mittlere Dichte der Platte, so ergeben sich für die untersuchten Schaumkernplatten in allen Parameterkombinationen höhere Werte als die spezifische Biegefestigkeit von 17700 Nm/kg einer normgerechte P2-Spanplatte mit 11,5 N/mm² und einer Dichte von 650 kg/m³.

### Querzugfestigkeit

Bedingt durch die Belastungsrichtung haben die Qualität des Schaumes in der Mittellage und die Verbindung zwischen Decklage und Schaumkern einen entscheidenden Einfluss auf die Ergebnisse der Querzugfestigkeit (*DIN EN 319,* 1993). Wie aus Abb. 5 ersichtlich, unterscheiden sich die Querzugfestigkeiten der bei 130 °C hergestellten Schaumkernplatten (A, B, C) erheblich von den bei 160 °C hergestellten Platten (D,

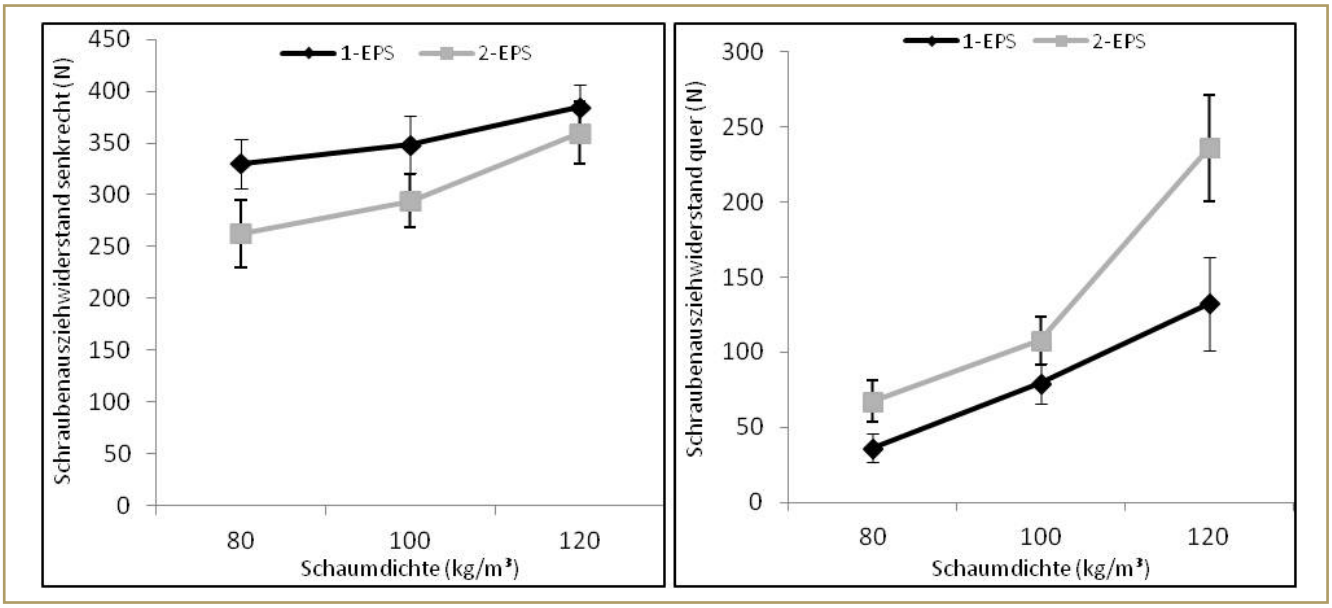


**Abb. 6: Schraubenauszugwiderstand senkrecht zur Plattenebene (links) und parallel zur Plattenebene (rechts) (1-EPS-Schaumkernplatten produziert bei 130 °C, 2-EPS-Schaumkernplatten bei 160 °C)**

*Fig. 6: Face screw withdrawal-resistance (left) and narrow face screw withdrawal-resistance (right) (1-EPS foam-core particleboard produced at 130 °C, 2-EPS foam-core particleboard produced at 160 °C)*

E, F). Die bei etwas niedrigeren Presstemperaturen produzierten Platten zeigen ein Versagen in der Mittellage, also in der Schaumschicht, während die bei höheren Presstemperaturen hergestellten Platten allesamt einen Bruch in der Grenzschicht zwischen Decklage und Mittelschicht aufwiesen. Die geringeren Querzugfestigkeiten sind hier aller Wahrscheinlichkeit nach auf weniger stark verdichteten Späne auf der Innenseite der Deckschicht bei den mit höherer Presstemperatur hergestellten Platten zurückzuführen (siehe Abb. 2).

In allen Fällen wurde jedoch der in *DIN EN 312* (2010) festgeschriebene Wert von 0,24 N/mm² weit überschritten. Gleiches gilt für die berechneten spezifischen Querzugfestigkeiten, die im Falle einer 650 kg/m³ schweren Spanplatte bei 370 Nm/kg liegen würde.

Da so hohe Querzugfestigkeiten für den Einsatz von Leichtbauplatten nicht erforderlich sind, kann geschlussfolgert werden, dass auch bei wesentlich niedrigeren Schaumdichten in der Mittellage noch akzeptable Querzugfestigkeiten erzielt werden können. Wie zuvor bereits gezeigt, hat die Schaumdichte kaum einen Einfluss auf die Biegefestigkeit.

## Schraubenauszugwiderstand

Beim Einsatz von Spanplatten zur Herstellung von Möbeln stellt der Schaubenauszugwiderstand (*DIN EN 13446,* 2002) eine wichtige Kenngröße dar, da Scharniere sicher auf bzw. an Oberflächen befestigt werden müssen und Eckverbindungssysteme in der Regel ausreichend Halt in den Mittellagen der Platten finden müssen.

Erwartungsgemäß unterscheiden sich die Schraubenauszugwiderstände bei Spanplatten mit Schaumkern je nachdem, ob die Schrauben senkrecht oder parallel zur Plattenebene aus dem Schaum ausgezogen werden.

Im Falle des Schraubenauszugwiderstands senkrecht zur Plattenebene (Abb. 6, links) ergibt sich ein ähnliches Bild wie bei der Biegefestigkeit. Der Schaubenauszugwiderstand wird entscheidend von der Dichte und der Dicke der Decklagenschicht (*Johnson,* 1967) bestimmt. Da sich diese bei den untersuchten Parameterkombinationen kaum ändert, waren auch beim Schraubenauszugwiderstand keine nennenswerten Unterschiede zu erwarten (Abb. 6, linker Teil).

Gänzlich anders sieht die Situation im Falle des Schraubenauszugs parallel zur Plattenebene (Abb. 6, rechts) aus. Erwartungsgemäß zeigt sich hier ein sehr starker und deutlicher Einfluss der Schaumdichte. Anders als im Falle der Querzugfestigkeit zeigt hier jedoch der bei höheren Presstemperaturen entstehende feinzellige Schaum bessere Werte als der grobzelligere Schaum, der bei niedrigeren Temperaturen entsteht. Dies steht im Einklang mit den Ergebnissen von *Sand und Shivkumar* (2003) sowie *Gendon* (2005).

## Physikalische Eigenschaften

Bei Holzwerkstoffen wird als wichtige physikalische Eigenschaft meist die Dickenquellung nach 2 h bzw. 24 h Wasserlagerung bei 20 °C (*DIN EN 317,* 1993) bestimmt.

Vergleicht man die in Abb. 6 dargestellten Werte für die in die Untersuchung eingeschlossenen Schaumkernplatten mit den Werte von konventionellen Spanplatten, so erkennt man, dass die Werte für die Dickenquellung nach 2 h Wasserlagerung bei den Schaumkernplatten leicht oberhalb der Werte für normale Spanplatten, die 24 h-Werte aber weit unterhalb der Werte für die normale Spanplatte liegen. Obwohl im Falle der Schaumkernplatten nur die holzhaltigen Decklagen quellen können, liegt die Gesamtquellung der Schaumkernplatten

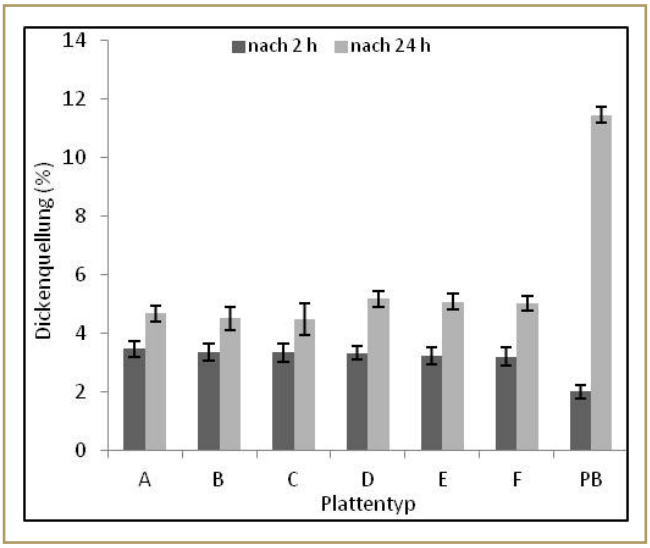


**Abb. 7: Dickenquellung nach 2 h und 24 h Wasserlagerung (Links: 130 °C Pressprogramm, Zielschaumdichte: A = 80 kg/m³, B = 100 kg/m³, C = 120 kg/m³; Rechts: 160 °C Pressprogramm, Zielschaumdichte: D = 80 kg/m³, E = 100 kg/m³, F = 120 kg/m³)**
*Fig. 7: Thickness swelling after 2 h and 24 h water storage (Left: 130 °C press temperature, target foam density: A = 80 kg/m³, B = 100 kg/m³, C = 120 kg/m³; Right: 160 °C press temperature, target foam density: D = 80 kg/m³, E = 100 kg/m³, F = 120 kg/m³)*

nach 2 h Wasserlagerung oberhalb der normalen Spanplatte, was dadurch erklärbar ist, dass bei der Produktion der Schaumkernplatten im Labor auf die Zugabe von Additiven verzichtet wurde. Marktübliche Spanplatten enthalten jedoch immer wachsartige Additive zur Verbesserung der Quellungseigenschaften.
Allerdings kann durch diese Additive die Wasseraufnahme allenfalls kurzfristig, nicht aber langfristig verbessert werden. Wie aus Abb. 7 erkennbar, ist offensichtlich der aus EPS bestehende Schaumkern kaum an der Dickenquellung beteiligt. Die 24 h-Werte der Schaumkernplatten liegen allesamt nur leicht oberhalb der 2 h-Werte, jedoch nur etwa bei der Hälfte der Werte für konventionelle Spanplatte.

## Zusammenfassung und Ausblick

Nach einem neuartigen einstufigen Verfahren hergestellte Holzwerkstoffsandwichplatten mit *in-situ* geschäumtem Kernmaterial aus EPS lassen sich hinsichtlich ihres Aufbaus in weiten Grenzen variieren. Darüber hinaus haben die Prozessbedingungen einen maßgeblichen Einfluss auf die Ausformung der mechanischen und physikalischen Eigenschaften. Die beispielhaften Ergebnisse zeigen, dass sich durch eine Variation des Aufbaus der Platten (Dicke der Decklagen und Dichte des Schaummaterials) sowie durch die gezielte Wahl der Prozessparameter in der Heißpresse die Eigenschaften gezielt beeinflussen lassen. Bei mittleren Dichten der Sandwichplatten von etwa 300 kg/m³ konnten Eigenschaften erzielt werden, die in der gleichen Größenordnung wie die konventioneller, etwa doppelt so schwerer Spanplatten oder sogar weit darüber lagen. Ermittelt man spezifische, dichtebereinigte Eigenschaften, so ergeben sich für die Sandwichplatten in aller Regel wesentlich verbesserte Werte.

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## ABSTRACT

***Physical and mechanical properties of lightweight wood-based panels with in-situ foamed core***

*There are several concepts for the production of light-weight wood composite materials. A sandwich-type structure is applicable for the production of panels with a property profile similar to conventional wood composite panels but drastically reduced weight. Conventional wood-based sandwich panels are normally produced in a multi-step process using components which have been produced in separate processes. Thuenen Institute for Wood Research, in close cooperation with Department of Wood Science at University of Hamburg, has succeeded in producing light-weight wood composites with a foam core in one single production step. By in-situ foaming of the core material in a hot press sandwich-type foam core panels can be produced which have similar physical and mechanical properties as conventional wood-based panels but only 50 % of their weight. The specific, weight-related properties of these panels outperform their conventional alternatives in most cases.*

***Keywords:*** *Lightweight design, sandwich construction, particleboard, EPS, foam-core*

 

# VI

# Flat pressed wood plastic composites made of milled lightweight foam core particleboard residues

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# Flat Pressed Wood Plastic Composites made of Milled Lightweight Foam Core Particleboard Residues

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## Abstract

Flat pressed WPC panels were produced on a lab-scale using residues of lightweight foam core particleboards as raw material. As influencing parameters on the panel properties, the ways of preparing raw materials (dry blending and pre-compounding by twin screw extruder) and the loading of wood flour content (WF) were varied and coupling agents (CA) were added in some variations. The results showed that panels produced with low WF content (75%) have better physical and mechanical properties. The adding of the CAs only influenced the panel properties when they were added prior to the compounding of the materials. Due to the higher wood degradation resulting from raw material compounding, the panel properties were inferior to the panels produced with dry blended materials.



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## INTRODUCTION

In the context of the increasing utilization competition for wood, the identification of suitable opportunities to produce resource efficient lightweight panels is a current effort of the wood-based panel industry. Besides other approaches, one of the most promising technologies to produce lightweight particleboards has been developed recently at Hamburg University, Germany[1]. Panels produced using this process consists of a conventional thin particleboard face layer and a polystyrene foam core. The usability of existing facilities and simultaneous manufacturing of face and core layer in one step are the major advantage of this process. However, in contrast to common particleboard production, trimming wastes cannot be recycled directly since the thermoplastic foam material would end up in the surface layers and might complicate the process. Its use for power generation might be beneficial when focusing on the energy value but inadequate when looking at the material composition[2]. In dependence on foam core density, face layer thickness and panel thickness, the residues consist of approximately 75% wood and 25% polymer, for example, and are consequently reminiscent of the consumption of a high-filled wood-plastic composite (WPC).

The use of waste as a raw material for WPC production has been investigated by a number of authors[3-8]. They showed promising opportunities for using industrial and municipal solid waste materials that are currently being burned or land-filled. Furthermore, WPC showed a good potential for using waste or recycled wood and polymers to make durable composites which in turn are potentially recyclable[8].

WPCs are usually manufactured into rod-shaped profiles by extrusion or 3-dimensional structured form parts by injection molding. In addition to these techniques, flat pressing technology can be considered a straightforward and cost-effective alternative to manufacture WPC[9-10]. The dimensions of such panels resemble more those of classical wood-based panels like particleboard and medium density fiberboard (MDF) than those of extruded WPC products like terrace planks. Since NewWood Manufacturing Incorporated (Elma, Washington, USA) began producing flat-pressed WPC panels on a multi-daylight press, WPC panels have made the leap from the research lab to industrial production and are currently discovering new fields of application, currently.

While a large number of papers focused on the manufacturing of WPC panels on a laboratory scale and NewWood arranges its production in a discontinuous process, Gardner et al.[11] and Benthien et al.[12] reported about the possibility to use of a continuous double belt press (DBP) in industrial scale for manufacturing flat pressed WPC panels.

The production of WPCs can be done either in a one-step or in a two-step process. Direct extrusion and direct injection molding, resembling one-step processes, combine

the mixing of raw materials and the product forming in one step, while, in a two-step process, raw materials are first compounded to WPC-granulate and subsequently processed to the final product. In this case the material is heated twice and cools down between the first and the second step. In principle, both concepts can be applied to flat pressing: Wood particles and polymer powder can be used as a dry blend without heating it prior to mat forming. Alternatively, the wood particles, polymer and, if required, additives can be compounded in a first step by using an extruder, a heating cooling mixer, an internal mixer or a die ring agglomerator[13]. The distribution of wood particles and additives in compounding is assessed as very efficient[14], while dry blending is considered relatively straightforward and cost effective.

The intention of this paper is to demonstrate that residues of lightweight foam core particleboard production can be processed into marketable products. In order to keep the potential production costs low and the final use as variable as posible, the residues were milled and then flat pressed into WPC panels. Physical and mechanical properties were determined to classify the obtained WPC panels in the context of classical wood-based panels. Based on milled lightweight foam core particleboards two different ways of preparing the raw materials were applied; dry blending and pre-compounding by twin screw extruder. Further the effect of wood flour content (WF) and coupling agent (CA) on the properties of the samples were studied.

## MATERIALS AND METHODS

### Raw materials

Three laboratory made layered foam core particleboards with a nominal thickness of 19 mm[15] were cut to small cubes (10 * 10 * 19 $mm^3$), which were crushed into a powder using a hammer mill (25 OUP Alpine Company, Augsburg/Germany). This powder was used as a raw material for WPC panel manufacturing. During the milling process, WF and polymer were already mixed intensively so that no subsequent dry blending was required.

With regard to the composition of the lightweight foam core panels, the powder consists of wood particles (with cured urea-formaldehydes resin) and expanded polystyrene (PS) (Terrapor 4, Sunpor Kunststoff GmbH, St. Pölten, Austria). The wood particles for the face layers were from softwood mainly spruce and pine, supplied from a particleboard mill. According to the surface layer thickness of the lightweight foam core particleboards (3, 4 and 5 mm), the WF content of these dry blends was 75, 83 and 88%. For further processing the powder was dried in an oven with a temperature of 100°C to moisture content below one percent. Table 1 shows the composition of the WPC panels.

For a better interfacial bonding between the polar-hydrophilic wood and the non-polar-hydrophobic polymer, poly styrene-co-maleic anhydride oligomer, SMA2000 was used as coupling agent supplied from Sartomer Co., Exton, USA. The amount of SMA2000 incorporated in the mixture was 2% based on the oven dry mass of the wood-polymer powder, because Poletto et al.[7] found this level to be optimal for SMA as coupling agent.

Table 1 Composition of the WPC panels.

| Sample | Wood content (%) | Polymer content (%) | Coupling agent (%) | Mixing methods |
|---|---|---|---|---|
| 1 | 75 | 25 | - | Dry blend |
| 2 | 75 | 25 | 2 | Dry blend |
| 3 | 75 | 25 | - | Compounded |
| 4 | 75 | 25 | 2 | Compounded |
| 5 | 83 | 17 | - | Dry blend |
| 6 | 88 | 12 | - | Dry blend |

**Sample preparation**

In addition to the already performed dry blending of the raw materials during the milling process, the raw material mixture with a WF content of 75% was compounded before panel manufacturing using a twin-screw extruder. This additional process step was only performed with the dry blend having a WF content of 75%. The compounding of mixtures with higher WF contents (83 and 88%) was found to be difficult. This phenomenon was already described by Myers et al.[16] and was attributed to the increased viscosity of the molten wood-plastic blend. For compounding a laboratory extruder (Micro 27G/GC, Leistritz, Germany) was used having a barrel temperature profile ranging from 200 to 220 °C (from the feeding to the die zone). The screw speed was set at 122 rpm. The temperature was controlled to melt the polymer and to run the blend easily through the extruder.

Panel manufacturing was arranged using a single opening hot press (Siempelkamp, Krefeld/Germany). The press temperature was 210 °C. Panels were produced with a nominal thickness of 10 mm. The panel size was 600 * 550 mm² with a target density of 1000 kg/m³. A frame made of polyurethane (PU) foam was used during mat forming and pressing to prevent lateral expansion of the boards. Copper tubes were placed in the PU frame for releasing air/vapour during pressing. The frame was placed on an aluminum caul plate. Siliconized paper was used to prevent the sticking on the aluminum plates. The mat was compressed for 400 s to the desired nominal thickness of 10 mm. At the end of the pressing cycle, cooling of the panels was performed under pressure (inside the press) by internal cooling of the press plates for the next 400 s.

With increasing WF content (75, 83 and 88%) the specific pressure had to be increased (1, 2 and 3 N/mm²) to reach the target thickness (10 mm). A picture from the novel foam core particleboard, milled into powder shape and finally produced flat-pressed WPC panels is shown in Figure 1.

Figure 1. Foam core particleboard milled into powder shape and produced flat-pressed WPC panels.

**Testing procedures**

Based on the technical specifications CEN/TS 15534:2007, physical and mechanical properties were determined according to the testing specifications shown in Table 2. The time of submersion in water to determine thickness swelling and water absorption was 2, 24, and 672 hours (periodically measured). Prior to testing, samples were conditioned at 65% relative humidity and 20 ˚C for two weeks until equilibrium moisture content (EMC) was achieved. Three replicates were manufactured from each panel variation. Three samples of each panel replicate (resulting in n=9) were randomly selected and tested. Particle size distribution of raw materials was determined according to DIN 66165:1987. A mechanical sieving machine (Retsch-AS 400, Germany) was used for screening the 50 g dried wood-polymer powder.

Table 2 Test specifications.

| Test | Standard type | Samples size (mm) | Repetition |
|---|---|---|---|
| Particle size analysis | DIN 66165 | - | 50 g |
| Density | EN 323 | 50*50*10 | 9 |
| Moisture | EN 322 | 50*50*10 | 9 |
| Thickness swelling | EN 317 | 50*50*10 | 9 |
| Bending properties | EN 310 | 250*50*10 | 9 |
| Charpy impact strength | EN 179-1 | 80*10*10 | 30 |

### Statistical analysis

The statistical data analysis was performed using parametric ANOVA tests with Statistical Package for the Social Science (SPSS software, IBM) to evaluate the physical and mechanical properties of WPC panels produced from milled foam core particleboards. Statistical differences between variations were evaluated by multiple comparisons, depending on their variance status using either LSD or Dunnett3 tests. The comparisons were done at a 95% confidence level.

## RESULTS AND DISCUSSION

A summary of the physical and mechanical properties of the flat pressed WPC panels made of milled lightweight foam core particleboards residues is presented in Table 3.

Table 3 Values for physical and mechanical properties of WPC made of milled ultra-light foam core particleboard as residues.

| | | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| Density (kg/m³) & EMC (%) | Conditioned | 966 (56) | 1016 (53) | 1090 (85) | 1140 (55) | 1059 (55) | 1100 (83) |
| | Dried | 918 (50) | 968 (50) | 1056 (82) | 1100 (55) | 998 (58) | 1033 (87) |
| | EMC | 5.1 (0.34) | 4.7 (0.31) | 3.9 (0.28) | 3.3 (0.45) | 5.6 (0.56) | 5.6 (0.54) |
| Thickness swelling (%) | 2 h | 0.68 (0.16) | 1.1 (0.3) | 0.46 (0.25) | 0.35 (0.15) | 2.5 (0.89) | 5.4 (1.1) |
| | 24 h | 2.16 (0.5) | 3.58 (1.2) | 1.8 (0.92) | 1.1 (0.4) | 6.1 (1.3) | 12.46 (2.3) |
| | 674 h | 7.07 (0.8) | 8.28 (0.6) | 7.45 (0.4) | 5.4 (1.5) | 13.7 (1.6) | 20.05 (2.5) |
| Water absorption (%) | 2 h | 1.3 (0.4) | 5 (1.7) | 1.3 (0.6) | 1 (0.4) | 9.8 (3.5) | 14 (2.2) |
| | 24 h | 5.6 (2.1) | 12.5 (3.7) | 4.1 (1.5) | 14.9 (1.3) | 25.4 (2.6) | 13.5 (4.6) |
| | 674 h | 16.3 (2.7) | 22 (4) | 23.6 (3.3) | 17.9 (4.2) | 25.8 (5.3) | 34.1 (4.7) |
| Bending properties (N/mm²) | MOE | 5700 (550) | 5100 (430) | 4500 (530) | 5000 (520) | 5200 (330) | 5100 (720) |
| | MOR | 40 (5.7) | 35 (4.7) | 15 (2.7) | 17 (2.9) | 32 (4.8) | 30 (4.6) |
| Charpy strength | kJ/m² | 1.4 (0.12) | 1.25 (0.15) | 0.58 (0.14) | 0.76 (0.13) | 1.3 (0.19) | 1.27 (0.21) |

**Particle size distribution**

Knowledge about the particle size is important for the evaluation of the composite properties. Effective surface area is strongly dependent on the particle size and shape which inversely affect the mechanical properties[17]. Visual inspection of particle size showed that the bigger particles mostly result from the PS foam core layer and the finer particles have its origin in the wooden material of the surface layers. The results of the particle size analysis are illustrated in Figure 2. The bars show that the dry blend with a WF content of 75% have the highest fraction of coarse particles (>0.3 mm). Inversely, the content of finer particles (< 0.3 mm) is highest in the dry blend with a WF content of 88%. This can be attributed to the decreasing amount of polymer in the dry blend while the wooden material originating from the surface layers increases. The major part (>70%) of the powder resulting from the milling process has a particle size from 0.1-0.5 mm.

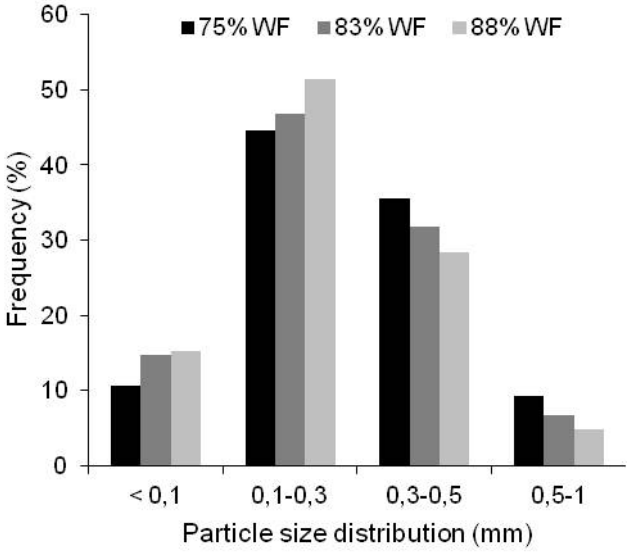


Figure 2. Particle size distribution of milled lightweight foam core particleboards.

**Panel density and moisture content**

Density measurements of the samples were performed after conditioning (at 20 °C and 65% RH) to constant mass and after drying for 24 hours at 103 °C. The results of density measurements are illustrated in Figure 3.

As can be seen in Figure 3a, the density of dry blend based samples increases with increasing WF content. It was observed during panel manufacturing, that the mat of dry blends with a higher WF content were more voluminous and needed a higher specific

pressure to reach the same target panel thickness. This leads to the more intensive compaction and higher crushing of the wood particles and, accordingly, higher panel density. This phenomenon was described before by Geimer et al.[18] and also observed for flat-pressed WPC panels by Benthien et al[12].

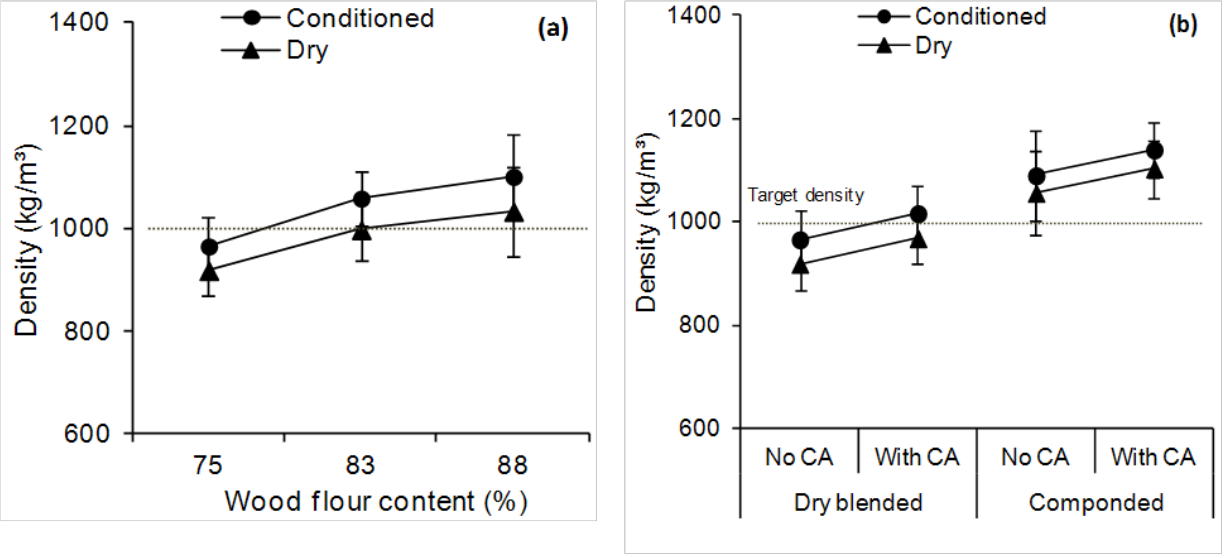


Figure 3. Density range of conditioned (20 °C, 65% RH) and dried (105 °C) WPC panels.

In comparison to panels made from dry blends, the density of panels made from pre-compounded raw material was higher. Due to the pre-compounding of the dry blends by means of an extruder, the bulk density of the raw material was increased before panel manufacturing. As a result, less specific pressure was needed. However, due to the pre-compaction, lower density panels cannot be manufactured from extruded raw materials. The density of panels produced with low WF content (75%) is lower than the calculated density for the desired thickness, while the density for panels with high WF (88%) is higher than the calculated density.

It was observed that panel density increased in conditioned and dried samples when two percent of coupling agent was added. This can be attributed to the improved dispersion of WF in the polymer and, as a result, to a lower amount of voids in the wood/polymer matrix[7].

The results for moisture content determination of the samples after reaching equilibrium moisture content (EMC) are presented in Figure 4. The moisture absorption is slightly increased with increasing WF content from 75 to 88% due to the hydrophilic property of wood. It is also observed in Figure 4b that the compounded samples have a lower EMC

compared to the dry blended ones due to the better covering of wood flour with the polymer which leads to a reduced accessibility of the hydrophilic hydroxyl groups (OH). Additionally, the use of CA also results in a reduced EMC especially for the compounded samples due to the enhanced bonding between wood flour and polymer matrix.

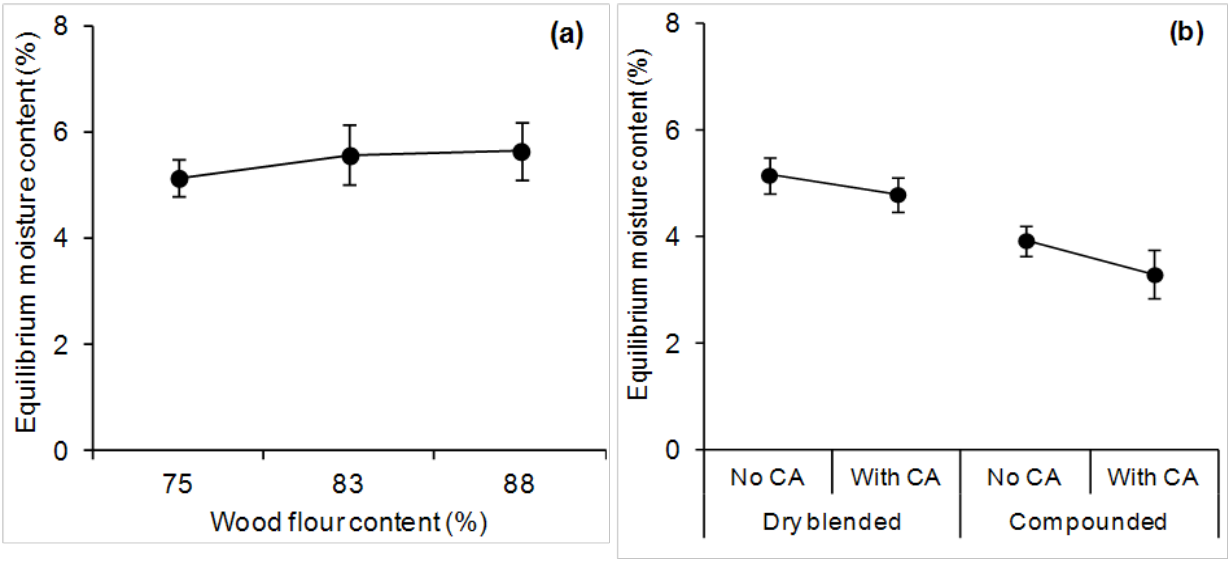


Figure 4. Moisture content of conditioned (20 °C, 65% RH) and dried (105 °C) WPC boards.

**Thickness swelling and water absorption**

The values for thickness swelling (TS) and water absorption (WA) in short (2 and 24 hours) and long (672 hours) term soaking are presented in Table 3. It is shown in Figure 5 that the TS significantly increases with both increasing WF content (from 75 to 88%) and immersion time until equilibrium conditions are achieved. This is attributed to the hydrophilic property of wood fibers. The higher the wood content, the more hydroxyl (OH) groups are available as sorption sites, and accordingly the TS increases[3, 19]. It was found that most of the swelling of the panels occurs during the first 200 hours of soaking. Afterwards, with increasing soaking time up to 672 hours the TS does not change significantly.

Figure 5b shows that TS values of panels produced from dry blends are relatively low compared to those from pre-compounded raw materials. It should be highlighted in this context that the samples from pre-compounded raw materials have to withstand one extra thermal treatment and mixing procedure during the extrusion process. This leads to more wood particle breakage and wood degradation[20] so that the surfaces of wood

exposed to the water is increased. The effect of thermal treatment becomes obvious from the samples appearance: the pre-compounded samples are much darker in color compared to those from dry blends. As a result, it can be said that the extruding of waste wood-polymer materials with high (>200 °C) temperature has a negative effect on the thickness swelling due to the degradation of lignocelluloses.

The influence of the added coupling agent was found to be different for the panel made from dry blends and those made from pre-compounded raw materials (Figure 5b). While TS of panels made from pre-compounded raw materials is significantly lower that TS of dry-blended panels, the addition of coupling agent into a dry blend leads to increased TS, whereas adding coupling agent to pre-compounded material reduced TS. Such a lack of improvement of properties fits to findings of previous investigations on flat pressed WPC panels from dry blended raw materials[21]. In conjunction with the improved properties found for samples from pre-compounded raw materials, this finding confirms the suggested reason - insufficient placement of CA in dry blends - for the missing effectiveness of the coupling agent. When applying a melt blending technique as was done for pre-compounded raw materials, the CA seems to be distributed and placed more efficiently and, consequently, it leads to an enhanced bonding between wood and polymer[3].

The water absorption (WA) after short and long-term immersion is presented in Figure 6. The same trend like as in TS is observed for the WA. The higher the WF content, the more water is absorbed during soaking[19]. The panels produced in the dry blend method have lower WA than those produced with pre-compounded raw materials. This is attributed to the enhanced degradation of wood particles during the compounding process. Additionally, the dry blended samples treated with CA exhibit significantly increased water absorption values, whereas the pre-compounded samples with incorporated CA show a reduced water uptake compared to those without CA. This, again, can be explained by the placing status of CA in panels made from dry blended and pre-compounded raw materials. In the dry blended samples CA is not exactly positioned, while in pre-compounded ones CA is perfectly mixed and coupled with the ingredients. Lowering the amount of WA in panels made of pre-compounded raw materials can be due to the crystallinity of the panels. Crystallinity of WPC panels can be changed by adding CA. Ichazo et al.[22] reported that the crystallinity of WPC panels incorporated with CA is much greater than that of the corresponding panels without CA. Crystaline regions are resistant to the penetration, so the water absorption is lower than the WA of corresponding samples without CA. Panels with low WF content (75%) show the lowest water absorption of 1.7, 5.7 and 16.3 percent for the 2, 24 and 674 hours soaking, respectively.

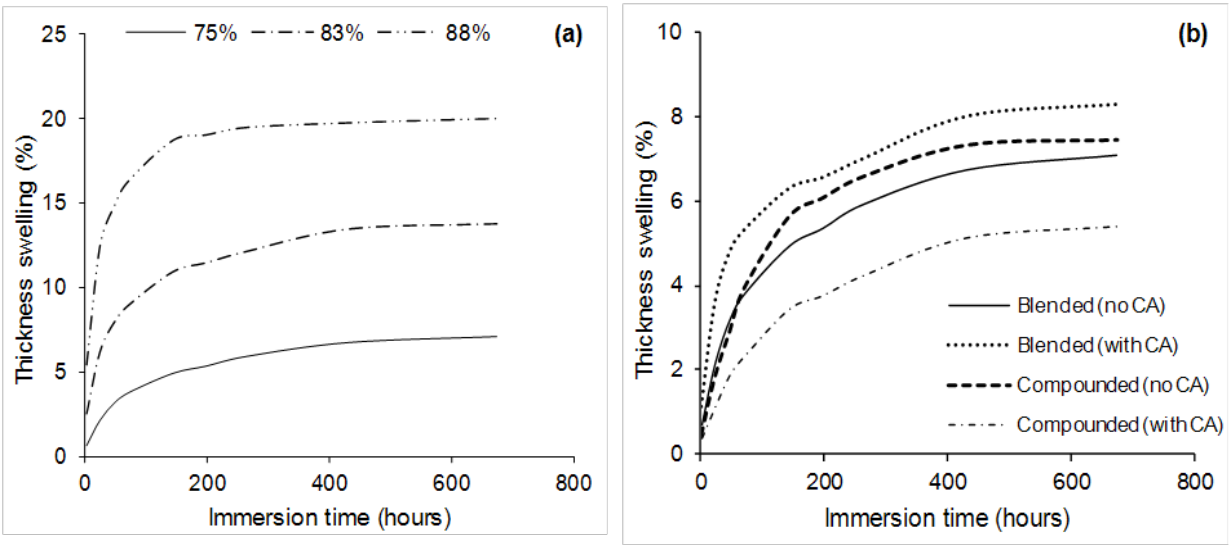


Figure 5. The thickness swelling of WPC panels produced with different variables.

**Bending properties**

The bending properties of the test panels are illustrated in Figure 7. With increasing WF content (from 75 to 88%) both modulus of elasticity (MOE) and modulus of rupture (MOR) decreased significantly (Figure 7a). The increase of WF content from 75 to 88% decreases the polymer content from 25 to 12% which caused a reduction in bending properties[20]. Reduction of polymer content results in a reduced binding between the wood flours. This relationship was described in the literature: in panels with high polymer content (>50%), the polymer forms a matrix and wood flour acts as the reinforcements trapped in the matrix, whereas in WPC panels with high WF content, polymer acts as an adhesive to bond wood flour together. Reduction of polymer amount leads to the weak bonding of wood flours and consequently to reduced bending properties. Chaharmahali et al.[19] and Sanadi et al.[23] also reported that the bending properties of WPC panels are significantly reduced with increasing WF content (>70%).

A comparison of the bending properties of test panels produced from dry blends and pre-compounded raw materials, with and without CA, is shown in Figure 7b. The panels produced from dry blended raw materials have relatively higher MOE in comparison to the panels produced from pre-compounded raw materials. Also, the bending strength was significantly higher for samples from dry blends. As explained earlier, more wood flour degradations occurs due to the extra melting and mixing in high temperature regime (>200 °C) during the compounding process of waste wood-polymer[20]. This affected the bending properties of compounded WPC panels negatively.

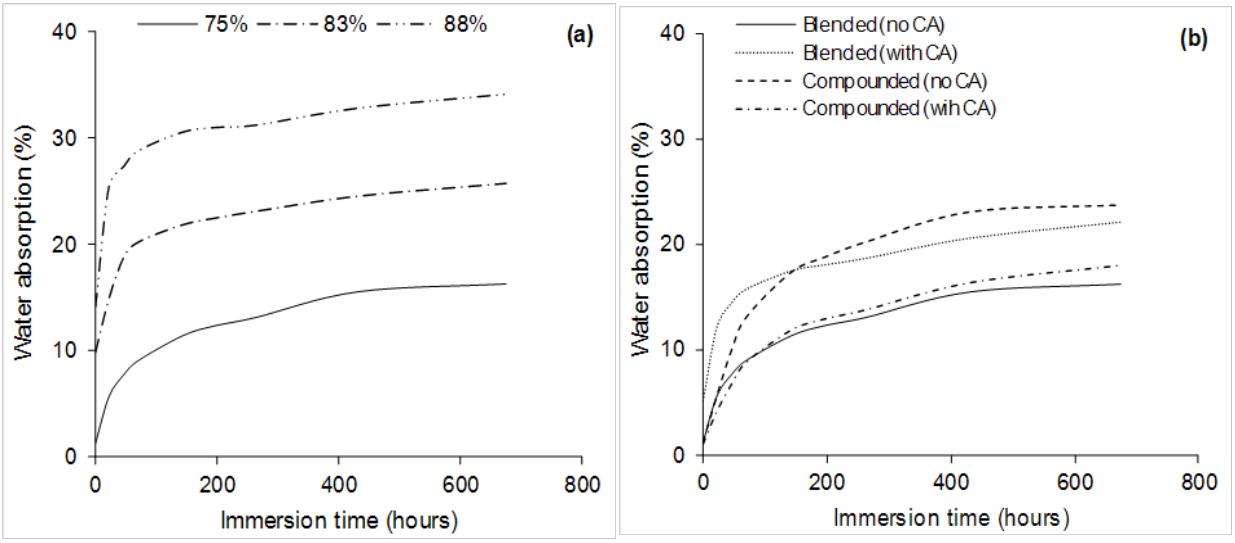


Figure 6. The water absorption of WPC panels produced with different variables.

The use of 2% CA leads to a significant decrease of both MOE and MOR for panels produced from dry blended raw materials. The CA acts as plasticizer in the mixture due to the insufficient placing and low molecular weight (7500 g/mol) of CA, and consequently reduces the mechanical properties of the panels. Poletto et al.[7] also found out that the SMA (styrene-co-maleic anhydride oligomer) used as CA could also act as plasticizer and reduces the mechanical properties of the WPC panels.

This deficiency was resolved when CA was added to raw material formulations prior to pre-compounding in the extruder. Figure 7b shows that the panels produced with pre-compounded raw materials and treated with CA have slightly higher bending properties compared to those without CA. Wetting of wood flour by the non-polar polymer matrix has been improved by adding CA on the extruder[24-25]. This is attributed to the correct placing of CA and, accordingly, enhanced dispersion of CA which results in a better interfacial adhesion between the wood and polymer in the compounding process. Superior values of MOE and MOR were observed for panels with low WF content (75%), produced from dry blended raw materials without adding CA.

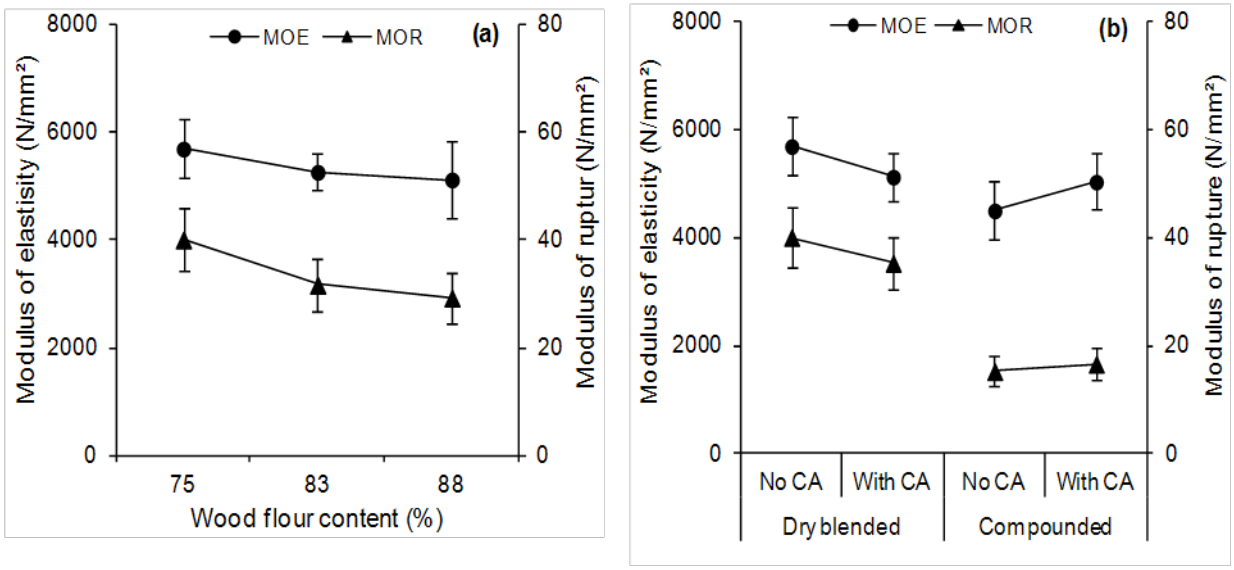


Figure 7. The bending properties of WPC panels produced with different variables.

**Charpy impact strength (CIS)**

Charpy impact strength indicates the material toughness and the yield strength by measuring the energy absorbed in material breaking. The charpy impact strength of WPC test panels made from milled foam core particleboard (representing production residues) are illustrated in Figure 8. With an increase of WF content from 75 to 88%, the charpy strength decreases slightly, although the statistical analysis shows no significant effect which is due to the large in-group standard variation. In the WPC panels without coupling agent, micro-cracks propagate easily because of poor interfacial bonding between the wood filler and polymer matrix[24]. The impact strength of the panels decreased with these micro-cracks[26]. The adding of wood flour results in a weakening of interface between the wood flour and polymer, thereafter the stress concentration and crack initiation takes place and results in the reduction of impact strength[6, 27].

The values for charpy impact strength for the panels with and without coupling agent produced with two processing methods are shown in Figure 8b. For the dry blended panels treated with coupling agent the charpy strength is significantly decreased. As explained earlier, the CA acts as a plasticizer in the dry blended samples due to the insufficient placing between wood and polymer which increases the polymer slippage and accordingly decreases the mechanical properties[7]. The impact strength of the WPC panels produced from compounded granulates is significantly increased due to the improved of interfacial bonding between the wood and polymer. Hence, more energy is needed for de-bonding and fiber pullout and thus the charpy impact strength increases[25]. It is also evident from Figure 8b that the charpy impact strength of the WPC

panels produced with pre-compounded raw materials is inferior to those produced with the dry blended material. This is attributed to the higher wood degradation during extra compounding process of waste materials. The panels produced with low WF content (75%) without any extra treatments obtained the superior values for the charpy impact strength.

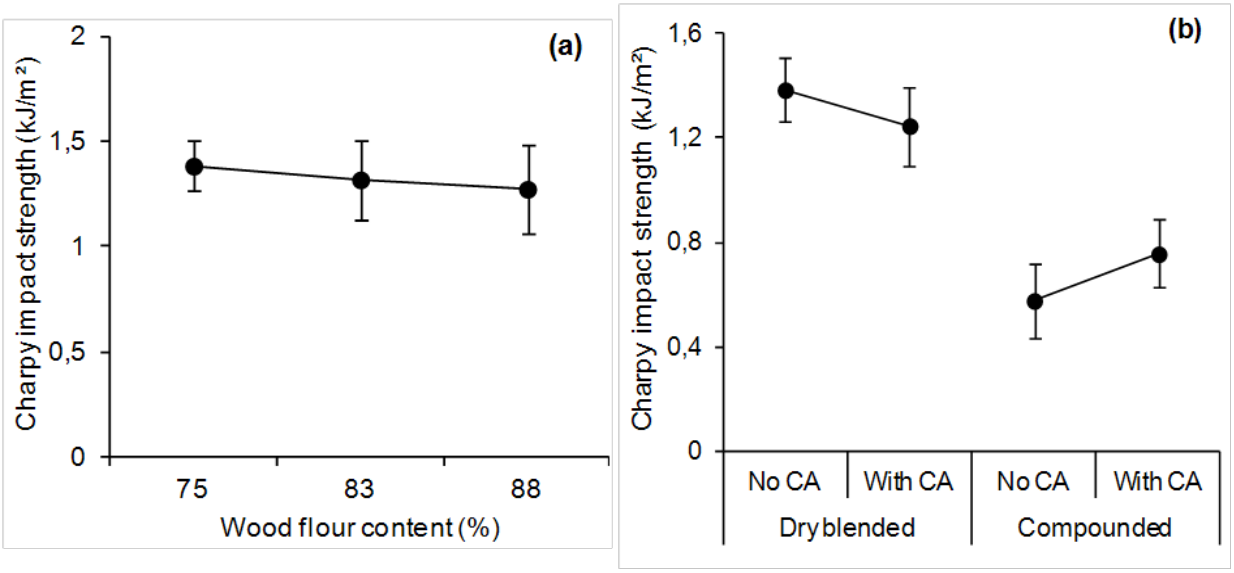


Figure 8. The charpy impact strength of WPC panels produced with different variables.

## CONCLUSION

The main purpose of this study was to determine the feasibility of using lightweight foam core particleboard residues as raw material for manufacturing flat-pressed WPC panels. The study shows that it is possible to produce durable and water resistant panels made from residues of lightweight foam core particleboards. WPC panels produced from dry blended raw material show superior values of mechanical and physical properties compared to the panels from pre-compounded raw materials. Crushing of lightweight foam core particleboard residues leads to a mixing of wood flour and polymer. Compounding of raw materials with a twin screw extruder lead to more wood degradation and showed significantly negative effects on the mechanical and physical properties of the produced WPC panels. Adding of a coupling agent showed positive effects only when added during the compounding process. However, the WPC panels made of pre-compounded raw materials treated with coupling agent still have lower mechanical and physical properties compared to the panels made of dry blended raw materials without coupling agent.

As final conclusion, it can be said that the costly treatments of adding coupling agent and even extra compounding of materials have no positive effect on the WPC panel properties. In other words, WPC panels based on recycled production residues of lightweight foam core particleboards can be easily manufactured with the dry blend material. Such WPC panels have a superior potential for use in exterior application.

## ACKNOWLEDGMENT

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# VII

# Fire performances of foam core particleboards continuously produced in a one-step process

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# Fire performances of foam core particleboards continuously produced in a one-step process

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**Abstract** For further progress of novel foam core particleboards, their fire performance was examined with cone calorimetry tests (ASTM E 1354-11a). Specimens with varying surface layer thicknesses, foam densities (polystyrene foam), and processing temperatures were tested. Using the initially recommended cone irradiance of 35 kW/m$^2$, different flammability parameters were measured. In comparison to particleboards, the foam core panels generally had much higher heat release rates, somewhat higher heat of combustion and much higher smoke production due to the EPS-foam component of tested panels. The time to ignition and total heat release did not vary significantly among the samples, although certain trends could be explained. The effects of variations in specimen foam densities and processing temperatures on the flammability parameters were not very significant. However, the flammability properties improved towards that of the reference particleboard as the surface layer thickness increased from 3 to 5 mm.

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**Brandverhalten von in einem einstufigen Prozess hergestellten Schaumkern-Spanplatten**

**Zusammenfassung** Im Rahmen der Weiterentwicklung neuartiger Spanplatten mit Schaumkern wurde das Abbrandverhalten mit Hilfe des Cone Calorimeter Tests (ASTM E 1354-11a).untersucht. Proben mit unterschiedlichen Decklagen-Dicken, Schaumkern-Dichten (Polystyrol-Schaum) und Presstemperaturen wurden geprüft. Bei Anwendung der empfohlenen Strahlungsintensität von 35 kW/m$^2$ wurden unterschiedliche Entflammbarkeiten festgestellt. Im Vergleich zu normalen Spanplatten zeigten die Schaumkernspanplatten aufgrund der EPS-Schaumanteile eine wesentlich höhere Wärmefreisetzungsrate, eine leicht erhöhte Verbrennungswärme sowie eine stark erhöhte Rauchentwicklung. Die Zeit bis zur Entzündung sowie die gesamte Wärmefreisetzung unterschieden sich nicht signifikant zwischen den Proben, wobei dennoch bestimmte Trends erklärbar waren. Die durch die Variation der Schaumkerndichten und Presstemperaturen bei der Herstellung verursachten Unterschiede waren nicht signifikant. Mit einer Zunahme der Decklagendicke von 3 mm auf 5 mm näherte sich die Entflammbarkeit der Schaumkern-Spanplatten an die Entflammbarkeit der als Referenz verwendeten normalen Spanplatten an.

## 1 Introduction

Sandwich panels are generally manufactured in batch processes where the layers are first separately produced and later glued together or in continuous processes by injecting a foamable liquid core material between the facings (Karlsson and Åström 1997; Zenkert 1997). The lack of a process for production of all layers in a simultaneous

manner is obvious. Having this in mind, a novel technology to produce sandwich panels with wood based facings and a foam core in one single production step has been presented by Luedtke (2011). This type of lightweight foam core panels can be manufactured with some modifications of existing particleboard production machines.

Though the general benefits of the lightweight panels are obvious, the foam core implies some restrictions. The fire safety of this type of innovative panels might become a crucial aspect preventing the market acceptance of the novel panels. Their reaction to fire should meet the requirement of conventional particleboards. Cone calorimeter has gained very wide acceptance world-wide and is especially useful for the development of new products (Scudamore et al. 1991; White and Dietenberger 2004; Schartel et al. 2005). The cone calorimeter test (ASTM E 1354-11a:2011) measures the relevant reaction–to–fire parameters that have good correlation to full–scale fire behavior. The ignitability, peak of heat release rate (PHRR), total heat released (THR), effective heat of combustion, mass loss rate (MLR) and specific extinction area are the main parameters in cone calorimeter which were measured and analyzed in this study.

Research determining fire performances of steel sandwich panels have been extensively conducted to determine their fire performance (Collier and Baker 2004). It should be noted that the facings play an important role in the classification of panels, and core materials have no effect on this classification (Cooke 2004). Literature reviews on the resulted products of thermal decomposition and toxicity of polystyrene were done by Gurman et al. (1987). They mentioned that polystyrene has the lowest level of toxicity in comparison with other materials used in buildings. Bakhtiyari et al. (2010) studied the fire behavior of expanded polystyrene foam (EPS) with the cone calorimeter test method. They concluded that the sample thickness and density have significant effects on the fire behavior of expanded EPS foam. Essential need for a comprehensive investigation into the fire performance is indicated by a lack of studies available for foam core particleboards.

The surface layers play an important role in the fire behavior of sandwich structures. Earlier works (Shalbafan et al. 2012b) showed that different press parameters result in different foam structure and panel properties. In the current study, 19 mm foam core particleboards were produced using two different press temperatures (130 and 160 °C) and three different surface layer thicknesses of 3, 4 and 5 mm. Foam core density has an important influence on the material cost of foam core particleboard (Shalbafan et al. 2012c). Three different levels of foam density (80, 100 and 120 kg/m$^3$) were used as foam core while the thickness of the surface layer was kept constant (3 mm) in this set of experiment. The aim is the evaluation of flammability parameters of produced panels and comparison with conventional particleboards as reference panel.

## 2 Materials and methods

### 2.1 Experimental approach

The foam core panels with a nominal thickness of 19 mm were manufactured from a three layered mat (600 × 550 mm$^2$) without additional gluing between the face and core layers. Wood particles resinated with urea formaldehyde resin (Kaurit 350, BASF, Germany) were used for the face layers. Expandable polystyrene (EPS, Terrapor 4, Sunpor, Austria) was used as core material. The three-layered mat was then pressed in a lab-scale single opening hot-press (Siempelkamp, Germany). The press cycle consisted of three consecutive stages: pressing phase, foaming phase and finally the stabilization phase by internal cooling of the press plates. The temperature of the press plates was set according to the test series at 130 °C (1–EPS) and 160 °C (2–EPS). These two press temperatures were applied to generate different foam structures. At low press plate temperature (130 °C) longer pressing and accordingly longer foaming times are needed than at the higher press temperature (160 °C). This is due to the less intense heat flow from the surface layer to the thermosensitive material in the core. As a consequence of different foaming conditions the resulted foam in the 1–EPS panels looks like the glassy state. The EPS foam in the 2–EPS panels resembles packaging materials. Figure 1 shows different varieties of lightweight foam core panels produced in two different press temperature regimes.

For each press temperature three surface layer thicknesses of 3, 4 and 5 mm made of resinated wood particles


**Fig. 1** Varieties of lightweight foam core panels; 1-EPS (130 °C: *A*, *B*, *C*) and 2–EPS (160 °C: *D*, *E*, *F*)
**Abb. 1** Variationen der untersuchten leichten Schaumkern-Spanplatten; 1-EPS (130 °C: *A*, *B*, *C*) und 2–EPS (160 °C: *D*, *E*, *F*)

were used to produce the panels. It should be mentioned that at a constant final panel thickness (19 mm) with increasing surface layer thickness from 3 to 5 mm, the core layer thickness decreases from 13 to 9 mm. The target face layer density made of resinated wood particles was calculated to be 750 kg/m$^3$ in all the panel variations. The foam core density of the panels was kept constant (124 kg/m$^3$) for the first set of experiments.

In the second set, fire performances of three different foam core densities (80, 100 and 120 kg/m$^3$) were also examined. The surface (3 mm) and core layer (13 mm) thicknesses were kept constant in the second set of experiments.

In each set of experiments three panels were produced as replicates and one sample from each panel was randomly selected for the fire performance tests (n = 3). Table 1 shows the experimental design of panel manufacturing. 19 mm conventional particleboard (PB) supplied from the market with a density of 650 kg/m$^3$ was also examined as the reference panel. According to ASTM E 1354-11a, all the samples were conditioned to constant mass at 23 °C and 50 % relative humidity for 2 weeks prior to testing. More information regarding pressing schemes and foaming conditions are explained in details in a previous publication by Shalbafan et al. (2012b).

Analysis of the data was performed using SPSS software (IBM). After checking of the data for normality, homogeneity of variances was controlled by Leven test. Thereafter, parametric ANOVA tests were performed to evaluate possible significant differences between the cone calorimeter data of panels produced using different pressing parameters. Statistical differences between variations were evaluated by multiple comparisons using either Duncan or LSD test depending on variance status. The $P$ value level of statistical significance was set at $P < 0.05$.

### 2.2 Expandable polystyrene beads composition

For this study expandable polystyrene (EPS) granulate, Terrapor 4 with a granule size of 0.3–0.8 mm was supplied by Sunpor GmbH, Austria. It is well known that the EPS is a thermoplastic polymer which starts to contract and melt when exposed to temperatures above 100 °C. According to the product data sheet, Terrapor 4 contains less than 1 % cycloaliphatic as flame retardant. Babrauskas and Parker (1987) mentioned that fire retardant in foams work for very low ignition flux (<25 kW/m$^2$), but fire performance is essentially unchanged when larger ignition sources are used. This EPS material also contains 5.7 % pentane (by weight) as blowing agent. Depending on process parameters (e.g., press temperature) between 2 and 3 % of the initial pentane content remains in the foam cells after expansion.

### 2.3 Cone calorimeter test

The tests were carried out according to ASTM E1354–11a (2011) test method with a cone calorimeter apparatus (Atlas Electrical Devices, Chicago, IL) at the Forest Product Laboratory in Madison, USA. Samples were

**Table 1** Composition of the panel variables
**Tab. 1** Herstellungsparameter der Platten

| No | Face thickness (mm) | Press temperature (°C) | Target density (kg/m$^3$) | Foam density (kg/m$^3$) | Pressing time (s) | Foaming time (s) | Stabilization time (s) |
|---|---|---|---|---|---|---|---|
| 1-EPS | | | | | | | |
| A | 3 | 130 | 320 | 124 | 80 | 45 | 130 |
| B | 4 | 130 | 390 | 124 | 105 | 45 | 140 |
| C | 5 | 130 | 460 | 124 | 130 | 45 | 150 |
| 2-EPS | | | | | | | |
| D | 3 | 160 | 320 | 124 | 45 | 10 | 140 |
| E | 4 | 160 | 390 | 124 | 55 | 10 | 170 |
| F | 5 | 160 | 460 | 124 | 65 | 10 | 200 |
| 3-EPS | | | | | | | |
| Ad1 | 3 | 130 | 290 | 80 | 80 | 45 | 130 |
| Ad2 | 3 | 130 | 305 | 100 | 80 | 45 | 130 |
| Ad3 | 3 | 130 | 320 | 120 | 80 | 45 | 130 |
| 4-EPS | | | | | | | |
| Dd1 | 3 | 160 | 290 | 80 | 45 | 10 | 140 |
| Dd2 | 3 | 160 | 305 | 100 | 45 | 10 | 140 |
| Dd3 | 3 | 160 | 320 | 120 | 45 | 10 | 140 |

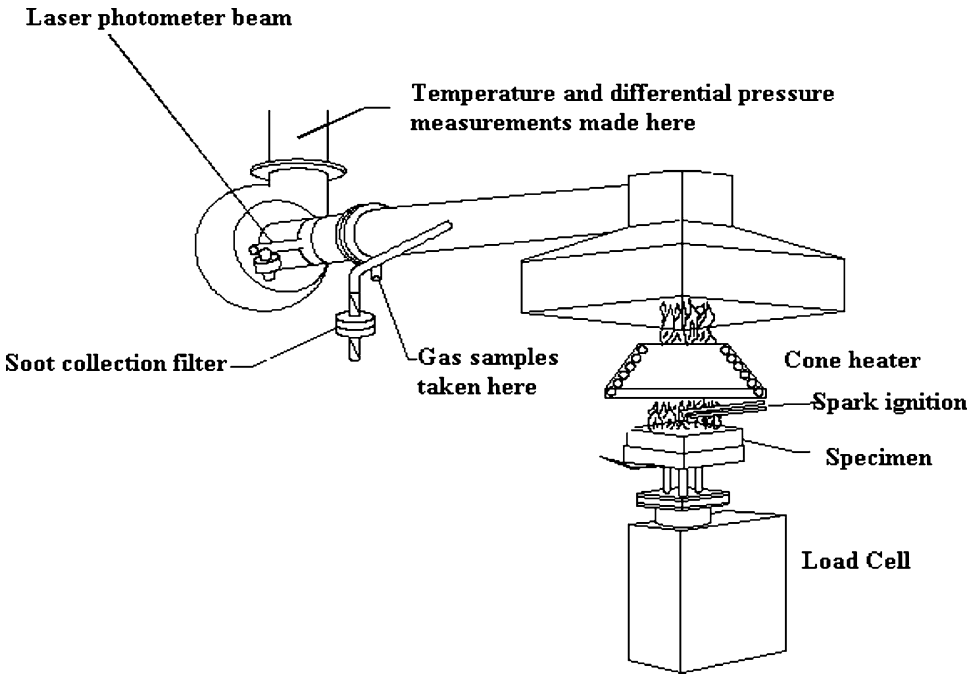


**Fig. 2** Cone calorimeter test set up (http://www.pslc.ws/macrog/mpm/analysis/cone.htm)
**Abb. 2** Konfiguration des Cone Calorimeter Tests (http://www.pslc.ws/macrog/mpm/analysis/cone.htm)

exposed in the horizontal orientation with the conical radiant electric heater set at a heat flux level of 35 kW/m$^2$. In ASTM E 1354-11a (2011) a heat flux of 35 kW/m$^2$ is recommended for the initial tests. The sample sizes were set at 100 × 100 mm$^2$ with a nominal thickness of 19 mm for all the variations. The surfaces of the samples were not sanded prior to fire testing. The cone calorimeter test set up is illustrated in Fig. 2.

The specimens were tested in the optional retainer frame with the wire grid over the test specimen. As explained earlier, some amount of the pentane still remained in the specimen. After ignition of the surface layer, the elevated temperature eventually reaches the foam core layer. This temperature stimulates the remaining pentane in the foam to cause a slight expansion of the foam during the test. To overcome excessive spalling and foam expansion that results in direct contact with the cone heater, a surface wire grid to restrain the heated surface was used in all the cone tests. Ignitability was observed as the time for sustained ignition of the specimen and determined by using 4 s criteria for sustained ignition.

## 3 Results and discussion

### 3.1 Panel properties

Physical and mechanical properties of the panels were obtained according to the methods described in the recent literature published by the authors (Shalbafan et al. 2012a, b, c). Briefly, panels produced by lower press temperature (130 °C) have a denser surface layer, higher bending strength and internal bond values. The interface between foam cells and wood particles is well established in case of the 1–EPS panels which has a positive effect on the internal bond values. The results also indicate that the panels produced by higher press temperature (160 °C) have a better cell configuration (more numerous and smaller cell sizes) due to the faster foaming of the EPS beads. Higher values for the edge screw withdrawal resistance in the 2–EPS panels can be explained by this finding. Soaking tests revealed that the lower amount of water absorption of the 2–EPS panels resulted from better foam cell fusion and less attainment of small voids between the foam cells. Reduction of core density from 120 to 80 kg/m$^3$ showed that physical and mechanical properties of EPS panels with low foam densities can still meet requirements comparable to those fulfilled by conventional particleboards.

### 3.2 Fire performances

Fire performances of foam core particleboards were analysed by measuring important parameters with the cone calorimeters like the ignitability, PHRR, THR, effective heat of combustion, MLR and specific extinction area. These values of all characteristic fire parameters are shown in Tables 2 and 3.

#### *3.2.1 Time to sustained ignition (TSI)*

Time to sustained ignition (TSI) is defined as the period in which a combustible composite can bear heat flux radiated from an external heat source, before sustained flaming combustion starts on the heated surface. Time to sustained

**Table 2** Fire performance results of the foam core particleboard with different face layer thicknesses
**Tab. 2** Ergebnisse zum Abbrandverhalten von Schaumkern-Spanplatten mit unterschiedlichen Decklagendicken

| Code | TSI | PHRR | tPHRR | AHRR-60 | AHRR-180 | AHRR-300 | AEHOC | AMLR 10–90 | ASEA | 2nd PHRR | 2nd tPHRR |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 87 (11) | 275.9 (13) | 158 (20) | 166.7 (9.9) | 150.2 (3.7) | 148.7 (11) | 18.48 (1) | 12.0 (0.5) | 517.8 (79) | 454.3 (32) | 439 (24) |
| B | 106 (4.9) | 239.0 (11) | 217 (22) | 129.9 (10) | 158.4 (4) | 118.4 (6) | 15.23 (0.2) | 12.2 (0.3) | 347.5 (36) | 434.7 (32) | 589 (50) |
| C | 107 (3.3) | 191.2 (29) | 228 (17) | 112.4 (6.7) | 146.9 (6.2) | 124.1 (7.7) | 13.20 (1.8) | 11.3 (0.3) | 306.6 (46) | 396.5 (36) | 676 (13) |
| D | 80 (6.3) | 330.4 (38) | 121 (10) | 211.0 (3) | 158.4 (7.9) | 189.0 (16) | 18.33 (0.9) | 12.6 (0.7) | 554.0 (40) | 426.2 (29) | 410 (24) |
| E | 86 (5.1) | 300.7 (17) | 156 (25) | 156.9 (12) | 153.9 (11) | 143.6 (17) | 17.18 (0.9) | 11.6 (0.7) | 481.1 (55) | 352.7 (20) | 539 (57) |
| F | 100 (4.6) | 279.9 (30) | 217 (5.5) | 117.8 (2.9) | 161.8 (5.9) | 130.0 (5.3) | 15.06 (0.2) | 11.0 (0.5) | 351.5 (21) | 307.2 (4.8) | 659 (11) |
| P | 92 (2.9) | 148.4 (7.1) | 125 (0.6) | 119.2 (4.6) | 107.3 (4.6) | 96.9 (5.6) | 10.72 (0.4) | 8.7 (0.1) | 27.0 (7) | 170.8 (10) | 1,234 (30) |

ignition of foam core particleboard is presented in Tables 2 and 3. TSI increases when the surface layer thickness increases from 3 to 5 mm what was also predicted for similar wood products by Dietenberger and Grexa (2004). Even though the TSI in the 1–EPS panels is slightly higher than those in the 2–EPS case, it is found that these differences are not statistically significant. Shalbafan et al. (2012c) showed that the density of the surface layer in the 1–EPS panels is higher than in the 2–EPS panels which could explain the longer time to reach the surface ignition temperature (Harada 2001). The similar TSI values between the foam core panels and conventional particleboard as shown in Tables 2 and 3 is indicative for the strong effect of the surface layer properties on ignition and surface ignition temperature (Dietenberger and Grexa 2004), because material density of the surface layers is similar for both types of panels.

### *3.2.2 Heat release rate (HRR) and total heat released (THR)*

The HRR is a strong indicator for the potential of fire hazard of a combustible material. In Fig. 3, HRR graphs of foam core particleboards are depicted. A delay was observed before the panels started to release combustion heat. This delay is essentially the TSI during which the material surface temperature remains below the pyrolysis temperature at which production of significant amounts of combustible volatile gases starts, which is coincident with the surface ignition temperature for thick organic materials (Dietenberger and Grexa 2004). It can be seen that in foam core panels the whole combustion period is approximately half of that for the conventional particleboard. The foam core particleboard burned faster than conventional particleboards because of the relatively higher heat release rates (HRR) even though the THR values are very similar. Increasing the surface layer thickness from 3 to 5 mm in both the 1–EPS and 2–EPS panels resulted in a prolongation of the combustion period. It is well understood that in constant heat flux conditions (35 kW/m$^2$) the polymeric materials tend to burn faster than building products made of wood (Mouritz et al. 2006).

For interpreting the cone calorimeter data, the influence of the EPS foam core should be considered first. All polymer-based foams are organic materials which are combustible. The thermal conductivity of the foam strongly affects the fire performances as follows. Expanded polystyrene foam has a low thermal conductivity which acts as a protective layer underneath the wood surface layer and diminishes the conductive heat loss from the surface layer. This leads to an enhanced temperature rise of the surface layer resulting in greater production rates of combustible volatiles (Dietenberger 2012). This, in turn, results in an accordingly increased first PHRR which is significantly higher than that of conventional particleboards. After the surface ignition (and prior to the point of PHRR at about 30 kW/m$^2$) the char layer begins to form, and the volatile emission rate is the result of the speed at which the pyrolysis front propagates into the wood-based material. The combustion of the volatiles is what gives the flaming HRR. The drop in the heat release rate after the first peak can be explained by slowing down of the propagation of the pyrolysis front due to the gradual development of an insulating char layer in conjunction with a thermal wave propagating through the wood. Since heat of combustion remains relatively constant while the wood is pyrolysed, the HRR will reflect the decreasing MLR, which in turn is due to the slowing down of the propagation of the pyrolysis front (White and Dietenberger 2010).

During the burning of the surface layer the foam core layer starts to volatize combustible materials. The foam does not char and its volatiles with their corresponding higher heat of combustion begin to be added to the volatiles originating from the thermal decomposition of the woody matter. This is reflected in the increasing heat of combustion after a steady state phase during the test (before the 2nd PHRR). EPS foam melts and boils at temperatures much lower than those of the pyrolysis front in the wood (i.e., less than 300 °C). As the thermal wave terminates at the back of the sample, the sample gradually attains a

**Table 3** Fire performance results of the foam core particleboard with different foam core density
**Tab. 3** Ergebnisse zum Abbrandverhalten von Schaumkern-Spanplatten mit unterschiedlichen Schaumkerndichten

| Code | TSI | PHRR | tPHRR | AHRR-60 | AHRR-180 | AHRR-300 | AEHOC | AMLR 10–90 | ASEA | 2nd PHRR | 2nd tPHRR |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ad1 | 102.2 (1.6) | 262.4 (8.6) | 173.3 (5.7) | 165.2 (8) | 153.4 (5.3) | 143.0 (7.4) | 17.4 (0.8) | 12.7 (0.1) | 395.9 (46) | 464.6 (63) | 466.6 (20) |
| Ad2 | 103.4 (2.3) | 281.6 (26) | 174.0 (5) | 167.2 (15) | 155.9 (4.8) | 137.1 (12) | 16.4 (0.8) | 12.9 (0.4) | 441.2 (41) | 447.5 (24) | 476 (6) |
| Ad3 | 87 (11) | 275.9 (13) | 158 (20) | 166.7 (9.9) | 150.2 (3.7) | 148.7 (27) | 18.4 (1) | 12.0 (0.5) | 517.8 (79) | 454.3 (32) | 439 (24) |
| Dd1 | 85.7 (7.8) | 316.2 (35) | 139.0 (18) | 193.1 (15) | 164 (1.7) | 171.1 (16) | 16.6 (0.08) | 14.0 (0.7) | 469.2 (15) | 461 (39) | 432.6 (27) |
| Dd2 | 87.1 (3.2) | 335.4 (26) | 144.7 (8.9) | 194.2 (18) | 161.4 (19.9) | 157.3 (32) | 17.7 (.04) | 12.5 (0.6) | 531.9 (31) | 453.6 (2.3) | 470 (1) |
| Dd3 | 80 (6.2) | 330.4 (38) | 121 (10) | 211.0 (2.9) | 158.4 (7.8) | 189.0 (16) | 18.3 (0.9) | 12.6 (0.7) | 554.0 (40) | 426.2 (29) | 410 (24) |

Values in parentheses are standard deviations. *TSI* time to sustained ignition, *PHRR* initial peak of heat release rate, *tPHRR* time of first peak heat release rate, *AHRR-60* average of heat release rate over 60 s of sustained ignition, *AHRR-180* average of heat release rate over 180 s of sustained ignition, *AHRR-300* average of heat release rate over 300 s of sustained ignition, *AEHOC* average of effective heat of combustion, *AMLR 10–90* average mass loss rate for 10–90 % of ultimate mass loss, *ASEA* average specific extinction area, *2nd PHRR* second peak of heat release rate, *2nd tPHRR* time of 2nd peak of heat release rate

Werte in Klammern sind Standardabweichungen. *TSI* Zeit bis zu anhaltender Flammenbildung, *PHRR* erster Peak der Wärmefreisetzungsrate, *tPHRR* Zeit bis zum ersten Peak der Wärmefreisetzungsrate, *AHRR-60* mittlere Wärmeabgabe über die ersten 60 s anhaltender Flammenbildung, *AHRR-180* mittlere Wärmeabgabe über die ersten 180 s anhaltender Flammenbildung, *AHRR-300* mittlere Wärmeabgabe über die ersten 300 s anhaltender Flammenbildung, *AEHOC* mittlere effektive Verbrennungswärme, *AMLR 10- 90* mittlere Masseverlustrate über den Masseverlustbereich von 10-90%, *ASEA* mittlere spezifische Extinktion, *2nd PHRR* zweiter Peak der Wärmefreisetzungsrate, *2nd tPHRR* Zeit bis zum zweiten Peak der Wärmefreisetzungsrate

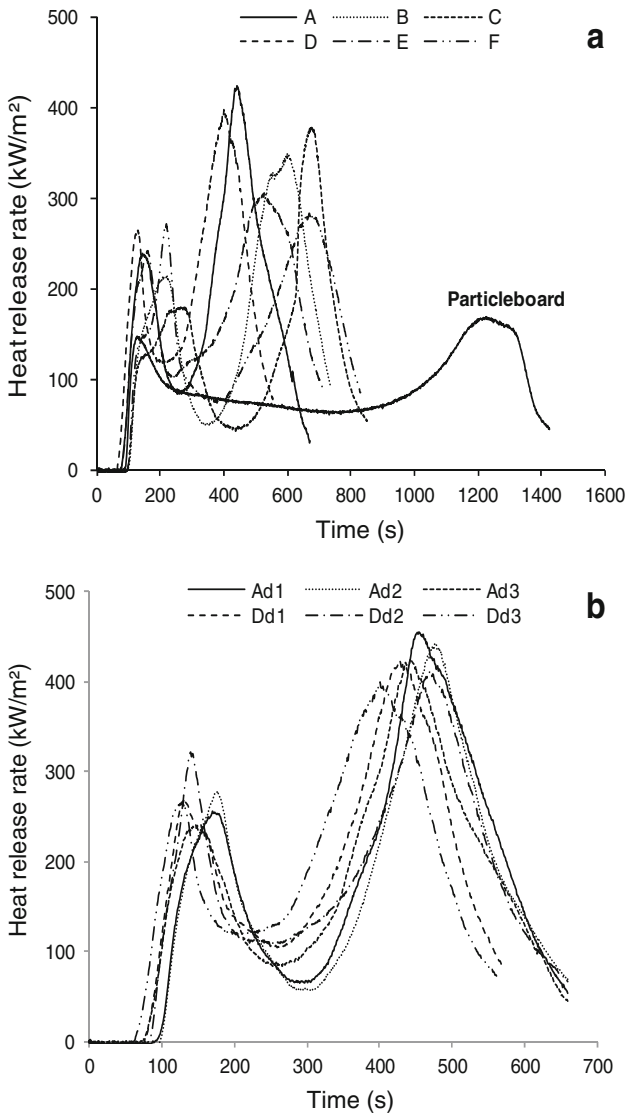


**Fig. 3** Heat release rate (HRR) of foam core particleboard with different surface thicknesses: **a** with different surface thickness, **b** with different foam core densities
**Abb. 3** Wärmefreisetzungsrate (HRR) der Schaumkern-Spanplatten: **a** mit unterschiedlichen Decklagendicken, **b** mit unterschiedlichen Schaumkerndichten

thermally thin response that leads to the second HRR peak due to the pyrolysis front accelerating and broadening into a pyrolysis zone while transitioning to a thermally thin condition (Dietenberger 2002; Hagge et al. 2004). Finally, the pyrolysis zone reaches the back of the samples and causes the thermal feedback effect for an elevated temperature for more rapid pyrolysis (Schartel and Hull 2007). Overall, the second HRR peak is due to the foam and the volatilization of the back side of the board. A transition to glowing which is seen by heat of combustion approaching 30 kJ/g, what corresponds with pure carbon. This means that the wooden matter has been transformed into almost pure carbon, which does not combust until the air is able to

penetrate into the carbonized matter until generation of volatiles has diminished. Conventional particleboards as a charring material also show a second peak at the end of the test due to a similar process as explained above.

A difference between the 1st and 2nd peak of the HRR in the foam core particleboards is shown in Fig. 4. Both peaks decrease significantly with raising surface layer thicknesses from 3 to 5 mm, which is consistent with their increased heat capacitance that lowered the temperature rise rate and the peak temperatures during pyrolysis. The differences between the 1st and 2nd peaks in the 1–EPS are higher than those in the 2–EPS panels. A corresponding comparison shows that the 1st peak of HRR in the 1–EPS panels is lower than those in the 2–EPS panels. Conversely, the 2nd peak of HRR in the 2–EPS is lower than the corresponding values of the 1–EPS panels. With respect to the similarly available combustible mass and according to insignificantly changes of MLR, this difference can be explained by the different foam structure which resulted from different foaming conditions. Presumably more volatiles are emitted from the 2–EPS foam after the surface ignites. Another possible explanation can be the lower temperature resistance of the 2–EPS panels and having a premature melting of that from the sides which result in higher combustible volatiles. The graph shows that the reference panels have lower 1st and 2nd peak of HRR rate when compared with the foam core particleboards.

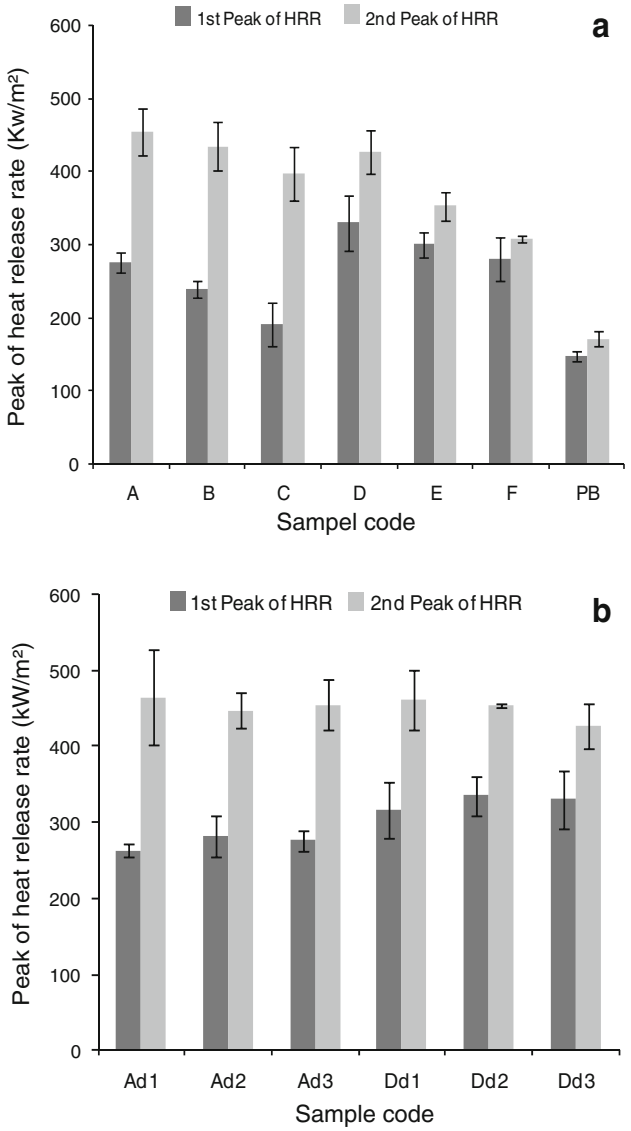


**Fig. 4** First and second peak of heat release rate (PHRR) of foam core particleboard: **a** with different surface thicknesses, **b** with different foam core densities

**Abb. 4** Erster und zweiter Spitzenwert der Wärmefreisetzungsrate (HRR) der Schaumkern-Spanplatten: **a** mit unterschiedlichen Decklagendicken, **b** mit unterschiedlichen Schaumkerndichten

In Fig. 4b, the difference of the peaks in foam core panels with different foam core densities is illustrated. Changing of foam core density has no significant effect on both the 1st and 2nd peaks of HRR in 3–EPS and 4–EPS panels. The same trend as for 1–EPS and 2–EPS was also observed for the 3–EPS and 4–EPS panels.

The THR of foam core particleboards is compared with conventional particleboards and illustrated in Fig. 5. The THR in the 2–EPS panels seems somewhat higher than that in the 1–EPS panels. In respect of the similar combustible materials in the corresponding samples, this difference can be explained by the different foaming processes for the 1–EPS and 2–EPS panels. Due to the longer pressing and foaming times in the 1–EPS panels, the EPS beads were transformed to a semi-viscous state and then slowly started to expand (Shalbafan et al. 2012b). Presumably more volatiles of EPS were emitted during the foaming phase of the 1–EPS panels. The THR does not significantly change in the 3–EPS and 4–EPS panels.

All the variations of foam core particleboards have about a 10–20 % lower amount of THR when compared with conventional particleboards. This is due to the substitution of a high amount of coarse wooden middle layer particles by a small amount of polymer in foam core particleboards. Since the heat of combustion of EPS foam (approximately 40–45 MJ/kg) is higher than wood (13 MJ/kg), the expected decrease in total heat release rate is partly compensated by the higher heat of combustion of the EPS foam (Luedtke 2011; Troitzsch 1990).

Some of the cone calorimeter data describe material properties, while other data are strongly dependent on the particular test setup. One of the most frequently used results from the cone calorimeter test is the PHRR which is strongly dependent on the test setup. This has to be considered for data interpretation (Schartel et al. 2005). Flashover propensity is a useful parameter of full scale fire behaviour. Flashover propensity is calculated by the peak

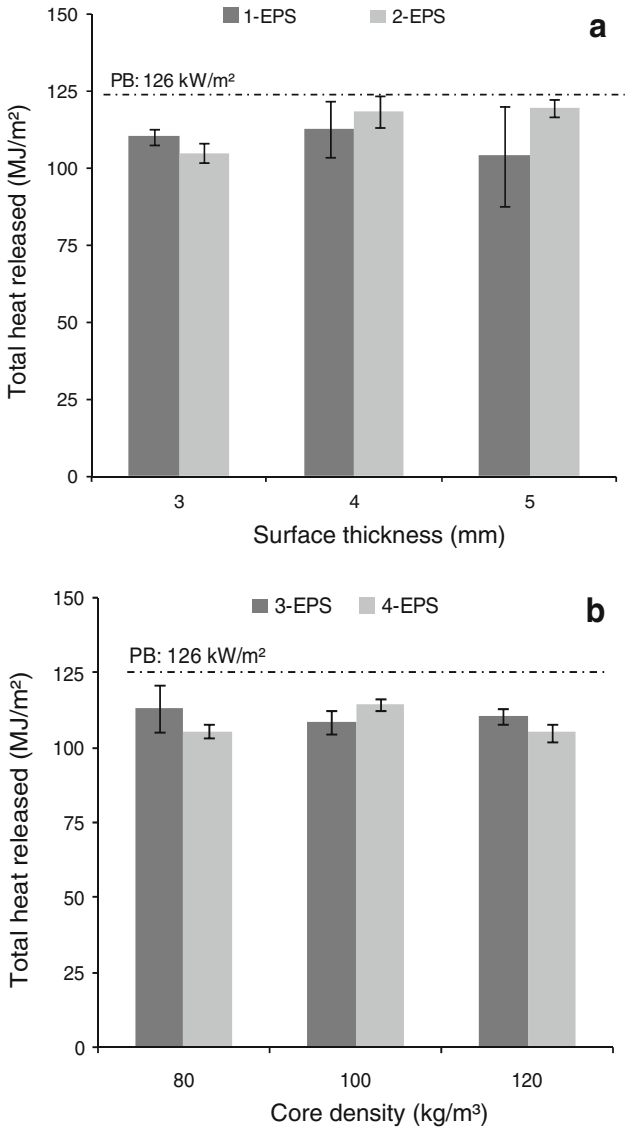


**Fig. 5** Total heat released (THR) of foam core particleboard: **a** with different surface thicknesses, **b** with different foam core densities
**Abb. 5** Gesamte Wärmefreisetzung (THR) der Schaumkern-Spanplatten: **a** mit unterschiedlichen Decklagendicken, **b** mit unterschiedlichen Schaumkerndichten

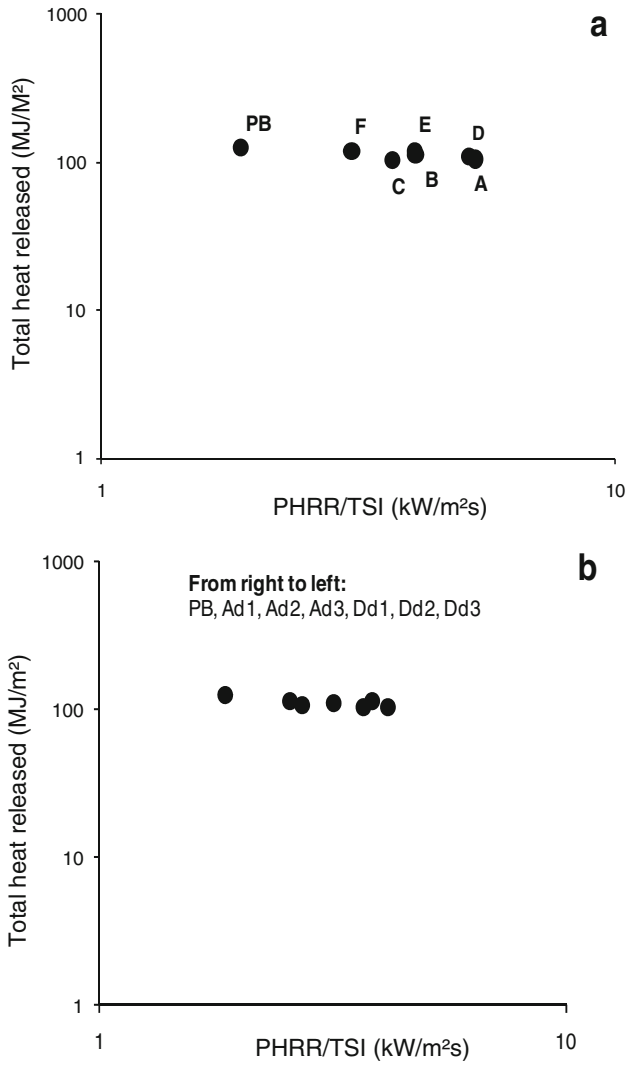


**Fig. 6** Flashover propensity and total heat released for the foam core particleboard, **a** with different surface thicknesses, **b** with different foam core densities, and conventional particleboard (PB)
**Abb. 6** Neigung zu schlagartiger Flammenausbreitung und gesamte Wärmefreisetzung von Schaumkern-Spanplatten, **a** mit unterschiedlichen Decklagendicken, **b** mit unterschiedlichen Schaumkerndichten, und normalen Spanplatten (PB)

heat release rate divided by the time to sustained ignition (Hirschler 1992). Petrella (1994) mentioned that when the flashover propensity (PHHR/TSI) is combined with the total heat release a better understanding of full scale fire behaviour is achieved. Figure 6 shows the flashover propensity and total heat release for the foam core panels and conventional particleboard. The slope of THR–flashover propensity in Fig. 6 is almost zero. The flatness of the slope can be explained by the small range of the THR from 100 to 130 MJ/m$^2$. Figure 6 shows that changing surface layer thickness in foam core panels increases the flashover propensity from 3 to 5.4 while having little or no effect on the THR. Higher flashover propensity means that the panels are ignited faster or that the resulting peak heat release rate is higher. As a conclusion it can be said that the panels with thinner surface layers (panels A and D) were ignited faster than those with thicker surface layers. And accordingly, it can also be expected that the panels with higher foam core density (Ad3 and Dd3) are ignited faster than the ones with lower foam core densities.

### *3.2.3 Effective heat of combustion (EHOC) and mass loss rate (MLR)*

The effective heat of combustion is calculated as the ratio of HRR to the MLR as a function of time, while the

average effective heat of combustion is calculated as the ratio of THR to total mass loss (ASTM E 1354-11a). The average effective heat of combustion of foam core particleboard is illustrated in Fig. 7. The EHOC is decreased while the surface thickness is raised from 3 to 5 mm. Enhancing surface layer thickness causes a reduction in the foam core layer thickness which has an important effect on the lowering of EHOC. Due to the higher THR in the 2–EPS panels, as a result of different foaming condition, a higher average EHOC is also obtained for the 2–EPS panels compared with the 1–EPS.

The amount of thermal decomposition and the resulting volatilization of a combustible material in fire is entitled total mass loss. The average MLRs between the time when the samples lose 10 and 90 % of their total mass and the average effective heat of combustion are tabulated in Tables 2 and 3. High HRR values generally indicate more complete pyrolysis and volatilization of the combustible materials which results in higher mass loss. Due to the dependency of HRR and MLR on the rate of decomposition reaction, a strong linear correlation can be seen between them shown in Fig. 8.

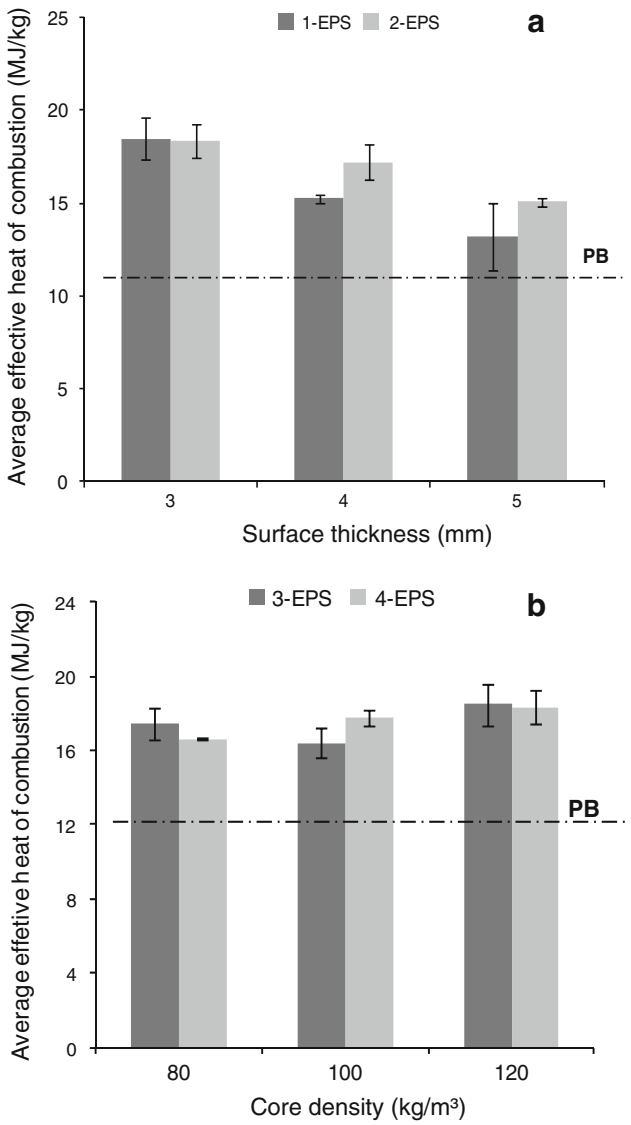


**Fig. 7** Average effective heat of combustion (EHC) for the foam core particleboard and conventional particleboard (PB): **a** with different surface thicknesses, **b** with different foam core densities

**Abb. 7** Durchschnittliche effektive Verbrennungswärme (EHC) der Schaumkern-Spanplatten: **a** mit unterschiedlichen Decklagendicken, **b** mit unterschiedlichen Schaumkerndichten

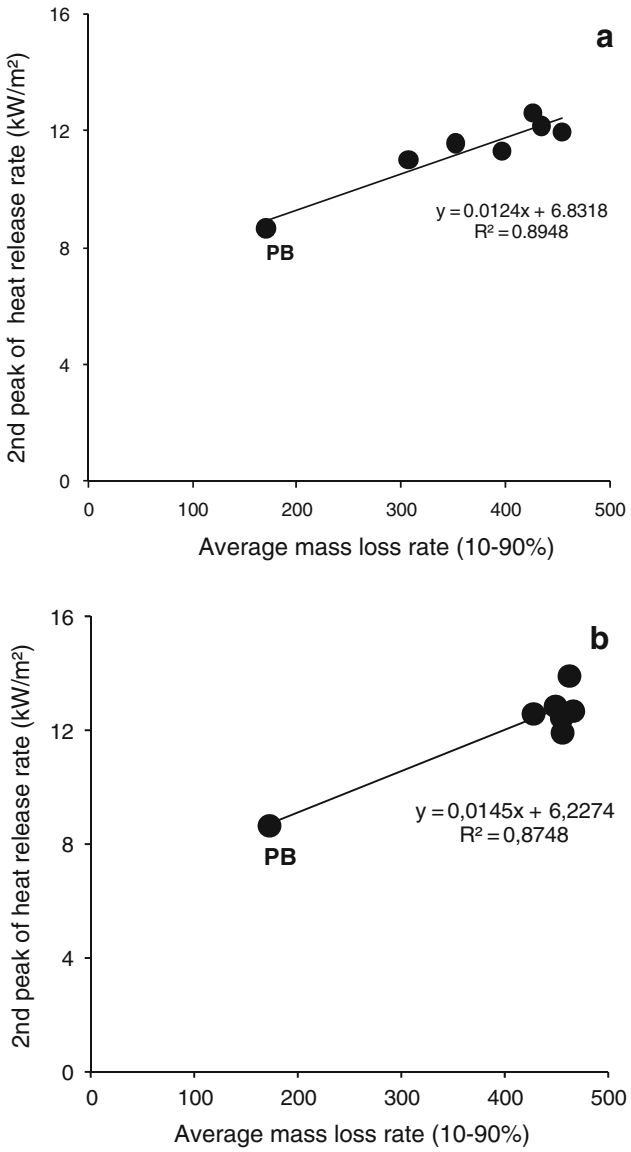


**Fig. 8** Average mass loss rate (MLR) against the 2nd peak of heat release rate: **a** with different surface thicknesses, **b** with different foam core densities

**Abb. 8** Durchschnittliche Masseverlustrate (MLR) aufgetragen gegen die Wärmefreisetzungsrate (zweiter Spitzenwert): **a** mit unterschiedlichen Decklagendicken, **b** mit unterschiedlichen Schaumkerndichten

### 3.2.4 Average specific extinction area (ASEA)

The main fire hazard is the smoke which is a result of incomplete combustion. The specific extinction area is characterized by the smoke obscuration where the reduction of light transmission is measured by a laser beam through the exhaust duct. The results of ASEA are illustrated in Fig. 9. Figure 9a shows that with increasing surface layer thickness from 3 to 5 mm, the ASEA is decreased. This can be explained by the decreasing amount of EPS–foam core materials while surface layers are thickened. It is also obvious that the 2–EPS panels have significantly higher ASEA compared with the 1–EPS panels due to different foam structures.

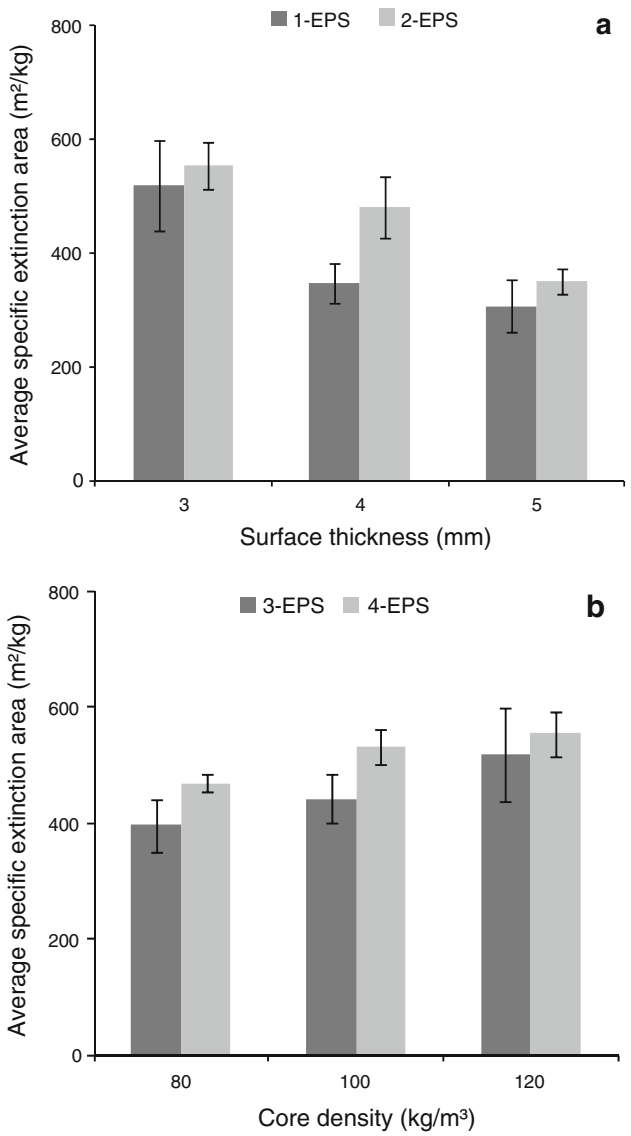


**Fig. 9** Average specific extinction area (ASEA) for the foam core particleboard: **a** with different surface thicknesses, **b** with different foam core densities

**Abb. 9** Durchschnittliche effektive Extinktionsfläche (ASEA) der Schaumkern-Spanplatten: **a** mit unterschiedlichen Decklagendicken, **b** mit unterschiedlichen Schaumkerndichten

Trends like this can also be found for Fig. 9b. With decreasing foam density from 120 to 80 kg/m$^3$ the ASEA is decreased for both the 3–EPS and 4–EPS panels. Additionally, the 4–EPS panels which were produced at higher press temperature (like the 2–EPS panels) show significantly higher ASEA in comparison with the 3–EPS panels. In comparison to conventional particleboards the foam core panels generally had much higher ASEA due to the EPS–foam component of the tested panels. Östmann and Tsantaridis (1993) mentioned that the polystyrene foam has lower smoke production in the room fire test than that of the cone calorimeter test. This is due to the falling down of the droplets in the room fire test which stops the smoke production, but it may result in other hazards.

## 4 Conclusion

To confirm and support general advantages of lightweight foam core particleboards, the possible restriction due to fire performance was examined with cone calorimetry tests (ASTM E 1354-11a) of specimens with variations of surface layer thicknesses, foam densities, and processing temperatures. Using the initially recommended cone irradiance of 35 kW/m$^2$ ignitability, PHRR, THR, effective heat of combustion, MLR and specific extinction area were measured and analyzed with the following results. In comparison to the reference particleboard the foam core panels generally had much higher heat release what reduced their burning times approximately by half. They also show higher heat of combustion and smoke production due to the EPS component of lightweight panels. Other measured parameters like time to ignition and total heat release did not vary significantly among the samples. The variation of foam densities and processing temperatures were likewise not very significant, although some trends could be identified. However, as the surface layer thickness was increased from 3 to 5 mm, the flammability properties began to improve and approached, as expected, those of the reference particleboard.

Some wood products used in paneling application have similar flammability properties as measured here for the lightweight foam core panels. Therefore, the lightweight sandwich panels without any treatment may find niche markets. If it is desired on the basis of fire performance to achieve better flammability results, then some means of fire retardant treatment (FRT) is recommended and tested in the cone calorimeter under appropriate conditions, such as the irradiance set to 50 kW/m$^2$. The option of applying a veneer treated with an intumescent FRT coating to the surface layer is subject of a follow–up investigation. It

should be pointed out that if the edge properties of the product are taken into account, the fire behavior may be worse. This has to be further studied if the product is being used with exposed edges.

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# VIII

# Treated and untreated foam core particleboards with intumescent veneer: comparative analysis of cone calorimeter

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# Treated and Untreated Foam Core Particleboards with Intumescent Veneer: Comparative Analysis of Cone Calorimeter

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**Abstract**

The effectiveness of treatments of the surface layer of novel foam core particleboards were evaluated by means of Cone calorimeter tests. Foam core particleboards with variations of surface layer treatment, adhesives and surface layer thicknesses under similar processing conditions were used to produce the test specimen for the Cone calorimeter tests. Ignitability, heat release rate profile, peak of heat release rate, total heat released, effective heat of combustion, mass loss rate, gaseous emissions and specific extinction area were measured using the cone irradiance of 50 kW $^{m-2}$. Additional analysis of this data provided fuel composition information that could reveal the pyrolysis events of the composite boards. Thermocouples at various depths were used to provide further verification of pyrolysis events. The unprotected foam core panels generally had much higher heat release rates, somewhat higher heat of combustion and much higher smoke production due to the polymeric foam component of tested panels, whereas time to ignition and total heat release were not pronounced from the veneer treated boards. Adding the commercial fire retardant veneer to the face particleboard provided a dramatic improvement to the measured flammability properties. It worked sufficiently well with a 3 mm thick surface layer to improve the predicted flame spread rating of the foam core particleboards.

**Key words:** Foam core particleboard . Cone calorimeter . Sandwich . FRT veneer . Polystyrene foam.

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# Introduction

A novel technology to produce lightweight, sandwich-type composites with particleboard facing and a foam core in one single production step has been developed [1]. This type of particleboard and foam core panel can be produced on standard particleboard production lines which can be adapted to the new technology with some modifications of the machines. The presence of the expandable polystyrene (EPS) for in-situ foaming of the core material implies some restrictions in the production process. But also the fire safety of this type of innovative panels might become a crucial aspect when introducing these novel panels into the market. The cone calorimeter for evaluating flammability has gained very wide acceptance world-wide and has been considered to be especially useful for the development of new products [2, 3]. This ASTM E 1354-11a [4] test apparatus measures the relevant reaction-to-fire parameters that have good correlations to full-scale fire behavior. The ignition time, heat release rate, total heat released, heat of combustion, mass loss rate, combustion products and specific extinction area are the main parameters measured and analyzed with ASTM 1354-11a. The need for a comprehensive investigation of fire performance of foam core sandwich panels is indicated by the limited studies available on similar thin foam core sandwich panels.

The first study in this project involved the cone calorimeter tests of samples exposed in the horizontal orientation with the conical radiant electric heater set at the irradiance 35 kW $m^{-2}$. By testing 19 mm-thick panels with variations in surface layer thicknesses, core foam densities, and processing temperatures, it was found that the surface layers have an important impact on the fire behavior of sandwich structures [5]. In that study, the heat release rates (HRR) for the sandwich panels were much higher than for the conventional particleboard panel. Their flammability properties improved as the surface layer thicknesses increased from 3 to 5 mm. However, the levels of HRR were similar to some existing wood-based panels, and thus should have at least some market use on that basis.

It is interesting that the EPS foam has thermal properties that suggest a fire retardant solution. It is stated that the polystyrene foams start to soften and shrink from 100 ˚C and melt at even higher temperatures (around 250 ˚C). Upon further heating, ignitable decomposition gases are created at about 350 ˚C. Without a flame source, temperatures above 450 to 500 ˚C lead to the ignition of the decomposition products. When exposed to a small flame, the flame retarded polystyrene melts away from the ignition source

without itself igniting and ignition might only be observed after longer flame exposures. If the contact with the external flame stops, further burning or smoldering might not be observed. In conjunction with other combustible substances, even flame retarded polystyrene foam can burn [6]. Thus to avoid this burning condition the polystyrene can be kept below its decomposition temperatures via the insulation effects of either a thicker surface layer or the use of surface intumescent veneer or coating. The testing of the commercial intumescent surface layer with a high fire rating required the use of the more severe cone irradiance of 50 kW $m^{-2}$, which is associated with large fires and severe reaction to fire tests.

This paper reports on the in-depth study to verify this added fire retardancy mechanism. In addition to the standard flammability measures discussed in ASTM E1354, this study also utilized imbedded thermocouples at various depths in the sandwiched panels and advanced evolved gas analysis to reveal the decomposition behavior of sandwich panels with and without intumescent veneer coating. The construction of three sandwich panels with varying surface layers and the enhancement to the cone calorimeter gas analysis are described in the material and methods section. In the results and analysis section each relevant flammability feature is explained for the three sandwich panels for the exposure to irradiance at 50 kW $m^{-2}$ and piloted ignition. Also from this data set, the flame spread index classifications according to ASTM E84 [7] were estimated.

# Material and Methods

### Three Variations for Surface Layers of Foam Core Particle Boards

Basically, the foam core particleboards with a nominal thickness of 19 mm were manufactured from a three layered mat without additional gluing between the face and core layers. The resinated wood particles and urea formaldehyde resin (Kaurit 350, BASF, Germany) was used for the face layers. The expandable polystyrene (EPS, Terrapor 4, Sunpor, Austria) with a granule size of 0.3 to 0.8 mm were used as the core materials. According to the data sheet of Terrapor 4, it contains a small amount of flame retardant. Babrauskas and Parker [8] mentioned that fire retardant in foams work for very low ignition flux (<25 kW $m^{-2}$) but fire performance is essentially unchanged when larger ignition sources are used. This material also contains 5.7% pentane (by weight) as the blowing agent. Our unpublished study showed that between 2 and 3% of the

initial pentane remains in the foam cells after expansion, depending on process parameters (press temperature etc.).

The three-layered mat was then pressed in a lab-scale single opening (Siempelkamp, Germany) hot-press. The press cycle consist of three consecutive stages: pressing phase, foaming phase, and stabilization phase by the internal cooling of the press plates. The temperature of the press plates was set at 130 ˚C. The target overall density was 320 kg $m^{-3}$ with a face density of 750 kg $m^{-3}$ and a core density of 124 kg $m^{-3}$. Nominal surface thickness was 3 mm which corresponds to the foam core thickness of 13 mm and overall thickness of 19 mm. Shalbafan et al. 2012a has described in details the pressing schedules and foaming conditions.

The two improvements utilized for this study were the use of conventional beech veneer without and with intumescent paper underneath of the veneer. The fire resistive adhesive used for veneering the samples was Firobond Ultra Adhesive (FUA) supplied from ENVIROGRAF, UK. The sandwich panels without any veneer were utilized as reference samples in this series of tests. At least two panels of each series were produced as replicates and one sample was cut out from each panel to do the fire performance test. All the samples were conditioned at 23 °C and 50% relative humidity for at least two weeks prior to testing to meet equilibrium moisture content (EMC).

## Cone calorimeter upgrades and test procedure

The tests were carried out according to the ASTM E1354 test method with a cone calorimeter apparatus (Atlas Electrical Devices, Chicago, IL) at the Forest Product Laboratory in Madison, USA. Samples were exposed in the horizontal orientation to the irradiance of 50 kW $m^{-2}$ upon opening the water-cooled thermal shutter and using an electric spark for piloted ignition. Prior to placing the specimen in the sample holder, four thermocouples were attached in the following manner. The exposed surface thermocouple (36 gauge Type K wire) was inserted into a slanted surface crevice formed with a razor blade. Two thermocouples (30 gauge Type K wire) were inserted in tiny long holes at the interface of the foam and particle board, with the bead situated at the sample's middle. The fourth thermocouple was taped to the backside surface at the sample's middle. These thermocouple measurements provided data to verify the insulating enhancements of the veneers. The Figure 1 shows the position of the inserted thermocouples in the cross section of the samples.

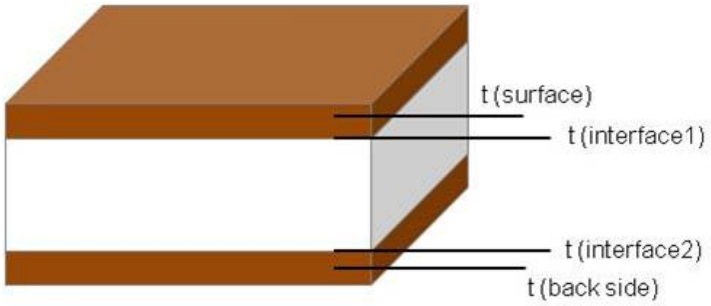


**Fig 1** The position of the thermocouples inserted in different places of the samples.

The specimens were tested in the optional retainer frame with a wire grid over the test specimen. As explained earlier, some of the pentane remained in the specimen. After ignition of the surface layer, the elevated temperature eventually reaches the foam core layer. This temperature stimulates the remaining pentane in the foam to cause slight expansion of the foam during the test. To overcome excessive spalling and foam expansion that results in direct contact with the cone heater, a surface wire grid was used in all the cone tests to restrain the heated surface. Ignitability was determined by observing the time for sustained ignition of the specimen with a 4 seconds criteria for sustained ignition.

Exhaust gas composition was determined using three gas analyzers from Sable Systems (www.sablesys.com) and a relative humidity sensor from U.P.S.I. (www.upsi.fr). Oxygen was measured using the PA-10, a paramagnetic analyzer capable of resolution to 0.0001% $O_2$ and modified to provide even faster response by reducing internal volume of the filters. Exhaust gas to the sensor was dried using the Sable ND-2, a permeable-membrane dryer. Carbon dioxide was measured using the CA-10, a dual wavelength infra-red sensor capable of resolution to 1 ppm. The same technology was used in the CM-10A for Carbon monoxide detection. Gas was delivered to the analyzers using two pumps. The first larger pump pulls exhaust quickly to the location of the Sable equipment through a pre-filter and water-bath controlled (50 °C) water-to-air heat exchanger to provide consistent incoming air conditions. Then a sub-sample pumps pulls exhaust smoothly through the dryer and analyzers.

The relative humidity was measured using the F-TUTA.34R, a quick responding sensor placed very early in the gas sample path inside the cone calorimeter. The lines and sample location were heated with heat tape to near 50 °C to avoid condensation on the lines after the ring sampler. The F-TUTA.34R provides analog signals corresponding to relative humidity and temperature. Similarly the Sable components provide analog signals, including the barometric pressure. These signals along with the type K

thermocouple readings at various locations in the specimen were captured by the data acquisition system (Measurement Computing USB-1616HS) at 4 Hz. Raw signals were then time-shifted based on time-of-flight to the sensor to have all changes correspond to the mass loss signal from the cone calorimeter.

Exhaust flow rate calculations were based on Bernoulli's formula using pressure drop across the orifice, temperature of the exhaust, and various gas concentrations. Further fine tuning of the exhaust flow rate is based on matching the computed mass flow rates of depleted oxygen, carbon dioxide, and water with that determined from nearly complete combustion of pure ethylene glycol, whose fuel mass flow is measured with the weigh scale. As a basis for comparison, we have that for any incomplete hot combustion, the dynamic mass flow rate (g $s^{-1}$) of a fuel mixture with empirical formula $C_XH_YO_ZN_US_V$ has six equivalent calculations as derived from simple mass balances as [9],

$$\begin{aligned}
\dot{m}_{fuel} &= \left(\frac{12X+Y+16Z+14U+38V}{32(X+V)+8Y-16Z}\right)\left(\Delta\dot{m}_{O2}+\frac{32\dot{m}_s}{12}+\frac{16\dot{m}_{CO}}{28}+\frac{(32+8W)\dot{m}_{CHw}}{12+W}\right) \quad > Form\ 1\\
&= \left(\frac{12X+Y+16Z+14U+38V}{44X}\right)\left(\dot{m}_{CO2}+\frac{44\dot{m}_s}{12}+\frac{44\dot{m}_{CO}}{28}+\frac{44\dot{m}_{CHw}}{12+W}\right) \quad > Form\ 2\\
&= \frac{12X+Y+16Z+14U+38V}{9Y}\left(\Delta\dot{m}_{H2O}+\frac{9W\dot{m}_{CHw}}{12+W}\right) \quad > Form\ 3\\
&= \frac{12X+Y+16Z+14U+38V}{14U}\Delta\dot{m}_{N2} = \frac{12X+Y+16Z+14U+38V}{70V}\dot{m}_{SO2} \quad > Forms\ 4\ \&\ 5\\
&= \dot{m}_{CO2}+\dot{m}_s+\dot{m}_{CO}+\Delta\dot{m}_{H2O}+\dot{m}_{CHw}+\Delta\dot{m}_{N2}+\dot{m}_{SO2}-\Delta\dot{m}_{O2} \quad > Form\ 6
\end{aligned} \tag{1}$$

With $X$=2, $Y$=6, and $Z$=2 for ethylene glycol that is combusting completely, we were able to use Forms 1, 2, 3, and 6 to compare with the time derivative of the dynamic mass loss. No fine tuning of zero and span parameters for oxygen, carbon dioxide, and carbon monoxide gas analysis were needed, whereas the relative humidity sensor required minor calibration adjustments. To match up their response times from 10% to 90% levels during step changes, small digital filtering was applied to sensor data for carbon dioxide, carbon monoxide, and water vapor, and a small digital deconvolution was applied to the oxygen sensor data. Since the molar fractions of $O_2$, $CO_2$, CO, and $H_2O$ are now available and synchronized, we followed the ASTM E1354 Annex procedure for calculating the mass flow rates, respectively, of the same molecules. The soot mass flow rate is merely calculated as the smoke production rate (product of volumetric rate and extinction coefficient) divided by the specific extinction area, 8.3 $m^2\,g^{-1}$, for the black smoke. Estimates of *THCs*, although quite small, could reasonably have $w$=2 in Equation 1 and their mass flow rates approximately 0.1% of the carbon

dioxide mass flow rates corresponding to flaming combustion [10]. These mass flow rates are then substituted into Equation 1 and some of the different forms of Equation 1 are compared in Figure 2 showing excellent agreement for burning of glycol. The calibrations derived for glycol burning was also applied successfully to the follow-on tests of the six sandwich panels for this study.

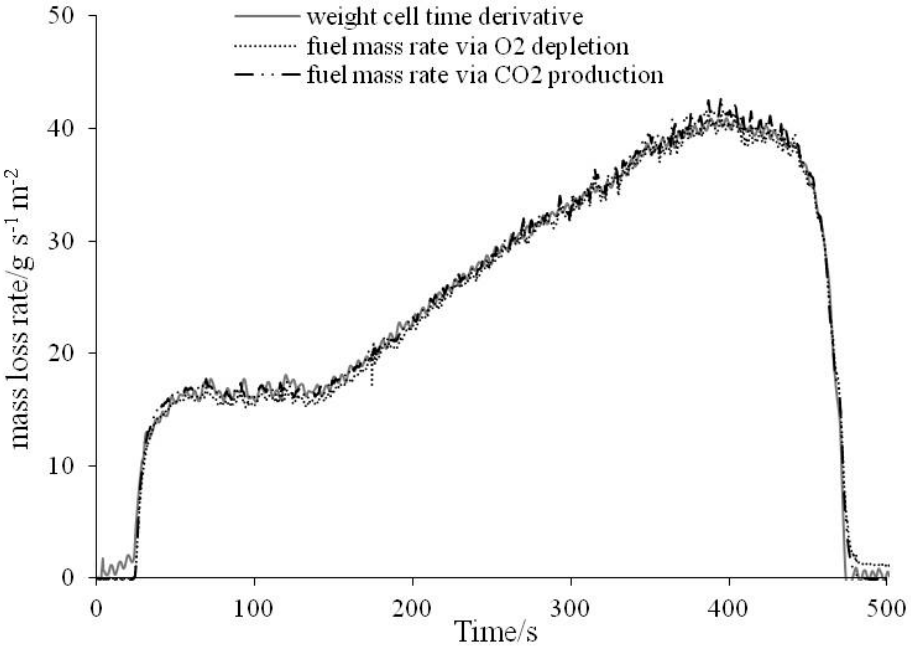


**Fig 2** Comparison of fuel mass rate between gas analysis and weight cell time derivative.

From Equation 1 we found we can derive further properties of the fuel combusted. Consider a volatile composition of fuel (tar), water vapor and carbon dioxide, $C_{X'}H_{Y'}O_{Z'}N_US_V + mH_2O + nCO_2$. The ratio of molar carbon content of the fuel mixture to its stoichiometric molar consumption of oxygen gas is derived as,

$$r_c = \frac{X'+n}{V + X' + Y'/4 - Z'/2} \cong \frac{\frac{\beta_{CO2}}{44} + \frac{\beta_s}{12} + \frac{\beta_{CO}}{28} + \frac{\beta_{CHw}}{12+W}}{\frac{\beta_{O2}}{32} + \frac{\beta_s}{12} + \frac{1}{2}\frac{\beta_{CO}}{28} + \frac{(1+W/4)\beta_{CHw}}{12+W}} \equiv \frac{8\beta_{CO2,st}}{11} \quad (2)$$

Betas are merely the mass ratio of combustion product changes to oxygen depletion mass. We note that carbon fuel loading (Equation 2) is independent of water content in any form because parameter m is factored out of Equation 2. Carbon fuel loadings calculated for hydrogen gas, methane, propane, polystyrene, carbohydrates, carbon monoxide, carbon dioxide from Equation 2, are respectively 0, 1/2, 3/5, 4/5, 1, 2, and 4 regardless of the $H_2O$ content. Therefore, the use of carbon fuel loading can assist in identifying fuel, even when combustion becomes incomplete. Suppose that during a test

period, the measured water vapor, excess nitrogen gas, sulfur dioxide, and *THC's* are attributed only to material pyrolysis. Using Equations 1 and 2, further fuel properties are derived as,

$$\frac{Y}{X}=\frac{Y'+2m}{X'+n}=\frac{[\dot{m}_{H2O}/9+W\dot{m}_{CHw}/(12+W)]}{\frac{\dot{m}_{CO2}}{44}+\frac{\dot{m}_s}{12}+\frac{\dot{m}_{CO}}{28}+\frac{\dot{m}_{CHw}}{12+W}}\cong\frac{[\beta_{H2O}/9+W\beta_{CHw}/(12+W)]}{\frac{\beta_{CO2}}{44}+\frac{\beta_s}{12}+\frac{\beta_{CO}}{28}+\frac{\beta_{CHw}}{12+W}} \quad (3)$$

$$\frac{Z}{X}=\frac{Z'+m+2n}{X'+n}=2+\frac{2V}{X}+\frac{Y}{2X}-\frac{11}{4\beta_{CO2,st}} \quad (4)$$

For wood, the stoichiometric net heat of combustion (kJ $g^{-1}$) is correlated closely as [11],

$$h_{c,st}=13.23r_o \quad (5)$$

$$r_o=(32X+8Y-16Z)/(12X+Y+16Z+14U+38V) \quad (6)$$

Polystyrene, $C_8H_8$ , ($r_0$=3.077), has the value 12.93 instead of 13.23 in Equation 5. Indeed, carbon solid and carbon monoxide fuel has further deviations, such that the heat release due to incomplete combustion (producing C and CO from oxidizing the organic carbon) has the adjustment to Equation 5 as [11],

$$HRR=13.23\Delta\dot{m}_{O2}-2.54\dot{m}_{CO}+2.48\dot{m}_s \quad (7)$$

The holocellulose, as the major component, is made up mostly alpha cellulose, mannan, and galactan that has the empirical formula, $C_6H_{10}O_5$ , ($r_0$=1.185), while minor components are xylan and arabinan with a slightly different empirical formula. Its heat of combustion via Equation 5 is in agreement with the measured value for fully volatized holocellulose [11]. An empirical formula of lignin can be used as $C_9H_6O_2(H_2O)(OCH_3)_{4/3}$ , ($r_0$=1.74), which also has net heat of combustion via Equation 5 in agreement with that measured for fully volatized lignin [11]. In the case of extractives, monoterpenes is the main component with empirical formula, $C_{10}H_{16}$, ($r_0$=3.294), which is consistent via Equation 5 for the net heat of combustion [11]. This also predicts that Equation 6 is linearly related to mass fractions of extractives, holocellulose, and lignin for any wood material and was established to a high correlation [11]. If any of the constituents are also charring, then its corresponding volatiles have a differing empirical composition than that of the virgin material, due to retaining the carbon into the char. As a result, the net heat of combustion of wood volatiles is not straightforward, requiring the techniques offered by the use of Equations 1 to 6. Therefore, for all samples the composition ratios of $r_c$, *Y/X*, *Z/X*, and $r_o$ as a

function of time will be discussed in the context of improving flammability performances with fire retardancy.

# Results and discussion

### Heat release rate (HRR) of panels with three surface layer variations

The potential fire hazard of a combustible material can be indicated by the heat release rates (HRR). Figure 3 shows the HRR profile, as computed with Equation 7, having the dual peak HRR profiles. The first peak is the result of ablating initially the surface exposed to a combined cone heater and flame radiance on the surface. The HRR then decreases as a result of surface charring and the thermal wave process following the ablative process. In essence the pyrolysis front develops and is decreasing in speed, and with the char density staying constant, the volatization mass rate is also decreasing. Since the volatile heat of combustion is fairly constant for initially dry wood (as shown later in Figures 6, 9, and 12 during dry portions of particle board volatization), the HRR is also decreasing [11, 12]. The HRR eventually begins to rise as a result of the thermal wave termination at the insulated rear surface, which means the sample is entering the thermally thin regime, and broadens and speed up the thin pyrolysis zones. For a surface layer sufficiently thin and backed by an insulation board such as EPS, the dual peaks in the HRR merge together into a single initial peak, such that the surface is treated as thermal capacitance that control the heating process, and thus the pyrolysis process [9]. However, since there is a second, backside surface layer of particle board, it is just a matter of time after the EPS has fully melted and charred remains of the exposed surface layer heats the backside surface layer by contact or radiation. Further volatization occurs when the backside particle board reaches its volatization temperatures after a period of heating. The glowing from the infusion of air takes over at some point, and as the material is consumed the HRR will decrease once again. More detailed measurements developed for this study is presented in later sections to explain further this pyrolysis process.

Indeed the size of a fire is correlated positively with the HRR and the HRR will in turn increase as the fire is spreading, unless the HRR can be made to decrease rapidly enough (burnout) or be kept to a low value to counter the increase in pyrolysis surface area [13]. That is, fire retardancy would serve its purpose by preventing fire growth rather than merely preventing ignition. The other factor is that the ASTM E84 test lasts

10 minutes, so that only the first 600 seconds of the cone calorimeter test is only relevant. In addition, the ASTM E84 specimen is backed by a heavy cement board that will absorb heat from the exposed specimen (the thermal wave moves on through rather than terminating), thereby drastically reducing the second HRR peak [13] and extending the period of glowing. However, there are real world fires in which the insulation backing is more the norm.

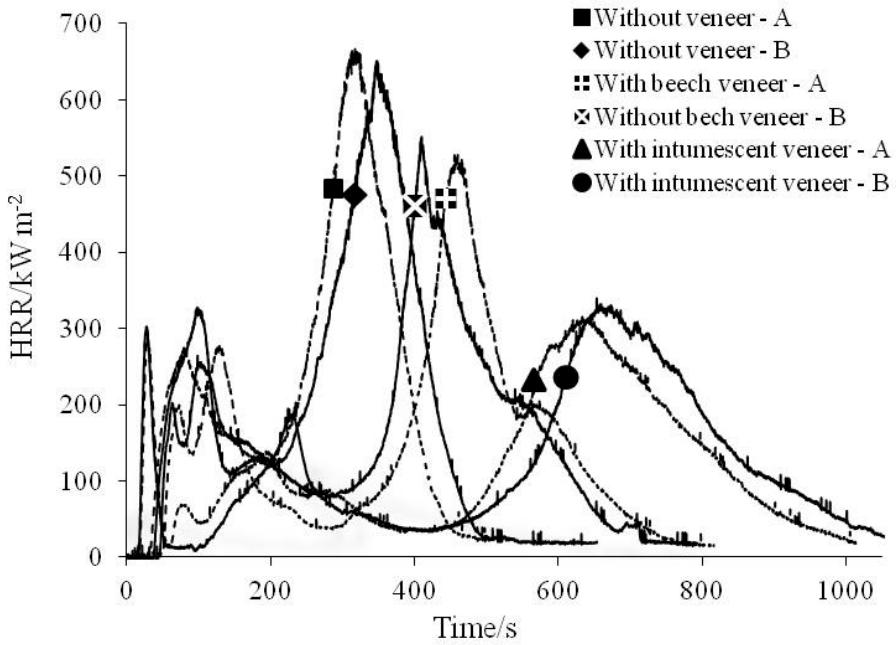


**Fig 3** Comparing sandwich panel HRR with three surface layer constructions.

It is seen that some reduction of the HRR profile in Figure 3 is obtained with the beech veneer adhered with Firobond Ultra Adhesive by EnviroGraph (FUA) to both sides of the sandwich panel, whereas the second large peak HRR peaking at 450s is both decreased and delay and some HRRs are now observed beyond 600s. However, the use of the veneer with intumescent paper (ES/MP/DK by Intumescent Systems LTD) adhered with FUA to both sides of the sandwich panel, has decreased HRR overall and the majority of the HRRs are now greater than 600 s. The repeated tests confirmed this result. The HRR profiles that are most amenable to analytical fire growth modelling are that of exponential decay function, for predicting the flame spread rating for the ASTM E84 test method that was successful with oriented strand boards (OSB), treated and untreated. Since the second large HRR peak can be ignored because of the heavy backing board, the closer attention to the first peak is targeted for this exponential decay function approximation. Wood products with peak HRR around 300 kW $m^{-2}$ are known as Class C materials [13]. If the initial narrow peak HRR for the intumescent veneered panel is also ignored in Figure 3, then a fitted exponential decay has the PHRR lowered

to 100 kW $m^{-2}$, ignition time increased to 55 s (using a high density veneer), and the total heat release (THR) remaining at 117 MJ $^{m-2,}$ should predict a Flame Spread Index in Class A category [13]. Further investigations with targeted variations of the surface layer should have merit.

## Pyrolysis mechanisms of panels with three surface layer variations

The thermal conductivity of the EPS foam strongly affects the fire performances. Due to its low thermal conductivity expanded polystyrene foam acts as a protective layer underneath of the woody surface layer. This leads to an intensive heating of the surface layer [5]. Accordingly, an increased first peak of heat release rate significantly higher than that of conventional particleboard does occur. After surface ignition (and prior to the point of PHRR at 30 kW $m^{-2}$) char formation starts, and the volatile emission rate is affected by the speed of the pyrolysis front propagating into the wood-based material. While the surface layer is burning the foam core layer first melts and then starts volatizing. The foam does not char and its volatiles with its corresponding higher heat of combustion begin to be added to that of the wood volatiles. This can be detected also with thermocouples by which polystyrene decomposition is indicated when temperatures around 350 °C are reached. At this time the pyrolysis zone reaches the back face of the samples and causes so called the thermal feedback effect [3]. The second Peak HRR is due to the volatizing of the foam and the back surface layer, and also to a transition to glowing, which is seen by heat of combustion approaching 30 kJ $g^{-1}$ or $r_o$ reaching 2.67 to correspond with pure carbon (ie. the char becomes mostly carbon, but will not combust until the air is able to penetrate after the volatiles has ceased emitting). Because of the challenge posed by the presence of the EPS foam core, a fundamental study was made of panel with three layer variations as reported here.

### *Mass loss rate, temperature profile, and volatile features of panel without veneer*

For the sandwich panel without veneer, it is seen that fuel mass rate derived from the gas analysis using Equation 1 to be in agreement with the weight cell time derivative for combustion times after ignition in Figure 4. This figure shows the dual peak feature noted for the corresponding HRR profiles. The temperature profiles in Figure 5 demonstrate the insulation capabilities of the exterior board only lasted for 100

seconds before the EPS settled at the highly degrading temperatures around 500 $^{o}$C until glowing began. The composition features shown in Figure 6 makes apparent that significant water evaporation (high *Y/X* and *Z/X* ratios) occur at the beginning and at 150 seconds. Thus during the time up to 150 seconds the free moisture moved to the back side under temperature gradient, and when the heat became available after the collapse of the EPS foam, the accumulated moisture evaporated in large amounts that was able to dilute the volatiles to cause a temporary reduction in $r_o$ (also net heat of combustion) values. The carbon loading remains close to unity, verifying that the volatiles and glowing char have carbohydrate-type empirical form. Finally the ratio *Z/X* goes to zero and *Y/X* goes to unity while $r_o$ values are reaching 2 or beyond at the time 325 seconds that indicates glowing combustion of highly carbonized char.

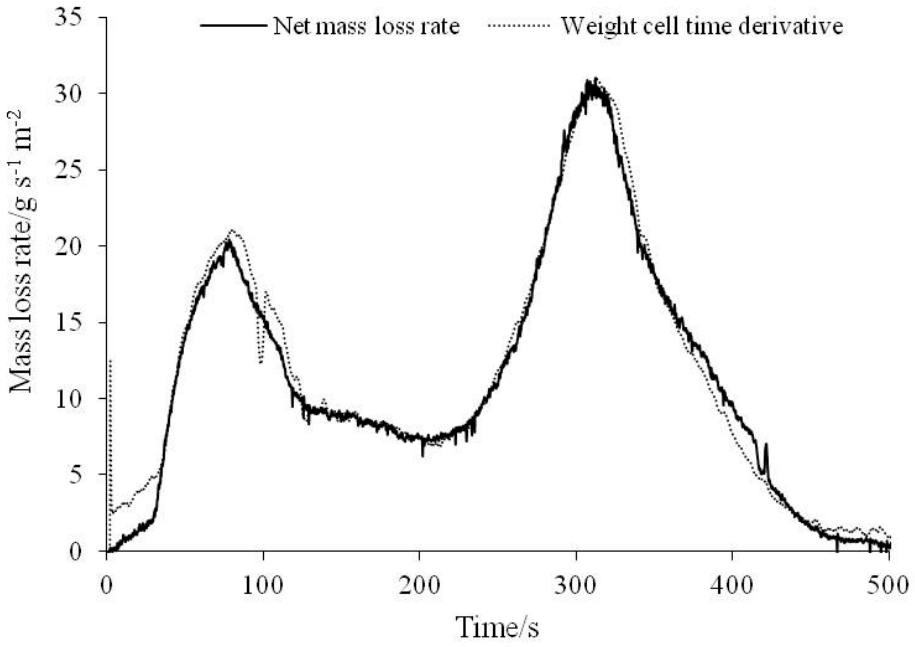


**Fig 4** Using Form 6 of Equation 1 to calculate fuel mass rate in agreement with weight cell time derivative for un-veneered samples.

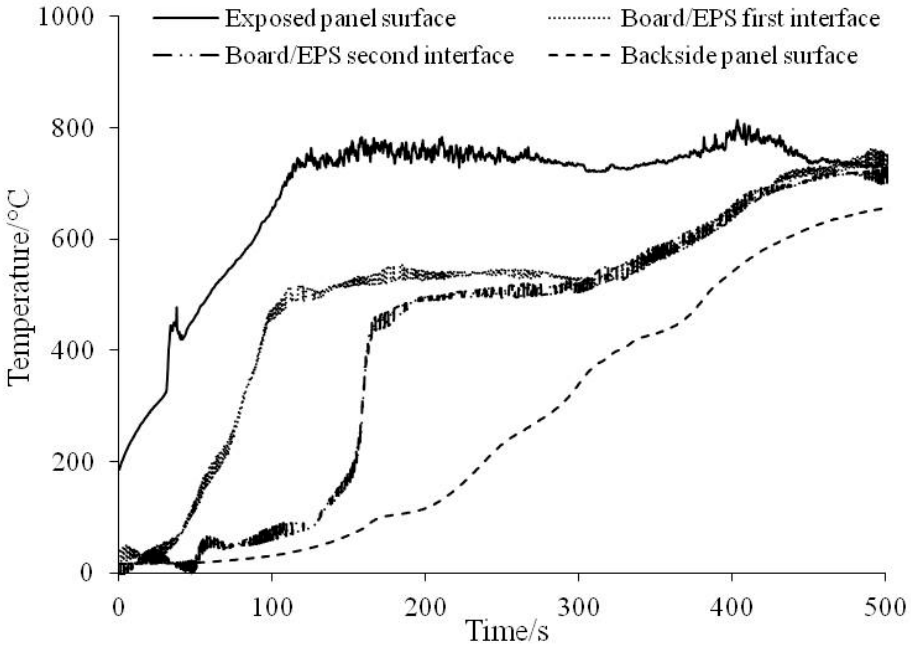


**Fig 5** Temperature measurements at various depths for un-veneered samples.

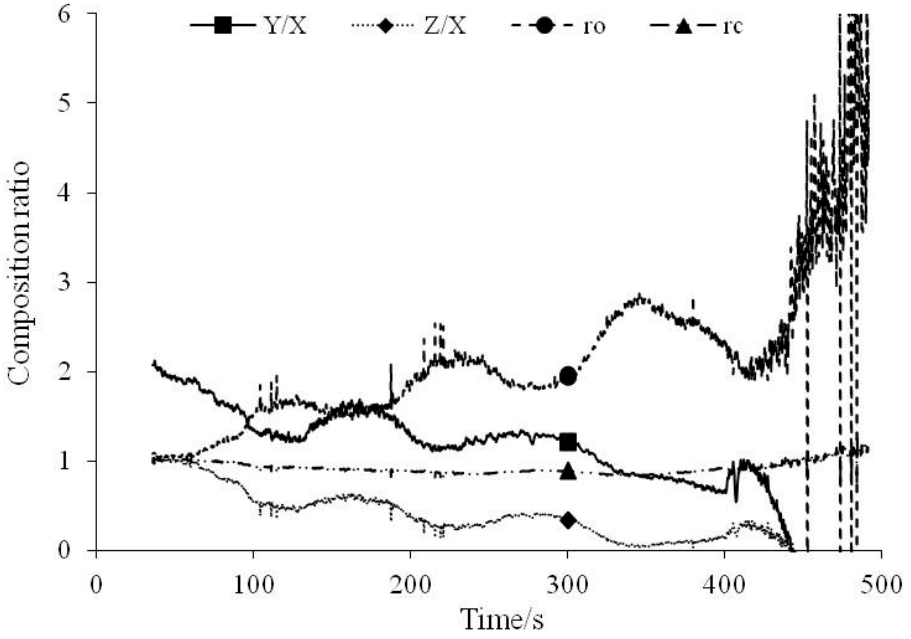


**Fig 6** Derived empirical compositions of pyrolysis for un-veneered samples.

### *Mass loss rate, temperature profile, and volatile features of panel with beech veneer*

For the sandwich panel with the beech veneer we likewise get good predictions of the fuel mass rate with the gas analysis, and Figure 7 shows a triple peak feature as also seen in the corresponding HRR profile. It is seen that nearly all pyrolysis still occurred within 600 seconds corresponding to ASTM E84 test time. Temperature profiles in Figure 8 still show the EPS degrading at temperatures around 450 $^{o}$C beginning at time 150 seconds. The empirical composition of the volatiles at 150

seconds in Figure 9 possibly shows the presence of EPS volatiles (carbon loading less than one and $r_o$ peaking), while the evaporation of water that has piled up towards the backside occurred at 250 seconds (quite high values of *Y/X* and *Z/X*), and finally the glowing combustion sets in at the time 500 seconds (*Y/X* approaching one, *Z/X* approaching zero, carbon loading slightly less than one, and $r_o$ approaching 2 and higher). However, this is not much improvement in flammability properties.

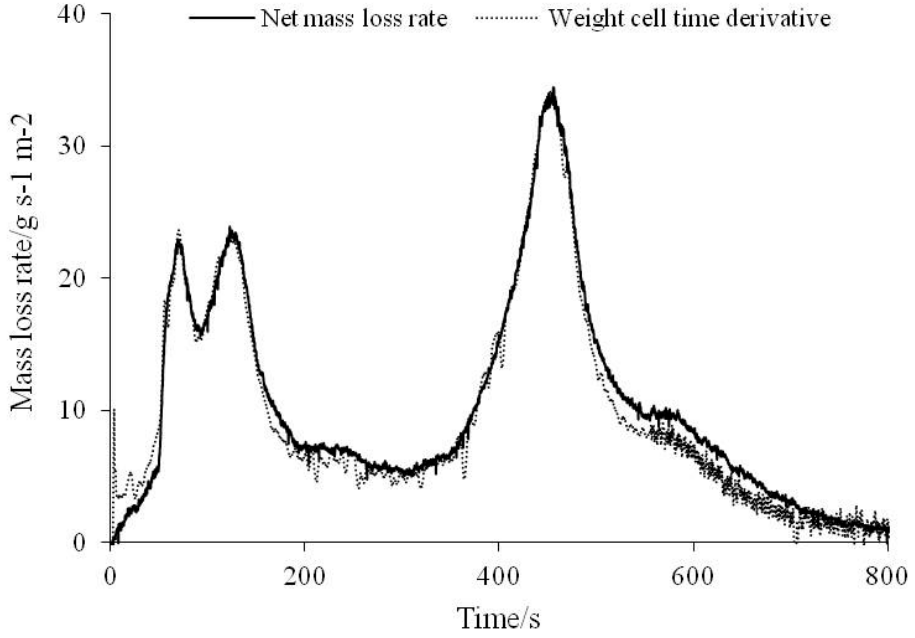


**Fig 7** Using Equation 1 to calculate fuel mass rate in agreement with weight cell time derivative for panel with beech veneer.

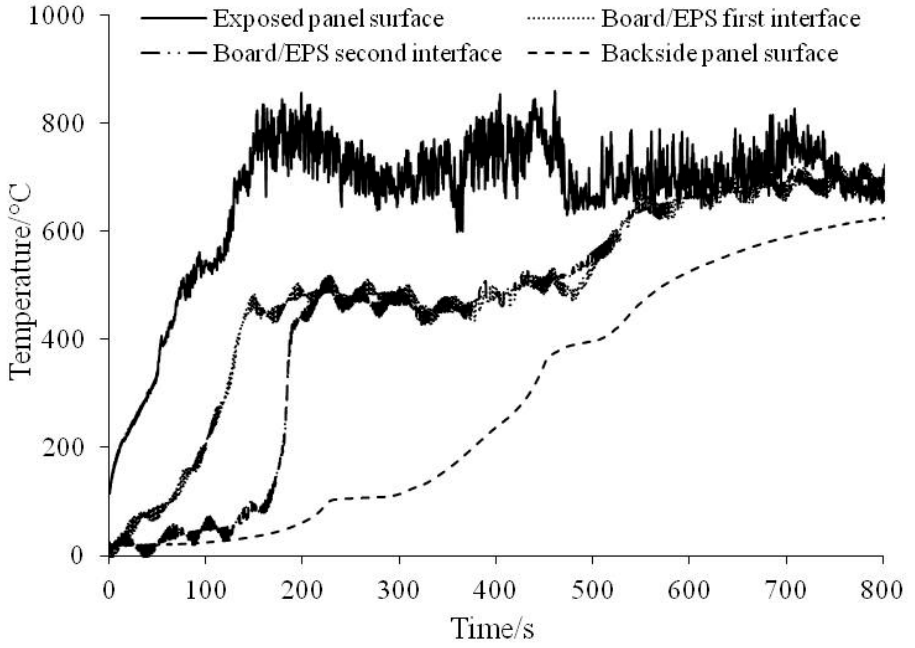


**Fig 8** Temperature measurements at various depths in the panel with beech veneer.

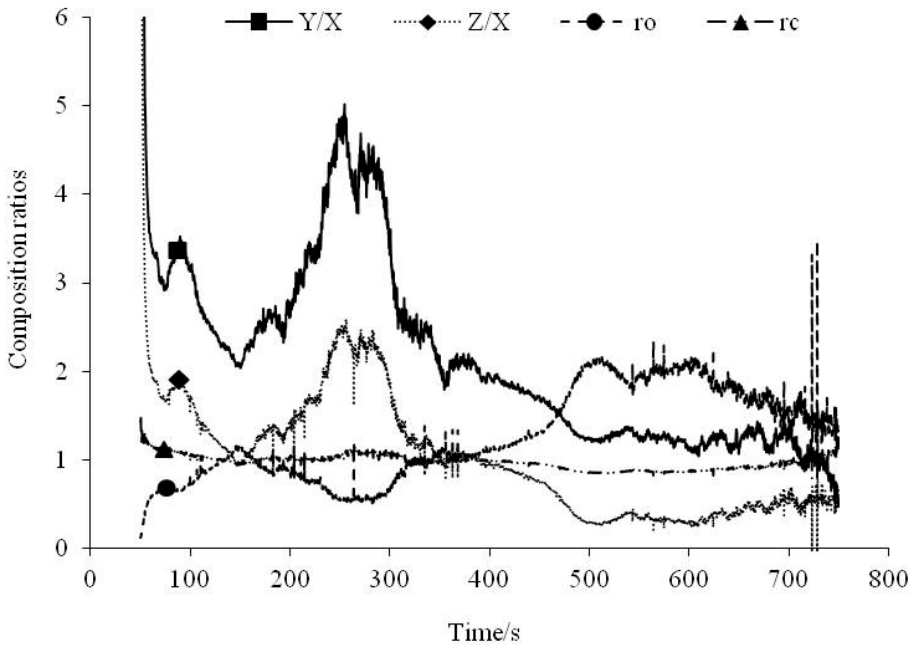


**Fig 9** Derived empirical compositions of pyrolysis for panel with beech veneer.

### *Mass loss rate, temperature profile, and volatile features of panel with intumescent veneer*

For the sandwich panel with intumescent veneer paper, once again good agreement of the fuel mass rate from gas analysis with the load cell time derivative is obtained in Figure 10, and it is seen that more of the pyrolysis is occurring after 600 seconds, thereby effectively reducing the HRR contributing to the ASTM E84 test environment. The temperature profiles shown in Figure 11 show that EPS remained below the degradation temperature of 350 $^{o}$C at times up to 600 seconds. In the empirical composition plots shown in Figure 12, it is apparent that glowing began around 500 seconds. It is seen from the high values of *Y/X* and *Z/X* at ratios of four and two respectively showed the moisture contribution from the intumescent paper up to 200 seconds. At 300 seconds is another incident of water evaporation from the moisture driven to the panel backside via temperature gradients. At times surrounding 200 and 400 seconds, the *Y/X* is about 2, and *Z/X*, $r_o$ and $r_c$ are around 1, all of which are closely the features of wood pyrolysis without water vapour and EPS volatiles.

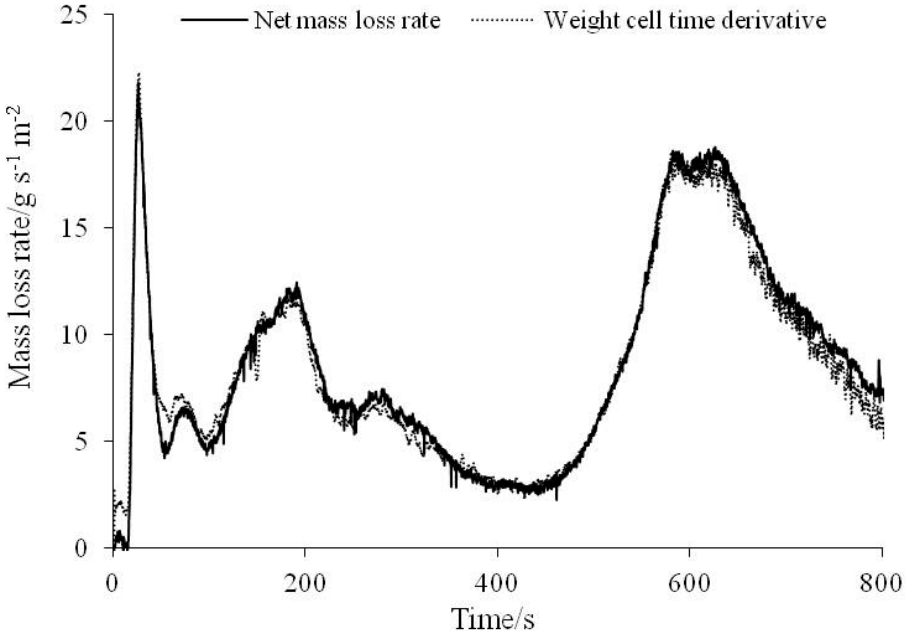


**Fig 10** Using Equation 1 to calculate fuel mass rate in agreement with weight cell time derivative for panel with intumescent veneer.

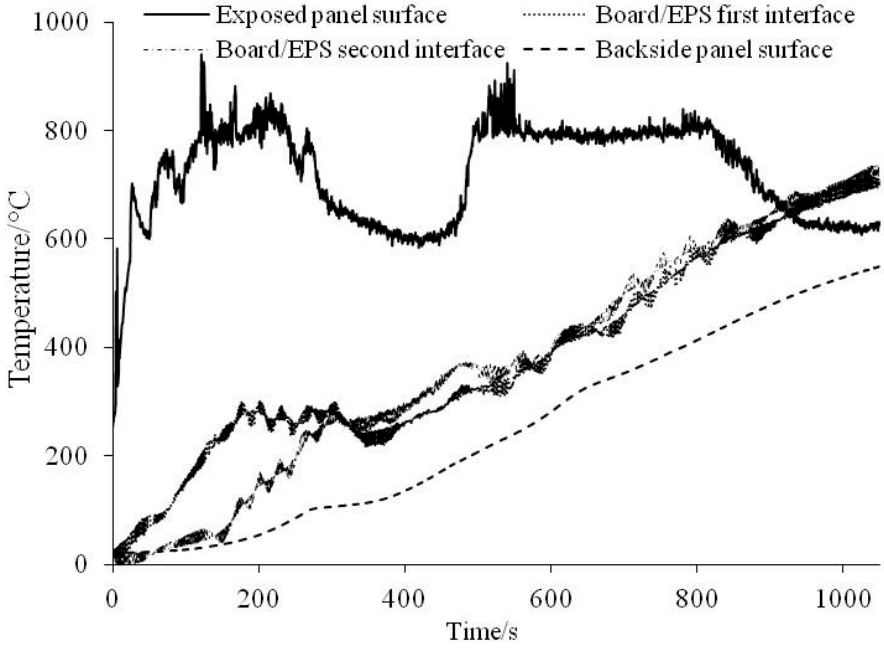


**Fig 11** Temperature measurements at various depths of the panel with intumescent veneer.

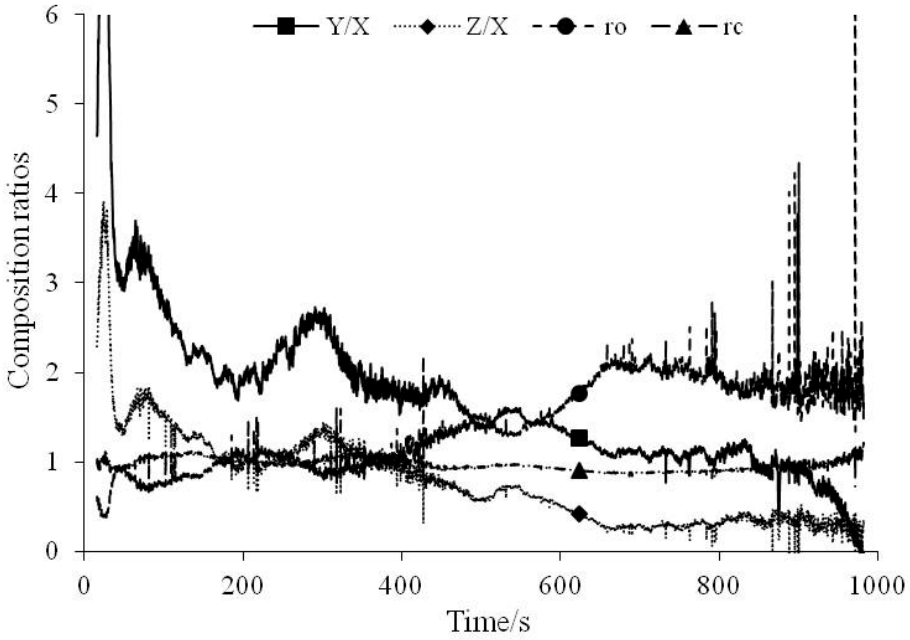


**Fig 12** Derived empirical compositions of pyrolysis for panel with intumescent veneer.

## Conclusion

In order to assess novel sandwich panels with fire retardant improvements, advanced cone calorimetry techniques were devised to analyse flammability properties. Improved heat release rate calculations were devised. Four thermocouples attached to the specimen at the various depths were used to determine the physical state of the EPS foam core that defined softening, melting, decomposition, and ignition. A state-of-art gas analysis procedure was devised to determine composition features of panel pyrolysis, which resulted in validating the calculations of empirical composition of the volatiles as *Y/X* and *Z/X*, and of carbon loading and oxygen mass to fuel mass ratio. These various analytical procedures were used to evaluate sandwich panels that had (1) surface layer without veneer, (2) surface layer with beech veneer, and (3) surface layer with veneer-intumescent paper composite. HRR of the both samples with beech veneer and intumescent paper is lowered and delayed, significantly for the samples with intumescent paper. The cone calorimeter tests at 50 kW $m^{-2}$ show that the veneer-intumescent paper composite protected the core EPS foam from degrading, as well as seal and dilute wood volatiles in the early stages of pyrolysis, to where it may be possible to achieve a Class A flame spread rating. Although we used the measured $O_2$, $CO_2$, CO, $H_2O$ and soot mass flow rate in determination of the pyrolysis properties, they were not presented directly in this paper, as they will be reported in a future

publication in which several datasets are utilized, in contrast to the fundamental study for this work.

## Acknowledgment

The authors wish to thank Dr. Robert White and Carol Clausen of the Forest Products Laboratory for their support of this research, and to technician Ms. Anne Fuller for collecting the data. We also thank Hamburg University and Ministry of Science, Research & Technology of Iran for financial support of this work, and of Dr. Luedtke for support of this research. The work was performed by the United States employees on official time and is not subject to copyright.

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# Additional Publications

# IX

# 53rd International convention of society of wood science and technology, Geneva, Switzerland (2010)

**Ali Shalbafan**
Jan Luedtke
Johannes Welling
Heiko Thoemen

*Proceedings of the International Convention of Society of Wood Science and Technology and United Nations Economic Commission for Europe – Timber Committee*
*October 11-14, 2010, Geneva, Switzerland*

# Multi–layered Lightweight Panels Made by In-process Foaming: Comparison of Core Materials

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**Abstract**

Sandwich panels have been widely used during recent decades. Still, their use in typical wood-based panel applications is limited due to some basic disadvantages. The production has to be done by several processing steps, the density gradient between the layers of multi-material sandwiches is very steep and direct painting of the edges is not possible.
When aiming to produce sandwich panels, the wood based panel industry faces two major challenges: Reducing the density of a panel shall not cause deterioration of its mechanical properties, and products have to stay competitive despite increasing raw material and energy costs. On the other hand, the customers and furniture producers demand for weight-reduced solutionsThe development of an innovative process as presented in this paper allows the production of lightweight foam core sandwich panels in a one step process. Such process includes resource efficient material and energy usage. The panels are manufactured from a three layered mat without additional gluing between the face and core layers. The surface layers comprise of resinated wood particles and the core is formed from an expandable material. Such mat is then processed in a hot press. The press cycle is divided into three phases. The resinated particles in the surface layers are compacted and cured in the first phase. When the temperature of the thermo-sensitive core materials reaches the activation point, the press opens to the predefined distance (final thickness of the panel) to allow core expansion. At this time, the pressing distance is kept constant until the expansion is finished. With the attained experience and the know-how needed for adapting the press parameters, high quality foam core sandwich panels can be made in a one step process.

Lightweight panels have been produced following the above process. Expandable microspheres (MS) and polystyrene (EPS) were used as core materials. The influence of surface thickness and core materials on mechanical and physical panel properties was investigated. In addition, FE-SEM-microscopy and gamma-ray densitometry were used to characterize the panels.

**Keywords** lightweight panel, multi-layered panel, foam core, sandwich, one-step process.

## Introduction

A wood-composite sandwich panel comprises two identical face sheets which are separated by a thick and light core material. The faces are bonded to the core material to obtain a load transfer between the components (Vinson 1999). Actually, sandwich panels are not new products, since they have been used and showing widely growth mainly in construction, aerospace and furniture industries during few recent decades. Numerous approaches have been made to save weight, since the costs for raw materials and energy have been rapidly increasing recently. In addition, sustaining the mechanical properties of the produced panels in a desirable range for certain usage is the critical point of view (Wang et al. 2008).
The variety of wood-based sandwich panels basically depends upon the configuration of the different type of core material (irrespective of the face material constituents). Developing core materials also has continued from the 1940s through to today in an effort to reduce the weight of sandwich panels (Zenkert 1997). The main benefits of the lightweight foam core panels for the furniture applications are high strength to density ratio, lighter and easier for transporting and handling products and also cheaper transportation cost (Michanickl 2006).
In this study, the panels are manufactured from a three layered mat without additional gluing between the face and core layers. The surface layers comprise resinated wood particles and the core is formed from an expandable material. Such a formed mat is then processed in a hot press. The press cycle is divided into three phases. The resinated particles in the surface layers are compacted and cured in the first phase. When the temperature of the thermo-sensitive core materials reaches the activation point, the press opens to the predefined distance (final thickness of the panel) to allow core expansion. At this time, the pressing distance is kept constant until the expansion is finished (Luedtke et al. 2008).
This study was performed to get information about the mechanical properties of multi–layered lightweight panels using expandable microspheres (MS) and polystyrene (EPS) as core materials. The objectives of the study were to determine and compare the bending strength, internal bond and specific strength of the produced panels following the above process.

## Materials and Methods

### Facing Materials

For each type of produced panels, resinated wood particles (> 90 % softwood) from a particle board mill were used for the surface layers. The urea formaldehyde resin (BASF) content was 12 % based on oven dry mass of wood. 1 % hardener (Ammonium sulfate) based on solid content of resin was added. The wood particles were resinated by using a

rotating drum-type blender. The final density was calculated as 750 kg/m$^3$ for the surface layers.

**Core Materials**

Two different types of expandable materials were used for the cores. Expandable microspheres (MS) were supplied by AkzoNobel. The activation temperature for the microsphere is 85 ˚C. Since the microspheres are very fine, they have been mixed with unresinated particles for a better mat forming. The amount of unresinated particles was 450 g/m$^2$ in each type of panel. Earlier studies revealed that this amount of unresinated particles only minor-influence on the panel properties (Luedtke et al. 2008).
The second type of core material used was expandable polystyrene granulate (Sunpor). The activation range for EPS lies within 95 - 115 ˚C. Granulate diameter of EPS particles was 0.3 - 0.8 mm. Since the EPS materials can be spread evenly, because of the granulate size, EPS was not mixed with unresinated particles.

**Production of the Panels**

Lightweight panels have been produced following the above process. A laboratory hot press (Siempelkamp, press plate size: 800*600 mm$^2$) was used to produce the panels. The temperature of the press plates was 160 ˚C. As the core temperature reaches the activation point, the press opens to the predefined distance of 19 mm and the core thickness increases steadily. The panels were produced with varying surface thicknesses 3, 4 and 5 mm. For each thickness four panels were produced using the two different core materials. Table 1 shows the composition of the variables.

*Table 1: Composition of variables at the produced panels*

| No | Surface thickness | Core material | Target density kg/m$^3$ | Core density kg/m$^3$ |
|---|---|---|---|---|
| 1 | 3 | *MS+ wood particles | 300 | 120 |
| 2 | 4 | *MS+ wood particles | 400 | 150 |
| 3 | 5 | *MS+ wood particles | 500 | 180 |
| 4 | 3 | +EPS | 320 | 124 |
| 5 | 4 | +EPS | 390 | 124 |
| 6 | 5 | +EPS | 460 | 124 |

*MS: Expancel Microspheres 031 DUX40
+ EPS: Sunpor expandable polystyrene Terrapor 4

**Preparation of Samples**

For a better understanding of the panel formation, a determination of the density was conducted using gamma-ray densitometry with measuring steps of 75 µm (Figure 1).
The bending strength tests were performed with a universal testing machine (Zwick-Roell) and the samples were tested at a constant cross head displacement of 8mm/min. For the three point bending test, the samples and tests were conducted in accordance to EN310. Four

samples of 430*50*19 mm for each type of variables were prepared and the module of rupture (MOR) was calculated.

The internal bond strength tests were accomplished according to EN319 using universal testing device (Losenhausenwerk). According to the standard, the samples were prepared on 50*50*19 mm with four repetitions of each variable. All the specimens were allowed to condition for two weeks before testing at 20˚C and 65% relative humidity.

The structure of the interfaces between surface and core layers was characterized using Field-Emission Scanning Electron Microscope (Quanta FEG 250) at an acceleration voltage of 5 kV. The samples have been glued on stubs. The surfaces were sputtered with gold prior to the microscopy work.

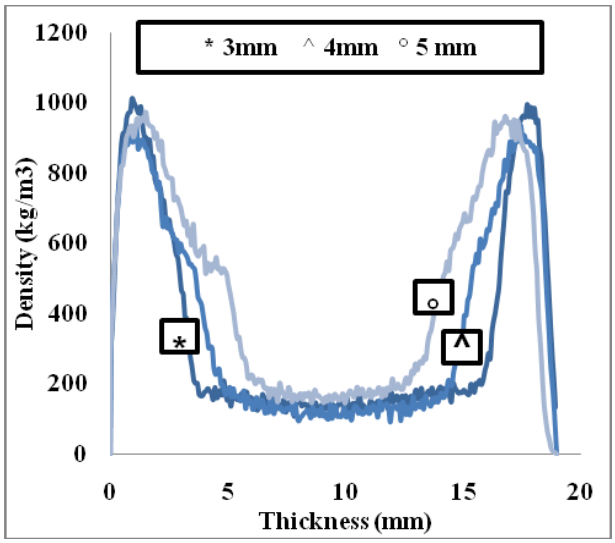
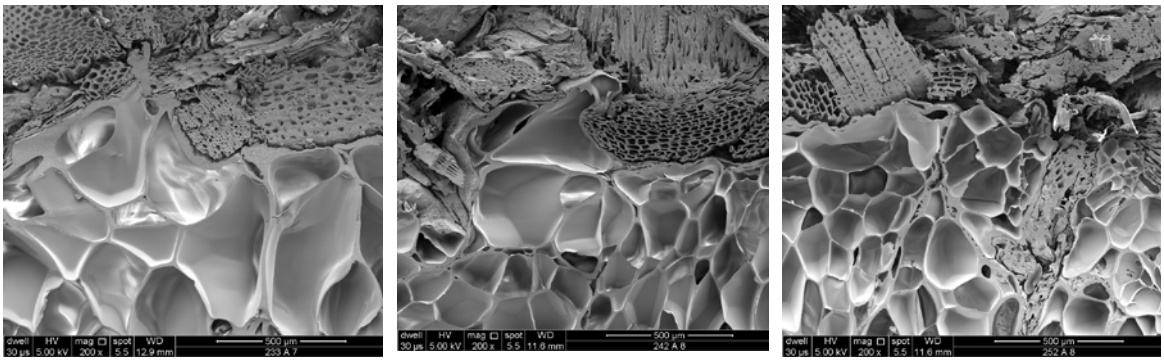



*Figure 1: Density profiles for different surface thicknesses of EPS panels*

## Results and Discussion

In order to investigate the mechanical behavior of the produced panels, mechanical tests were performed. The influence of panel parameters on the properties with varying surface thickness and core materials are reported below. Figure 2 shows the typical microstructure of interphases between foam and particles. With increasing the surface thickness, the gap between core and surface layer is increased. The detailed survey revealed a high compaction density of particles in the panels with a thinner surface thickness.

*Proceedings of the International Convention of Society of Wood Science and Technology and United Nations Economic Commission for Europe – Timber Committee October 11-14, 2010, Geneva, Switzerland*



**[A]** **[B]** **[C]**

*Figure 2: Microstructure of EPS samples with different surface thicknesses A: 3mm, B: 4mm, C: 5mm*

**Bending Strength (MOR)**

Three point bending experiments were performed. The resulting bending strength is shown in Figure 3. It can be seen that with increasing surface thickness, the bending strength is steadily raising 6.5 N/mm$^2$ for 3 mm to 12 N/mm$^2$ for 5 mm face thickness of MS-core sandwich panels and from 8.3 N/mm$^2$ for 3 mm to 10.9 N/mm$^2$ for 5 mm surface thickness for EPS-core sandwich panels**,** respectively.

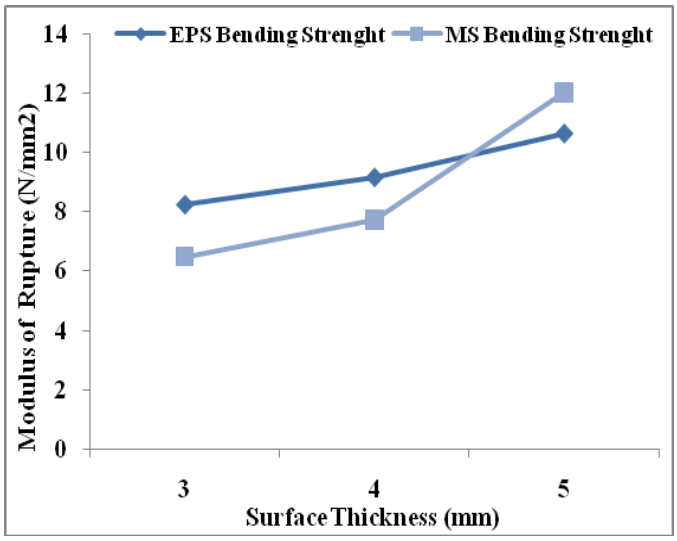



*Figure 3: Results of the bending strength tests with different core materials*

The results revealed that bending strength in the panels with polystyrene foam core with 3 mm and 4 mm surface thickness is 27.7 % and 19.5 % higher than that with microspheres core, respectively. Bending strength of 5 mm MS panels is 12 % more than that of the corresponding panel with EPS core. This can be due to higher density of the MS panel (11.6 %) and higher core density (45 %) at this variable (5 mm MS panels) when compared to the corresponding EPS samples. Since the core density increased, unresinated particles acted as localized agents that cause a stronger link between the foam cells and accordingly lead to a higher bending strength.

Since EPS foams are quite rigid, most of the EPS samples failed because the tensile stress in the lower face exceeds the maximum allowable stress. Just in some samples with 5 mm face thickness, the crack formation was observed in the interface between foam and particles. On the contrary, with the increase of surface thickness in the samples with microspheres, the failure mode changed from shear failure at the upper interface to tensile failure in the lower face. According to EN312, minimum requirement for standard particleboard is 11.5 N/mm$^2$ MOR.

**Internal Bond (IB)**

The results of Internal Bond test are shown in the Figure 4. The average values for MS panels with 3, 4 and 5 mm surface are 0.17, 0.21 and 0.28 N/mm$^2$, respectively. As it can be seen, with the increased surface thickness, the internal bond for MS panels raised about 65 % from 3 to 5 mm surfaces. With increased face layer thickness in the case of MS-type panels, the density of the core increases which results in a higher internal pressure during the expansion phase. An increasing internal pressure causes a better interface between foam and particles and also higher internal bond values.

The values of internal bonding for EPS-type panels declined about 240 % from 3 to 5 mm surfaces. These values reached from 0.36 N/mm$^2$ to 0.15 N/mm$^2$ as the surface thickness increased from 3 to 5 mm. This is attributed mainly to the weaker interface of EPS samples when the surface is increased (Figure 2). Enhanced interface connectivity between particles and polystyrene with 3 mm surface was observed, which is believed to play an important role on internal bond values. The IB requirement is 0.24 N/mm$^2$ for general-purpose particle boards following EN312.

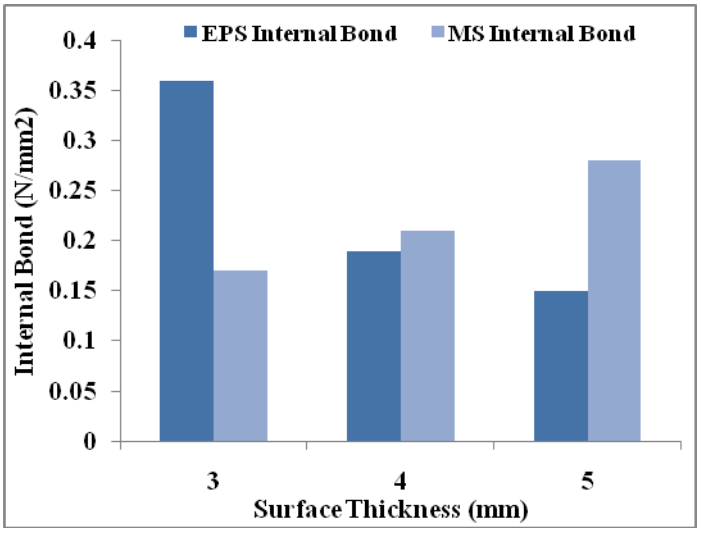



*Figure 4: Results of the internal bonding tests with different core materials*

**Specific Strength**

One of the most important reasons to use multi-layered lightweight panels is that they provide a high strength to density ratio. Values listed in Table 2 clearly demonstrate that high specific bending strength and high specific internal bond of foam core panels can be assumed when compared to normal particle board with the same thickness.
A comparison of corresponding specific strengths for EPS and MS-type sandwich panel was performed. The results show that there is a significant increase of specific strength for EPS panels in comparison with MS panels. The relationship between these parameters can be explained more clearly by comparing the microstructure.

*Table 2: Results of the specific bending strength and internal bond tests*

| | **3-MS** | **4-MS** | **5-MS** | **3-EPS** | **4-EPS** | **5-EPS** | ***PB/P1** |
|---|---|---|---|---|---|---|---|
| **Specific bending strength (Nm/kg)** | 20935 | 19325 | 23569 | 25617 | 23589 | 23851 | 16429 |
| **Specific internal bond (Nm/kg)** | 548 | 525 | 549 | 1111 | 512 | 328 | 343 |

*PB/P1: Standard Particleboard for indoor applications

Since the specific strength of foam core panels is higher than that of conventional particleboard, while saving a large amount of mass, the use of this promising type of light weight panel in certain applications seems possible.

## Conclusion and Outlook

Sandwich panels with different type of foam cores can be produced in one-step process. Expandable microspheres (MS) and polystyrene (EPS) were used as core materials. A significant improvement was observed in both bending strength and internal bond of EPS panels, compared to that of MS panels. Additionally, the price for polystyrene is much lower than that for expandable microspheres which makes it economically feasible to use EPS for the production of lightweight foam core panels. It was also found that the specific strength of this type of panels is more than that for conventional particleboard. Accordingly, the use of these novel lightweight panels can offer an alternative for certain applications in the furniture industry.

As a result of further innovation, multi–layered lightweight foam-core panels can in future increasingly be used to replace conventional wood-based particleboards in furniture industries. With a suitable design, structural constructions made of lightweight panels can achieve weight reductions of up to 50 % compared to conventional particleboards, while still maintaining comparable strength. Further developments in materials design processes will lead to even lighter components with strength and stiffness properties that can be optimally adapted to suit the requirements.

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# X

# 1st Think light international conference on lightweight panels, Hannover, Germany (2011)

**Ali Shalbafan**
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Johannes Welling

# Lightweight sandwich panels produced in a one-step process following different pressing schemes

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**Abstract:**

Several years after the development of the first lightweight wood-based panels at industrial scale, the substitution of "heavy" wood-based panels still did not reach its full potential and the production of light panels is not a routine business. In this study, the authors present the behavior of the mechanical and physical properties of light wood-based panels produced with different pressing schemes.

The panels consist of particleboard surfaces and an expandable polystyrene [EPS] based core with densities between 300 and 500 kg/m$^3$. Experiments have been conducted with pressing temperatures of 130 and 160 °C and changing pressing schedules. The mechanical and physical tests revealed that the bending strength [MOR] and internal bond [IB] were increased with decreasing the initial press temperature due to the improved interface between face and core layer. The pressing schedules seem to have no effect on thickness swelling and water uptake after 2 hours submersion in water. The results are compared to conventional wood-based panels as well in absolute as in specific values (density related). The lightweight foam core panels show an overall superior behavior to conventional wood-based panels.

**Key words:** lightweight panel, polystyrene, foam core, EPS, sandwich, continuous process.

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## 1. Introduction

Using lightweight panels is not a new idea but already started several years ago. For a general classification four strategies for reducing the density of the panels can be identified. 1) Wood and annual or perennial plants with low density like poplar, maize, sunflower, hemp can be used to reduce the overall density of the boards by substituting heavier raw materials. 2) For bonding purposes foamed adhesives create low-density spaces between the particles while maintaining the inter-particle connection. 3) The introduction of hollow sections like tubes and paper or plastic honeycombs replaces core material with cells in a variety of shapes and sizes, generally filled with air. 4) The use of sandwich structures with foam core layers breaks up the monolithic panel cross-section and replaces heavy core material by a homogenous lightweight layer [Allen 1969, Gibson and Ashby 1997, Michanickl 2006]. However, there is still a long way to go until novel lightweight panels have substituted a considerably share of the "heavy" wood-based panels. The production of light panels is not a routine business nowadays. But, recent developments in the field of sandwich construction have led to a renewed interest decreasing the weight of wood-based panels.

Major methods for manufacturing sandwich panels are either batch processes where the layers are combined and glued together or where a foaming liquid to form the core material is injected between prefabricated facings in continuous processes [Zenkert 1997]. The absence of simultaneous production of all layers together and some restrictions of production techniques like gluing the separate components which may result in either voids or unbounded areas due to air, and also quality control and dependency of the panel quality on quality of the ingredients are problems related to both methods. A novel approach following the strategy 4) mentioned above allows the continuous production of foam core sandwich panels with wood based facings in a one-stage process in already existing production lines [Lüdtke et al. 2008].

Shalbafan et al [2010] produced integrated lightweight panels using the above mentioned process. They used expandable microspheres and polystyrene [EPS] as core materials and examined the mechanical properties of the panels. For panels produced with EPS and thin surface thicknesses both bending strength and internal bond were significantly improved. Klempner and Frisch [1991] stated that the production process and its parameters are the major important factors which affect the foam structures. This leads to the necessity of deeper looking at the relationship between the process and the resulting product properties.

In the current study, the authors focus on enhancing the performance of the new generation of panels by varying the process parameters. The aim of this study is verifying the mechanical and physical properties of the produced panels with different pressing schemes.

## 2. Material and Methods

### 2.1 Face and Core Materials

The wood particles [> 90 % softwood] for the surface layers were supplied by a particleboard mill. Based on oven dry mass of wood particles, 12 % urea formaldehyde resin [BASF, Germany] and 1 % ammonium sulfate as hardener were mixed with the particles. A drum blender with a rotating shaft, equipped with paddles for breaking-up and distributing the particles helically through the blender drum was used. For spraying the resin a nozzle connected to an air compressor was applied. The target density of the surface layers was calculated to be 750 kg/m$^3$.

The expandable polystyrene granulates [EPS] for the core layers with an activation temperature of 95 - 115 ˚C were supplied by Sunpor Co, Austria. For EPS a glass transition temperature [Tg] of 103 ˚C for EPS was determined. Granulate diameters of EPS particles were in the range of 0.3 - 0.8 mm. The calculated target density for the foam core was 124 kg/m$^3$.

**2.2 Board making**

To produce the 19 mm panels, both the resinated wood particles and expandable polystyrene materials were hand-felted by employing a 600- by 550-mm forming box. The three layered furnish mat was then pressed in a lab-scale single opening hot-press [Siempelkamp, Germany] sustained at the desired temperature. The temperature of the press plates was varied between 130 and 160 ˚C. By controlling the press scheme the simulation of a continuous hot press with a cooling zone can be conducted.

The press cycle comprises three consecutive stages. First, the specific pressure of the press was increased from 0 to 3 N/mm² during the first 10 seconds. Afterwards the specific pressure is kept constant for both compaction and curing of the faces and rising the temperature of core materials up to activation point. In the second step, the specific pressure is reduced from 3 to 0 N/mm² with press opening to the final thickness of the panel. At the same time the core starts to expand. Finally, the stabilization of the panel is done with decreasing the temperature of the core below the glass transition temperature by cooling the press plates.

The panels were manufactured with two different pressing schemes resulting from different pressing temperatures [130 and 160 ˚C] and surface thicknesses [3, 4 and 5 mm]. The major focus lay on the press temperatures which automatically changed the pressing and foaming times of the program. Four replicates were made for each press condition. Table 1 shows the composition of the variables.

Table1 Composition of the panel variables

| Code | Face thickness [mm] | Press temperature [˚C] | Target density [kg/m$^3$] | Pressing time [s] | Foaming time [s] | Stabilization time [s] |
|---|---|---|---|---|---|---|
| **A** | 3 | 130 | 320 | 80 | 45 | 130 |
| **B** | 4 | 130 | 390 | 105 | 45 | 140 |
| **C** | 5 | 130 | 460 | 130 | 45 | 150 |
| **D** | 3 | 160 | 320 | 45 | 10 | 140 |
| **E** | 4 | 160 | 390 | 55 | 10 | 170 |
| **F** | 5 | 160 | 460 | 65 | 10 | 200 |

### 2.3 Experimental procedure

All samples were kept in a conditioning chamber at 65% relative humidity and a temperature of 20 ˚C for approximately two weeks prior to testing. Density profiles for panel characterization and mechanical tests on bending [MOR] and internal bond [IB] were carried out as well as physical tests on properties like thickness swelling [TS] and water absorption [WA] after 2 h immersion in water.

Modulus of rupture [MOR] was determined using a universal testing machine [Zwick-Roell] with a constant cross head displacement of 8mm/min for each sample. The samples and tests for three point bending were performed in accordance to EN 310. Four repetitions of each variation and three samples of 430*50*19 $mm^3$ from each repetition [n=12] were tested.

The internal bond [IB] was determined using a universal testing device [Losenhausenwerk] according to EN 319. According to the standard, three samples of 50*50*19 $mm^3$ were prepared from each panel [n=12]**.**

The dimensional stability of the boards was determined by means of thickness swelling [TS] and water absorption [WA] tests. The thickness swellings and water absorption rates were determined after submerging the samples in distilled water for 2 h at 20 ˚C. The samples were prepared according to EN 317 with the dimension of 50*50*19 $mm^3$.

## 3. Results and discussion

### 3.1 Structural properties

The vertical density profile was determined to get information about the panel formation. A gamma-ray densitometer with measuring steps of 75 µm was used. Figure 1 show the six density profiles of the panels with different surface thicknesses, which were produced by varying pressing schemes.

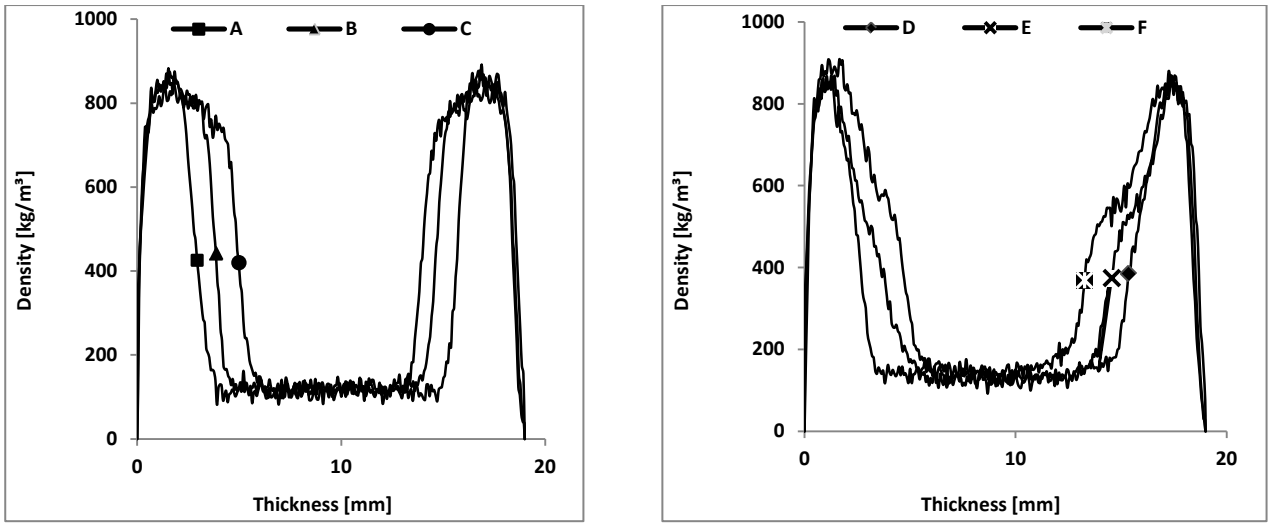



Figure 1 Density profile from EPS-panels produced with different surface thickness and press schemes

The graphs show a highly symmetric density profile for each panel. It is clearly shown that with increasing the facing thickness, the core thickness is equally decreased. A closer examination reveals that the density gradient from the surface to core layer in the D, E and F samples (high pressing temperature) is less pronounced as compared to A, B and C samples (low pressing temperature). This effect is also observed in the interface when surface thickness is increased from 3 to 5 mm, especially in A, B and C samples.

### 3.2 Mechanical properties (MOR and IB)

Modulus of Rupture as a function of sample strength and specific bending strength are shown in Figure 2. The graph shows that with increasing the surface layers from 3 to 5 mm the bending strength is almost linearly increased for all the panels in each of the pressing schemes. The panels [A, B and C] produced with lower pressing temperature [130 ˚C] show bending strength slightly higher than those panels [D, E and F] produced with higher a pressing temperature [160 ˚C]. The average values for A, B and C panels are 9, 10 and 11.5 N/mm² while the corresponding panels pressed with 160 ˚C range from to 8.2 to 9.2 and 10.6 N/mm$^2$. According to EN 312/P2 the minimum requirement of bending strength for general purposes panels is 11.5 N/mm².

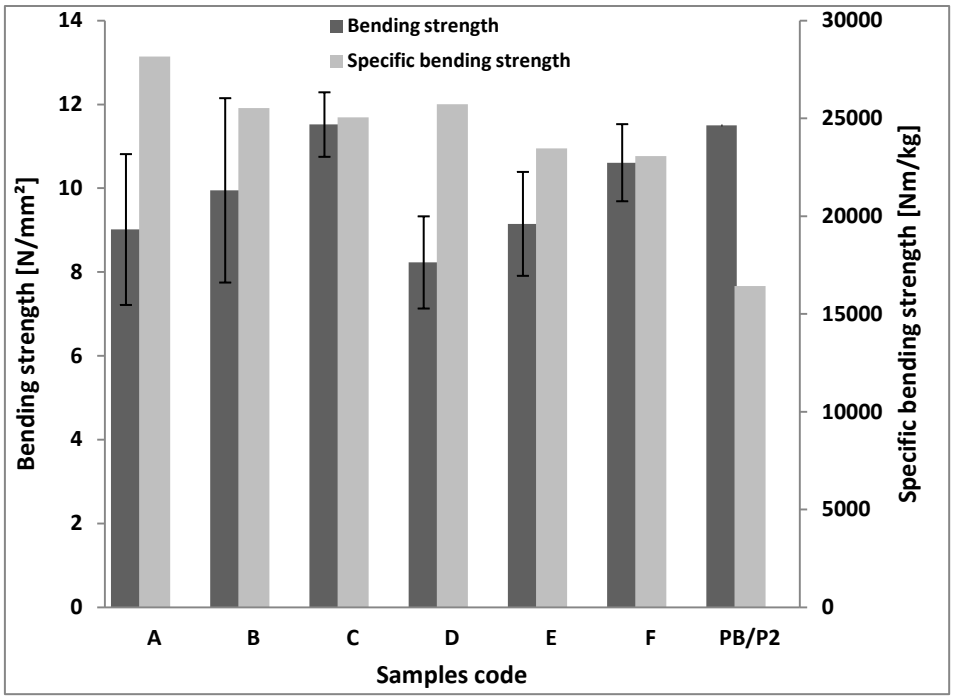



Figure 2 Bending strength and specific value of the samples

Relating the bending strength value to the mean density of the panels leads to specific bending strength which is a frequently used indicator for characterizing lightweight sandwich panels. As it can be observed from Figure 2 the calculated specific bending strength [Nm/kg] from all panels fulfills the specific bending strength of 16400 Nm/kg deducted from EN 312 for standard particleboard with a density of 700 kg/m$^3$. The values for the produced panels in two different

pressing schedules decline with increasing the surface thickness from 3 to 5 mm due to increased mean density.

The bar chart of the internal bond is depicted in Figure 3. A tremendous difference of the internal bond values from panels produced with low pressing temperature is obvious in comparison with panels produced with a higher pressing temperature. When the press temperature is increased from 130 to 160 ˚C the IB values decreased. This can be explained by the longer foaming process at the lower pressing temperature which results in an enhanced interface connectivity between foam cells and face particles. It should be mentioned that the A, B, and C samples broke during the test in the foam core, whereas the majority of the D, E and F samples failed in the interface between foam and face layers. This showed enhanced interface strength in panels produced with a low press temperature. Declining IB values with increasing surface thickness from 3 to 5 mm are due to increased low compacted particles near the interface. This also becomes obvious by lesser pronounced density gradient when comparing the density profiles of the panels [Figure 1].

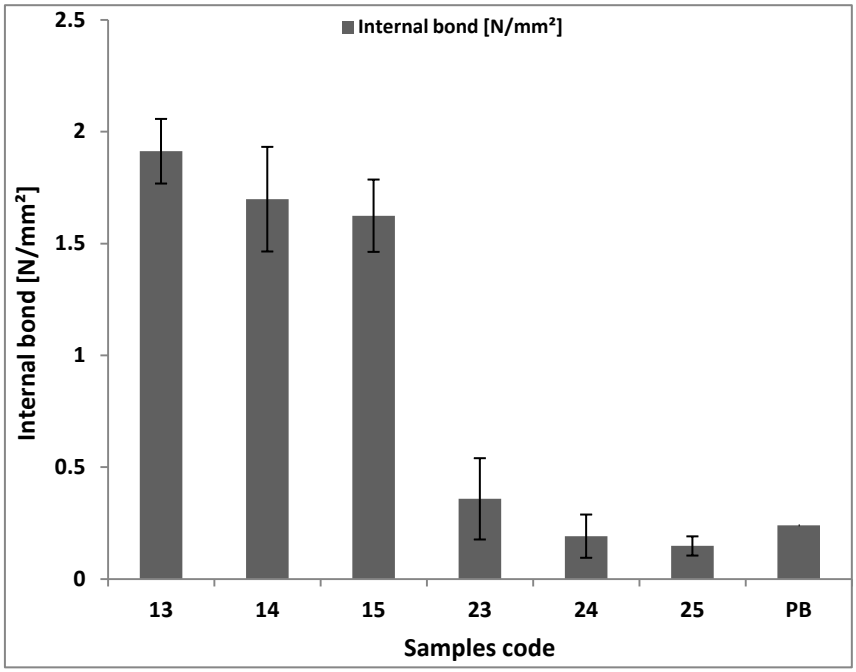



Figure 2 Internal bond average value of the samples

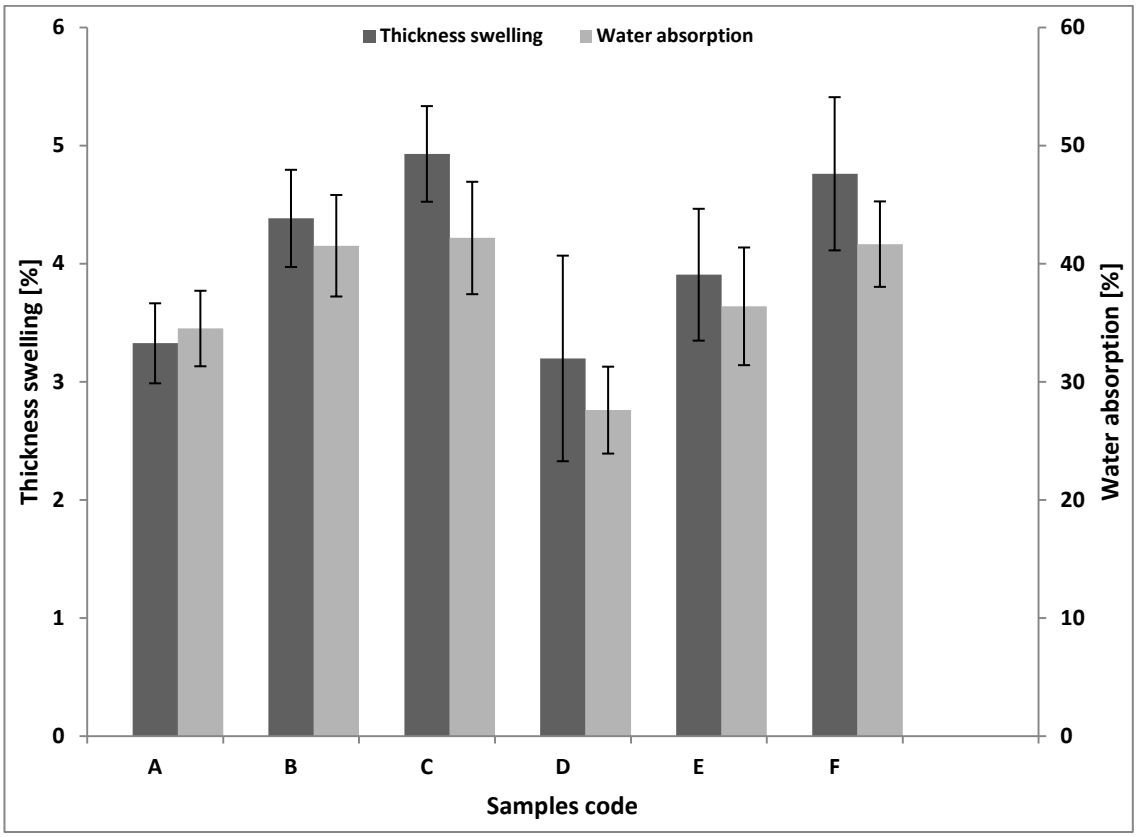
The specific values of the IB are listed in Table 2. Except sample F, other panels fulfill the calculated minimum requirement for specific IB deducted from conventional particleboard. The minimum requirement of internal bond and specific internal bond for conventional particleboard is derived 0.24 N/mm$^2$ and 340 Nm/kg following the EN312, respectively. With increasing density by increasing the surface thickness specific IB is declined. Lightweight sandwich panels offer significantly more strength per unit weight compared to standard particleboards. Using of foam core panels gives an opportunity to save considerable amounts of mass in certain applications.

Table 2 The specific internal bond [Nm/kg] values of the samples

| Samples code | A | B | C | D | E | F | PB/EN312-P2 |
|---|---|---|---|---|---|---|---|
| Specific Internal Bond [Nm/kg] | 5940 | 4460 | 3480 | 1110 | 510 | 330 | 340 |

### 3.3 Physical properties [TS and WA]

The values for thickness swelling [TS] and water absorption [WA] after submersion for 2 hours are summarized in Figure 3. With increasing the surface thickness from 3 to 5 mm, TS and WA are raised due to increasing usage of wooden particles which results in an increased the number of water-attractive hydroxyl groups in the thicker surfaces of the panels. A corresponding comparison of TS after 2 h water soaking shows that there is no difference between the samples with the same facing produced in different schemes. At short immersion time (2 h), the main parameter which is believed to play an important role on the TS is surface layer thicknesses which are alike for both panel types.




Thickness swelling and water absorption after immersion in water [2 h]

The mean water absorption after 2 h for the panels with lower pressing temperature ranged from 35 % for 3 mm to 43 % for 5 mm facing and accordingly for higher pressing temperature from 28 % for 3 mm to 42 % for 5 mm facing, respectively. A similar trend like TS is visible to water absorption. The higher the surface thickness, the higher the water absorption is.

## 4. Conclusion

Low density wood based panels with EPS in the core were produced in two different pressing schemes by changing press temperature and accordingly pressing and foaming times. The results showed that controlling press parameters can lead to different panel characteristics. MOR values are increased by approximately 10 % in panels produced with lower pressing temperature and slower foaming process in comparison with the corresponding panels produced with higher press temperature and faster foaming process.

The most important property that is influenced by the various pressing schemes is internal bond. Lower pressing temperature and accordingly a longer foaming process leads to strongly increased IB values. A longer foaming process gives the possibility for development of a strong interface in A, B and C panels which are believed to play an important role in the IB values.

While the thickness swelling and water absorption increased in all panels with increasing surface thickness, the pressing schedules seem to have no effect on TS and WA after short-term immersion in water [2 hours].

Due to the manifold variables (thickness of facings, density of facing and foam-core layers, pressing parameters) involved in the production of foam core sandwich panels in one single production step, it is difficult to optimize the properties of such panels. Further research is needed to get a better insight in the interactions between material properties, process parameters and the physical and mechanical behaviour of the novel type of wood-based panels.

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# XI

# 65th International convention of forest products society, Portland, Oregon, USA (2011)

**Ali Shalbafan**
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# Effect of Pressing Schedules on Mechanical Properties of Multi-layered Lightweight Panels

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**Abstract**

The use of lightweight panels has been extended considerably over the last decades. Reasons for their success, especially in the field of cash and carry furniture, are not only the low weight, but also improved energy and resource efficiency, design aspects, and easy handling and erection properties of the furniture produced from lightweight panels. The developed technique at Hamburg University to produce lightweight foam core panels in a one-stage process is a milestone for augmenting the production of lightweight panels for the furniture industry.

In this study, foam core sandwich panels were manufactured using resinated wood particles for the faces and expandable polystyrene for the core materials. The effect of the pressing schedule on the produced panels was investigated. Two different press temperatures of 130 ˚C and 160 ˚C for producing panels with three different surface thicknesses were selected which result in changes in pressing and foaming times in the press program. Foam core sandwich panels having the same core densities and different cell structure were produced by controlling the foaming conditions.

Bending strength (MOR) of the panels, produced with the first press program with 130 °C (1-EPS), was approximately 10% higher than the MOR of the corresponding samples produced at 160 °C (2-EPS). The improved internal bond of both types of foam core panels (1-EPS and 2-EPS) in comparison to conventional particle boards and their high specific strength related to density allow a promising outlook of this type of panels.

**Key words:** sandwich panel, polystyrene, foam core, EPS, lightweight, one-step process.

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# Effect of Pressing Schedules on Mechanical Properties of Multi-layered Lightweight Panels

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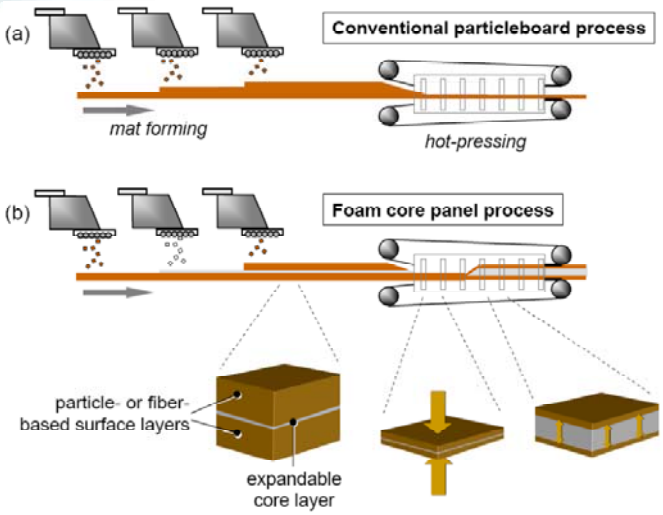
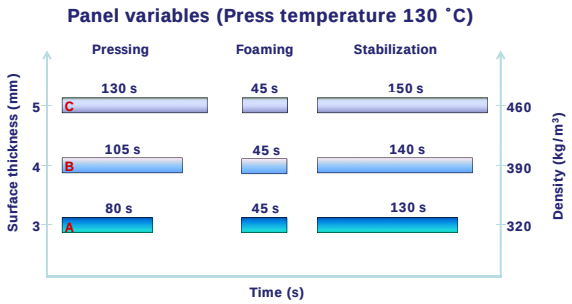
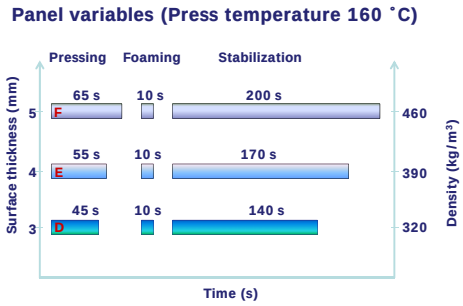
## Background:

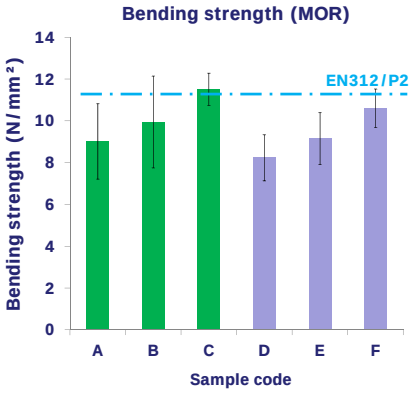
The use of lightweight panels has been extended considerably over the last decades. To produce lightweight foam core panels in a one-stage process a technique derived from particleboard production line was developed at vTi and Hamburg University. This technique can be a milestone for augmenting the production of lightweight panels for the furniture industry. In this research foam core panels were produced using resinated particles as faces and expandable polystyrene (EPS) as core layer. Two press schemes which resulted from varying the press temperature (130 & 160 ˚C) have been implemented to manufacture the panels.



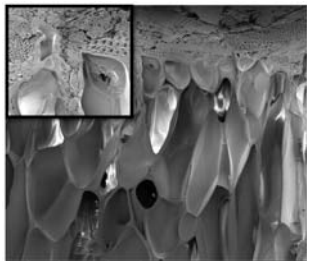




## Results

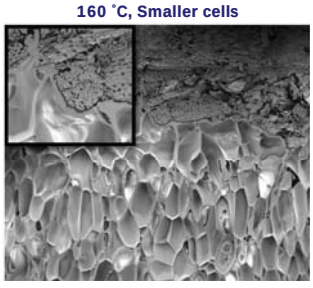


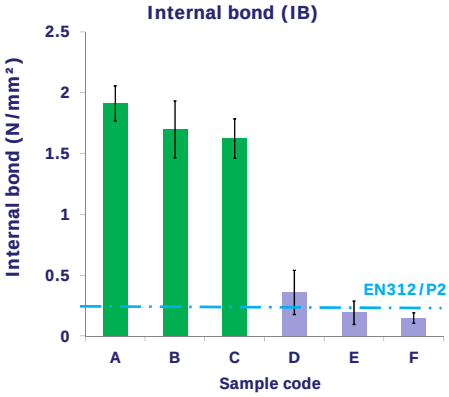

Interface between wood and foam core for different pres temperature,

130 ˚C, Bigger cells



160 ˚C, Smaller cells






## Conclusion & Outlook

- ✓ The introduction of an appropriate foam system and a corresponding pressing scheme can lead to a tremendous enhancement in panel properties compared to conventional particleboard.
- ✓ Panels produced with lower pressing temperature and slower foaming process have approximately 10 % higher MOR.
- ✓ Panels produced by lower pressing temperature showed an enhanced interface with strongly increased IB values.
- ✓ It is possible to reduce panel density by >50% without sacrificing panel properties.
- ✓ Continuously produced sandwich panels can be regarded as a full alternative to particleboard.

# XII

# 5th International wood fibre polymer composites symposium, Biarritze, France (2011)

**Ali Shalbafan**
Johannes Welling
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# Innovative Lightweight Wood Plastic Composites produced in a one-step process

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## Abstract

The use of wood plastic composite (WPC) has grown considerably over recent years. In South-east Asia there is significant interest to use WPC in the furniture industry but the heavy weight and the high price of the solid material of WPC is a disadvantage. Lightweight WPC panels as new solution have the potential to replace heavy WPC panel as well as particleboard in regions with humid environmental conditions. The lightweight innovation from WPC will contribute to more efficiency in energy usage during production and transport while saving a large quantity of weight.

In this research, three layered lightweight WPC panels have been produced in a one-step process without additional gluing between the surface and core layers. For the faces, extruded wood flour mixed with polyethylene with three different wood flour/polyethylene ratios (50/50, 60/40 and 70/30) was used. The core layer is formed by using expandable polystyrene. The three layered mat is hot pressed. The press cycle consists of three consecutive stages. During the first stage, the facings are compacted and formed while the core temperature increases. When the thermo-sensitive core material reaches the activation point, the core is expanded after opening the press to the predefined distance (final thickness of 19 mm). During the last stage, the pressing distance is kept constant until the expansion and stabilization of the panel is finished.

Lightweight WPC panels with a density of 500 kg/m³ have been produced following the above described process. The influence of different wood flour/polyethylene ratios in the faces on mechanical properties of the panels was investigated. FE-SEM-microscopy and gamma-ray densitometry have been done for characterizing the panels.

**Key words:** lightweight WPC, multi-layered panel, foam core, polystyrene, one-step process.

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# Innovative Lightweight Wood Plastic Composites Produced in a One-step Process

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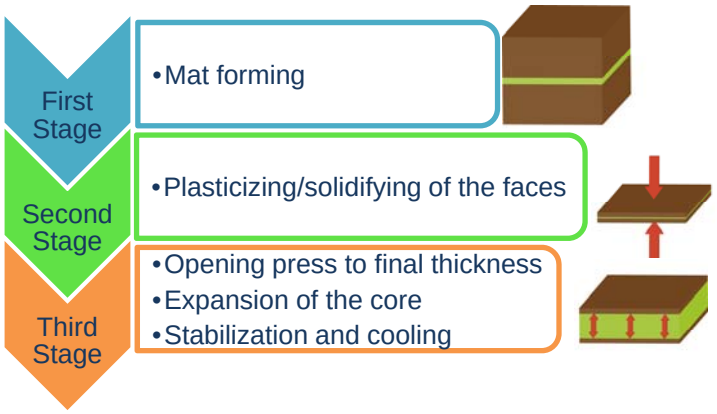
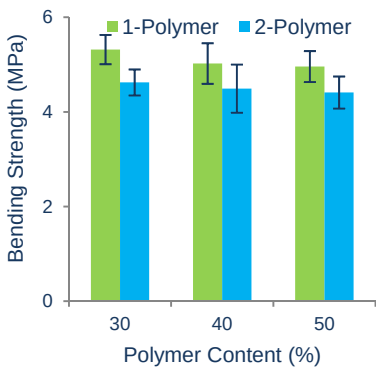
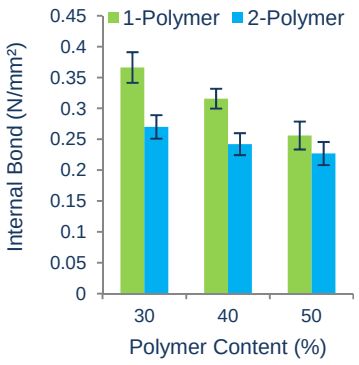
**Introduction:** Lightweight WPC panels have the potential to replace heavy WPC panel as well as particleboard in regions with humid environmental conditions. Thus, there is significant interest to use WPC in the furniture industry in South-east Asia. Three layered lightweight WPC panels (19 mm) have been produced in a one-step process without additionally gluing the layers. The 3 mm faces have been formed using extruded granulates. The core is formed by using expandable polystyrene. The mat is hot pressed at three consecutive stages.

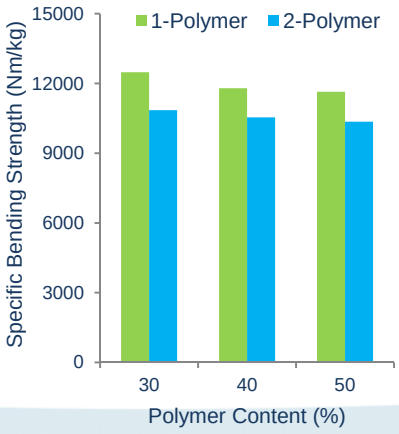


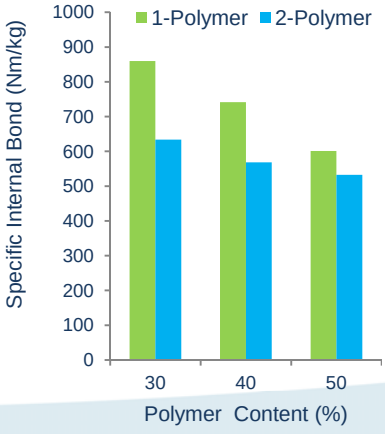

| Panel Compositions | Polymer content | Density (kg/m³) Face | Core | Panel |
|---|---|---|---|---|
| **1-Polymer** (Melting 109 °C, MFI 22g/10min) | 30 | 1000 | 120 | 400 |
| | 40 | | | |
| | 50 | | | |
| **2-Polymer** (Melting 123 °C, MFI 50g/10min) | 30 | 1000 | 120 | 400 |
| | 40 | | | |
| | 50 | | | |

## Results




## Conclusion & Outlook

- ✓ Increasing polymer content and different types of PE have no effect on bending strength.
- ✓ Internal bond has decreased with increasing polymer content.
- ✓ Panels produced with 1-Polymer show higher IB values.
- ✓ This project has shown that lightweight WPC have the potential to be used in certain applications for humid condition.
- ✓ Future steps would be research in increasing face thicknesses, use of coupling agents and other types of polymer to enhance mechanical properties.

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# XIII

## 8th International conference on wood science and engineering in the third millennium, Brasov, Romania (2011)

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# Effect of Core Densities on Mechanical Properties of Lightweight Foam Core Sandwich Panels

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## Abstract:

Nearly two centuries have passed from the first time of developing the idea of sandwich structures for construction purposes. Reaching structural performance comparable to conventional materials while saving a large amount of weight are the main advantage of sandwich structures. The transfer of sandwich structures to the wood-based panel industry is rather slow due to two main reasons: high costs and specialized process technologies. Recent developments to produce sandwich panels in a one-stage process to consider the aforementioned problems have opened a new opportunity for enhancing the application of light sandwich structures in the furniture industry.

In this study, lightweight foam core sandwich panels produced in a one-stage process using glued particles for the faces and thermo-sensitive expandable polystyrene as core layer material were produced. Two different pressing schedules were applied changing pressing temperatures of 130 °C and 160 °C. This study explored the effects of three different levels of foam core densities (80, 100 and 120 kg/m³) on the mechanical properties, like bending strength (MOR) and internal bond (IB) of produced light panels. The results revealed that with decreasing core density up to 33% the mechanical properties remained in a desirable range.

**Key words:** sandwich, light wood composites, polystyrene, foam core, EPS, one-stage process.

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# Introduction

About two centuries passed from the first time stating the idea of sandwich structures in construction by Fairbairn in 1849 in England. First use date of sandwich in construction was in the Mosquito night bomber of World War II (Zenkert 1997, Vinson 2005). The main advantage of the sandwich structures is reaching structural performance comparable to conventional materials while saving a large amount of weight. This can be done by replacing heavy core materials with a homogeneous lightweight layer (Allen 1969, Karlsson and Aström 1995).

The transfer of sandwich structures to the wood based panel industry is rather slow due to two main reasons; high cost and specialized process technology. High costs are caused either by too laborious production processes or by the high price of the substituting material for the core. Specialized process technology for manufacturing lightweight sandwich panels like edge-processing and bonding the separate layers are the provocative factors for a slow penetration of high volume production of sandwich panels in wood-based panel industries. Recent developments to produce sandwich panels in an integrated process to overcome the aforementioned problems have opened a new opportunity for enhancing the application of light sandwich structures in the furniture industries. This integrated approach has been derived from conventional production line for particleboard (Luedtke et al 2008).

In the current study lightweight foam core sandwich panels were produced in a one-stage process using glued wood particles for the faces and thermo-sensitive expandable polystyrene granulate in the core. Two different pressing schedules were applied by pressing temperature of 130 °C and 160 °C to reach different foam structure (Michaeli et al 2008). The lowest level of core density has high influence on determining the panels' production cost. Hence, verifying the effect of core density on the mechanical properties of panels has been done in this research. The aim of the study is to review the effect of three different levels of foam core densities (80, 100 and 120 kg/m³) on the mechanical properties of the panels produced by two different press temperature regimes.

# Materials and Method

## Panel Manufacturing

The 19 mm three-layered panels were produced in an integrated process. Details regarding the press cycle were described by Shalbafan et. al 2011. The boards were produced by using glued wood particles of 12 % urea formaldehyde (BASF, Germany) for the face layer with a target density of 750 kg/m$^3$. The expandable polystyrene granulates (EPS) provided by Sunpor Kunststoff GmbH (Austria) were used for the core layer. EPS particles have a diameter of 0.3 - 0.8 mm. The activation and glass transition temperatures for the EPS have been recorded at 95-115 °C and 103 °C, respectively. The core densities were varied in three different levels of 80, 100 and 120 kg/m$^3$. The surface (3 mm) and core (13 mm) layer thicknesses were kept constant at all panel variations.

After forming of the face and core materials into a mat (600 * 550 mm²), the three layered mat was then pressed in a computer controlled single opening lab hot-press with cooling option in three consecutive stages. First, the faces are compacted till UF-resin is cured. Second, the press will be opened at the appropriate time to allow core expansion. At the third stage, the cooling of the panel will be done to stabilize the panel in the press.

Two press temperatures of 130 (A, B and C panels) and 160 °C (D, E and F panels) were applied to reach different foam structures. Four panels of each series as repetitions were produced. Table 1 shows the technical information regarding the panel manufacturing.

Table 1 Technical information for the 19 mm foam core particleboard

| Number | Sample name | Press temperature (˚C) | Target core density (kg/m³) | Target panel density (kg/m³) | Face thickness (mm) | Core thickness (mm) |
|---|---|---|---|---|---|---|
| **A** | | 130 | 80 | 295 | 3 | 13 |
| **B** | 1-EPS | 130 | 100 | 310 | 3 | 13 |
| **C** | | 130 | 120 | 325 | 3 | 13 |
| **D** | | 160 | 80 | 295 | 3 | 13 |
| **E** | 2-EPS | 160 | 100 | 310 | 3 | 13 |
| **F** | | 160 | 120 | 325 | 3 | 13 |

## Sample preparation and testing procedures

For panel characterization, vertical density profiles were measured using gamma ray densitometry with measuring step of 75 µm. The density profiles of lightweight panels through the thickness are illustrated in Figure 1. The graphs show the three different levels of core densities (80, 100 and 120 kg/m$^3$) in both 1-EPS and 2-EPS type panels.

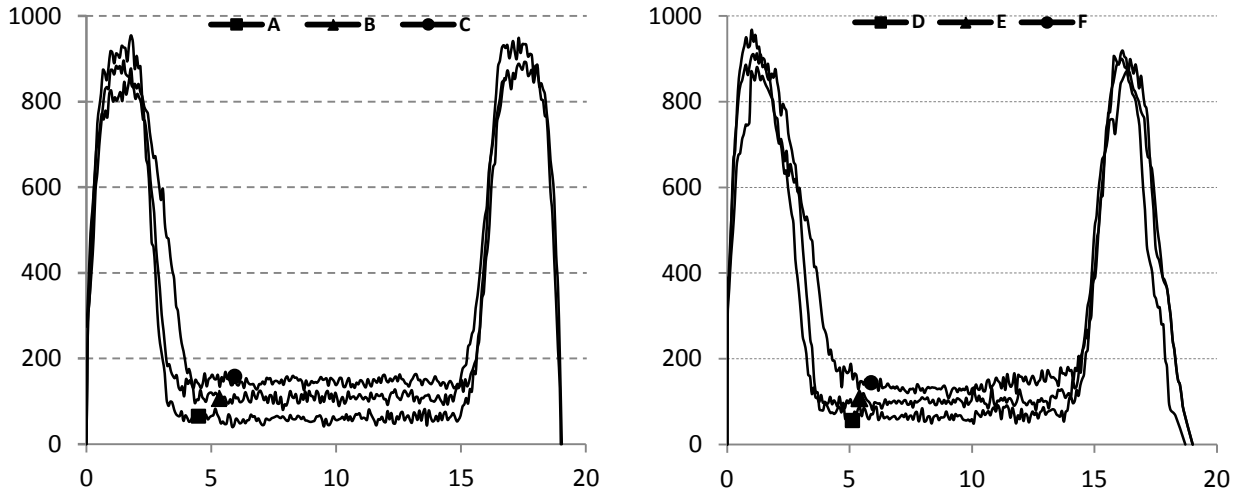


Figure 1 Density profile of 19 mm foam core particleboard produced with different core densities and press temperatures

Bending strength and internal bond samples were cut from produced panels and tested using universal testing machines according to EN 310 and EN 319, respectively. Three samples of each of the four repetition (n=12) were tested. Prior to testing all samples were conditioned in a climate

chamber at 65 % relative humidity and a temperature of 20 ˚C for two weeks. Table 2 shows the specification for the experiments.

Table 2 Size and number of test samples

| Test | Samples size (mm) | Repetitions |
|---|---|---|
| **Density profile** | 50 * 50 * 19 | 4 |
| **Bending strength (MOR)** | 430 * 50 * 19 | 12 |
| **Internal bond (IB)** | 50 * 50 * 19 | 12 |

## Results and discussions

### Bending strength (MOR)

Modulus of rupture (MOR) has been measured by three point bending test. The results are illustrated in Figure 2. By increasing core density from 80 to 120 kg/m$^3$, the modulus of rupture ranged from 8.5 to 9 N/mm² in 1-EPS and from 8 to 8.2 N/mm² in 2-EPS, respectively. The values of MOR for the panels produced by less pressing temperature are higher than those using higher pressing temperature but due to the high standard deviations these differences are not significant.

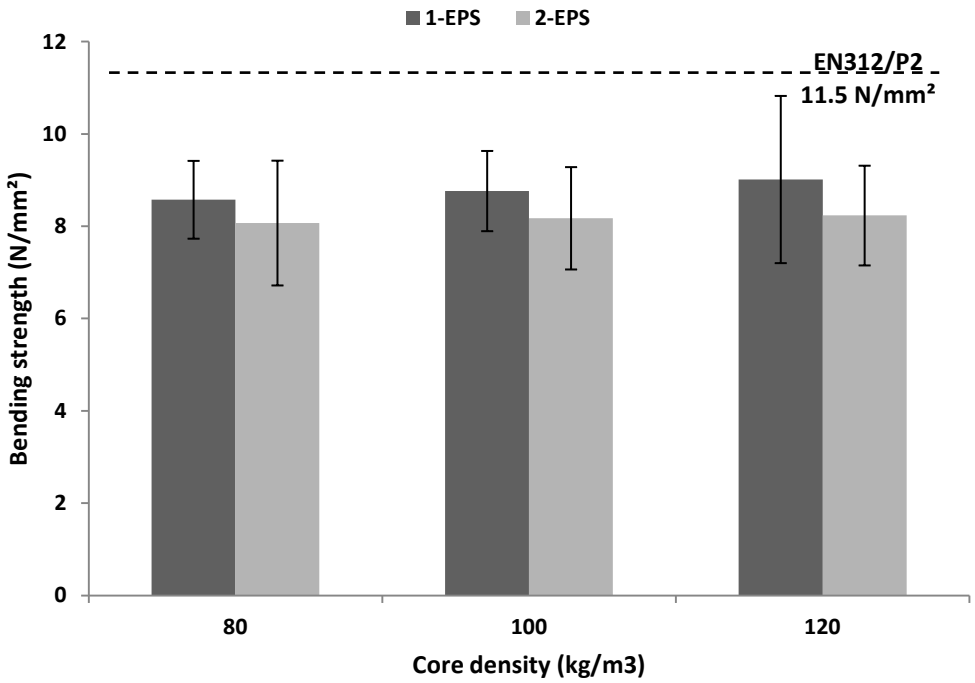


Figure 2 Bending strength values of 19 mm foam core particleboard

It is concluded that changing both core densities in the range of 80 to 120 kg/m³ and pressing temperature (from 130 to 160 °C) have no effects on the bending strength of this type of foam core panels. Such results would cause evident economic advantages because lowering the density of the core material will have a very positive effect on reducing material cost. The graph shows that the minimum requirement of bending strength for conventional particleboard according to EN 312/P2 (11.5 N/mm²) are not fulfilled. It should be mentioned that these types of foam core panels have total density nearly half of the conventional particleboard. But they still have a desirable bending strength.

## Internal bond (IB)

The values for the internal bond are shown in Figure 3. The graph shows significant changes of internal bond while the core density is increased. Two different trends for the Internal Bond values are observed while core density increased from 80 to 120 kg/m$^3$; increasing the IB values from 1 to 1.9 N/mm$^2$ in 1-EPS panels, and decreasing the IB values from 1 to 0.36 N/mm$^2$ in 2-EPS. The tested samples revealed that the panels produced at a lower pressing temperature (130 °C) broke in the core layer, while the fracture was monitored at the interface between face and core layer in panels produced by higher pressing temperature (160 °C). This indicates an improved interface between foam cells and wood particles in 1-EPS. The interface plays an important role in the development of Internal Bond of foam core panels (Shalbafan et al. 2011).

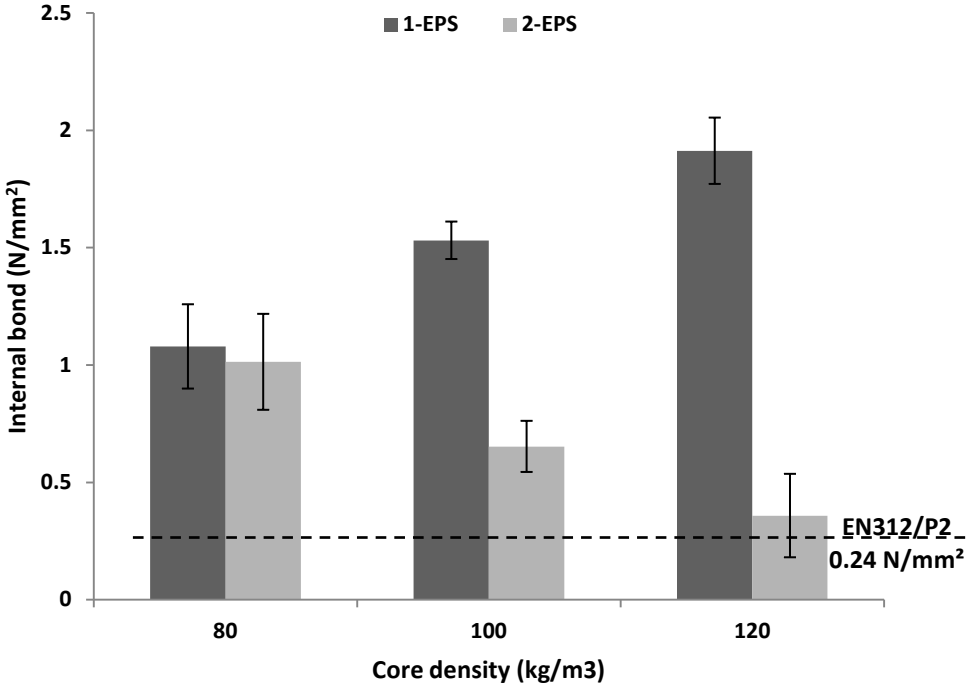


Figure 3 Internal bond values of foam core particleboard

IB values increase in A, B and C panel with increasing core density which can be due to increased foam cells number resulting from enhanced density. The higher number of cells per unit volume, the stronger the foam is (Klempner and Frisch 1991, Gendorn 2005). The reason for declining IB for the 2-EPS panels while the core density increased is not so obvious, but it can possibly be

explained by weakening of the interface between the core and face layers. The graph showed that all panels in 1-EPS and 2-EPS have fulfilled the minimum requirement of internal bond for general purpose particleboard according to EN312/P2 (0.24 N/mm$^2$).

## Specific strength

To compare functional units the properties of panels with different densities can be compared by relating them to a parameter like panel density. In this study, the bending strength and internal bond values were divided by the target panel density yielding specific strength values.

Figure 4 depicts the specific bending strength derived from absolute bending strength divided by corresponding panel density. The graph shows that there is no large difference between panels with different core densities and different pressing schemes. The specific bending strength ranged from 29000 to 27700 Nm/kg in 1-EPS and from 27300 to 25300 Nm/kg in 2-EPS.

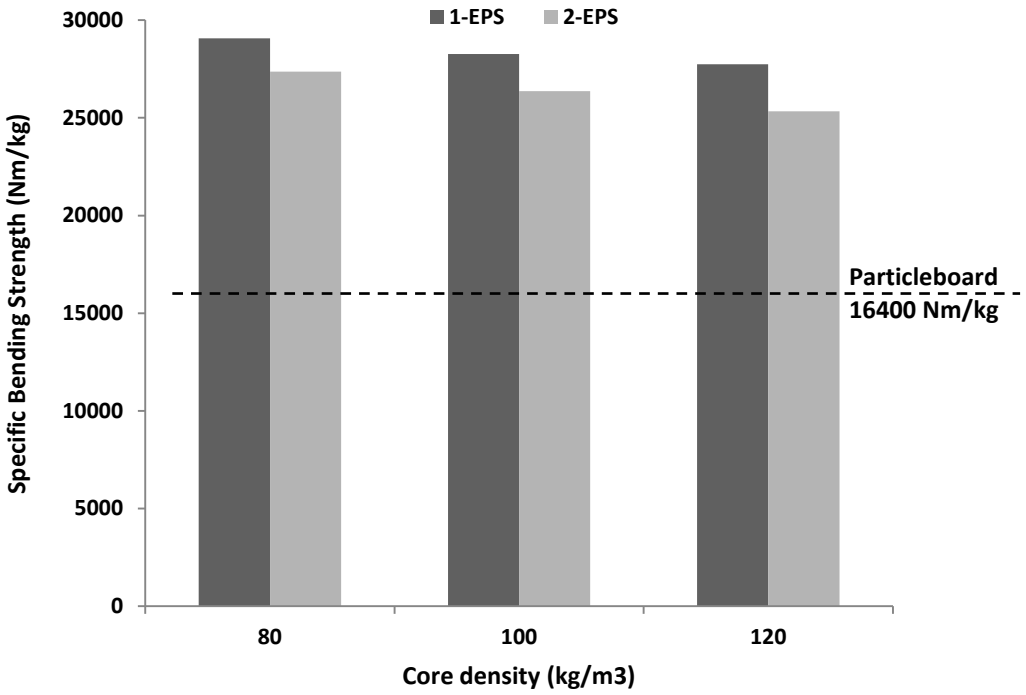


Figure 4 Specific bending strength of 19 mm foam core particleboard for different core densities

Figure 5 shows the specific internal bond values. The same trend like absolute IB is gained for the specific internal bond. By increasing the core density from 80 to 120 kg/m³ the specific values are increased from 3600 to 5900 for 1-EPS, and decreased from 3400 to 1100 Nm/kg for 2-EPS. The minimum calculated specific bending strength and internal bond for a 700 kg/m³ particleboard is fulfilled by all panels.

In many applications preserving the minimum requirements of strength would be possible, hence replacing of lightweight foam core panels due to the higher specific strength instead of conventional panels is reasonable.

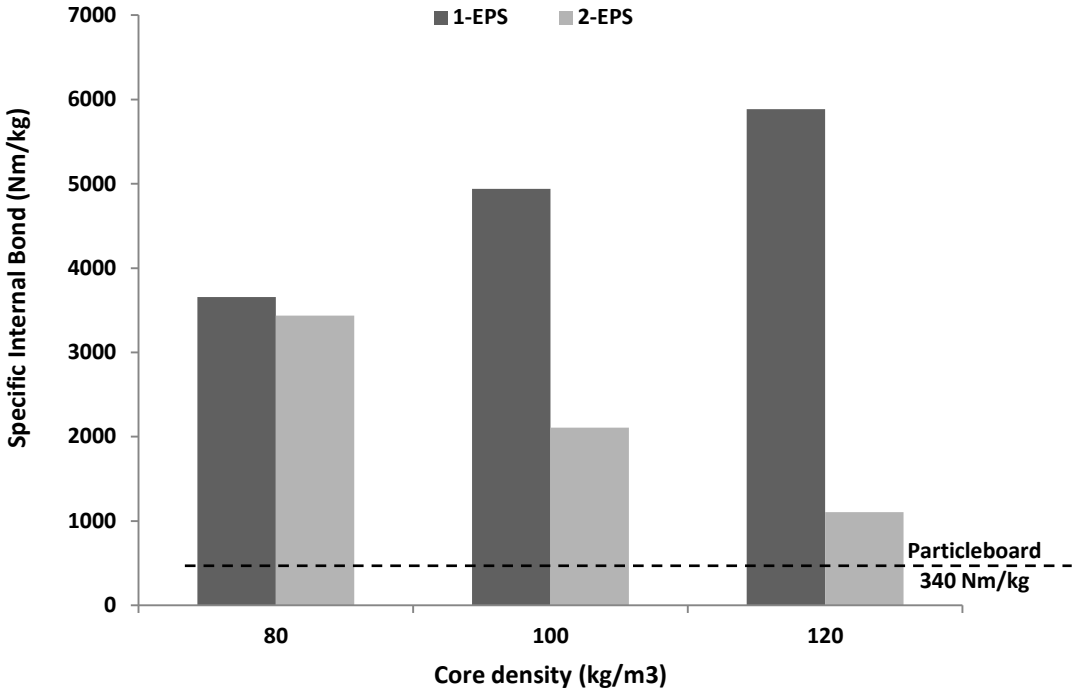


Figure 5 Specific internal bond for 19 mm foam core particleboard for different core densities

## Conclusion

Lightweight foam core panels with three different levels of core density (80, 100 and 120 kg/m³) which is an important factor determining the final panel price, have been produced using two different press temperature (130 and 160 °C). The results show that reducing core density by 33 % has no effect on bending properties of the panels. Also there is obviously no effect of press temperatures on bending strength.

The results reveal that due to the enhanced interface between foam and particles, panels produced by lower press temperature (1-EPS) have higher internal bond values than those produced at higher press temperature (2-EPS). Increasing core density showed two different trends on the internal bond values; increasing IB in 1-EPS panel and decreasing IB in 2-EPS panels.

The specific strength gives a much better overview of the quality of the sandwich panels. The calculated specific bending strength and internal bond of foam core sandwich panels surpasses the corresponding specific strength of conventional particleboard.

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# XIV

## 15th Holztechnologische Kolloquium, Dresden (2012)

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# Physikalische und mechanische Eigenschaften von leichten HWS-Platten mit in-situ geschäumtem Kern

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## Abstract

Für die Herstellung von leichten Holzwerkstoffen gibt es verschiedene Konzep-te. Für Platten mit einem ähnlichen Eigenschaftsprofil wie konventionelle Holz-werkstoffen bei gleichzeitig drastisch reduziertem Gewicht eignet sich der Sandwichaufbau. Während konventionelle Sandwichplatten in der Regel in ei-nem mehrstufigen Verfahren aus unabhängig voneinander hergestellten Kom-po¬nenten hergestellt werden, ist es am Johann Heinrich von Thünen Institut in enger Zusammenarbeit mit dem Zentrum Holzwirtschaft der Universität Ham-burg gelungen, leichte Holzwerkstoff mit Schaumkern in einem einzigen Pro-zessschritt zu erzeugen. Durch das Aufschäumen der Mittelschicht in-situ in der Heißpresse lassen sich Schaumkernplatten erzeugen, die bei etwa 50% Gewichtseinsparung in ihren physikalischen und mechanischen Eigenschaften konventio¬nellen Holzwerkstoffen weitgehend entsprechen. Die spezifischen, also auf die Dichte bezogenen, Eigenschaften dieser Platten liegen zum Teil weit oberhalb der spezifischen Eigenschaften der konventionellen Alternativen. Einleitung.

Keywords: Spanplatte mit Schaumkern, Sandwich-Aufbau, in-situ Aufschäumen, EPS

## Herstellung von leichten Holzwerkstoffen mit in-situ geschäumtem Kern

Die Dichte von Span- und Faserplatten liegt üblicherweise im Bereich zwischen etwa 600 und 750 kg/m³. Seit vielen Jahren wird vor allem seitens der Hersteller von Mitnahmemöbeln der Wunsch geäußert, das Gewicht von Holzwerkstoffen zu reduzieren, um das Gewicht der Verpackungseinheiten reduzieren und dem Kunden die Manipulation der Pakete zu erleichtern zu können. Durch die erhebliche Ausweitung der Holzverwendung im stofflichen und energetischen Bereich in den letzten 10 Jahren, hat sich die Konkurrenz um den Rohstoff Holz verschärft, was letztendlich zu einem Anstieg der Preise für den Rohstoff geführt hat. So ist es verständlich, dass sich die Hersteller von Holzwerkstoffen um eine Verbesserung der Rohstoffeffizienz bemühen.

Um Holzwerkstoffplatten leichter zu machen, bieten sich verschiedene Strategien an (*Lüdtke et al: 2008*). Neben der Verwendung von leichten Rohstoffen (z.B. Pappel oder Küstentanne), lässt sich durch die Ausgestaltung des Rohdichteprofil sowie durch die gezielte Beimengung von leichten Zuschlagstoffen (Flachsschäben, expandiertes Polystyrol, etc.) eine gewisse Gewichtsreduktion erreichen. Je nach Plattendicke und Plattenaufbau können auf diesem Wege Dichten von 450-550 kg/m³ erreicht werden. Will man zusätzlich Gewicht einsparen, so bietet sich die Herstellung von Holzwerkstoffen nach dem Prinzip dem Sandwich-System an (*Allen 1996, Kalson and Åström, 1997*). Bekanntestes Beispiel hierfür sind die bereits vor vielen Jahren mit Erfolg eingeführten Wabenplatten, bei denen durch die Kombination von dünnen hochverdichteten Decklagen und superleichten Papierwaben als Kernmaterial extrem leichte Plattenwerkstoffe hergestellt werden können (Wagenführ, 2005).

Nachteilig bei diesem Typ von Sandwich-Platten sind die Trennung der Produktion von Deck- und Mittellagen, das nachtägliche Zusammenfügen der Komponenten, das in der Regel erforderliche Einbringen von Stegen entweder vor dem Zusammenfügen der Komponenten an vorbestimmter Stelle oder aber nachträglich im Rahmen der Weiterverarbeitung. Beides ist mit hohen Aufwand verbunden.

Am vTI wurde in enger Zusammenarbeit mit dem Zentrum Holzwirtschaft der Universität Hamburg ein neuartiges Verfahren für die kontinuierliche Herstellung von Holzwerkstoffplatten mit in-situ geschäumtem Kernmaterial entwickelt. Mit diesem Verfahren sollte es in Zukunft möglich werden, extrem leichte Span- und Faserplatten auf konventionellen kontinuierlichen Holzwerkstoffpressen in einem einzigen Pressvorgang herzustellen.

Das von *Lüdtke (2007)* entwickelte und von der Universität Hamburg zum Patent angemeldete Verfahren wurde bereits mehrfach in der Literatur beschrieben (*Lüdtke et al. 2008; Lüdtke 2011*). Die von Lüdtke im Rahmen der Verfahrensentwicklung verwendeten expandierbaren Microsphären wurden zwischenzeitlich von *Shalbafan et al. (2012a)* durch expandierbares Polystyrol (EPS) ersetzt.

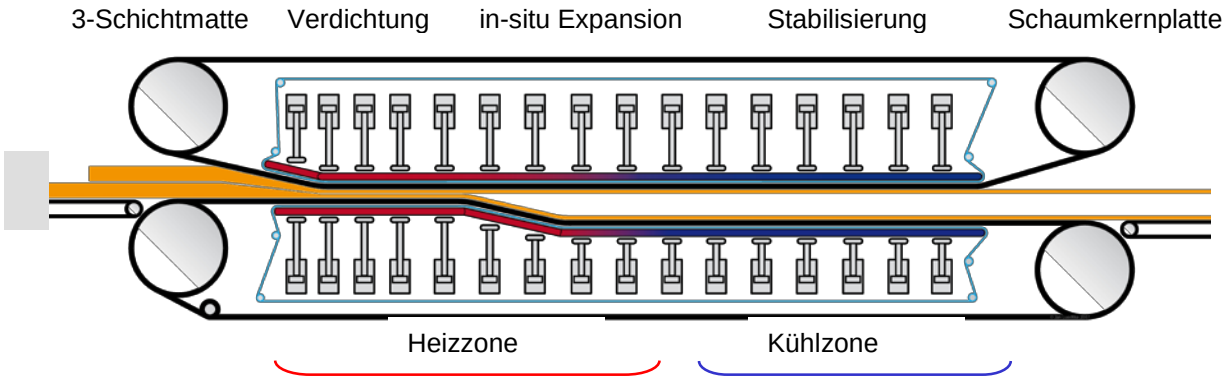


Abb. 1: Herstellung von Spanplatten mit in-situ geschäumtem Kern auf Doppelbandpresse mit Kühlzone

Die nachfolgend beschriebenen physikalischen und mechanischen Eigenschaften wurden für Sandwichplatten mit Span-Decklage und in-situ geschäumtem Kern aus EPS ermittelt.

## Charakterisierung der untersuchten Sandwichplatten

Die Eigenschaften von Sandwich-Platten werden von einer Vielzahl von Faktoren bestimmt. Im Falle der hier untersuchten Spanplatten mit Schaumkern wurde als Beispiel aus einer Vielzahl möglicher Produkte eine 19 mm Platte mit Spanplattendecklagen (Zieldicke jeweils 3 mm) und einer schaumförmigen Mittellage (Zieldicke 13 mm) untersucht. Variiert wurde der Einfluss der Presstemperatur (130°C und 160°C) sowie der Einfluss der Dichte des EPS-Schaumes in der Mittellage (Zieldichten 80, 100 und 120 kg/m³).

### Dichteprofil

Bei Span- und Faserplatten lassen sich aus dem Dichteprofil wichtige Charakteristika der späteren Performance ableiten. Während im Falle von Faserplatten meist ein möglichst flaches Dichteprofil mit geringen Unterschieden zwischen Plattenoberfläche und Plattenmitte erwünscht ist, bemüht man sich im Falle von Spanplatten normalerweise um eine möglichst hohe Dichte in der Decklage und um eine geringe Dichte in der Mittellage.

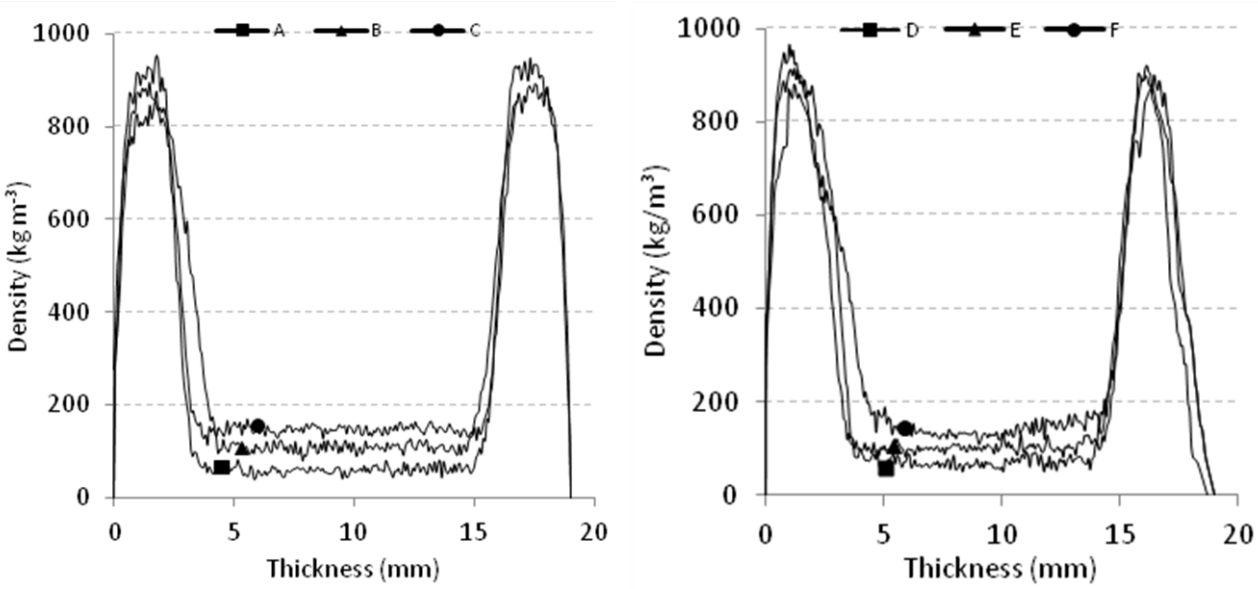


**Abb. 2 Vertikales Dichteprofil in Schaumkern-Spanplatten mit 3 mm Deckschichtstärke**
**Linker Graph: 130°C Pressprogramm, A 80 kg/m³, B 100 kg/m³, C 120 kg/m³ Ziel-Schaumdichte**
**Rechter Graph: 160°C Pressprogramm, A 80 kg/m³, B 100 kg/m³, C 120 kg/m³ Ziel-Schaumdichte**

Bei konventionellen Spanplatten findet man nach dem Schleifen in den Decklagen Dichten mit Zpitzenwerten zwischen 800 und 900 kg/m³. Bei den in-situ geschäumten 19 mm starken Platten wurden bei einer Zieldicke für die Decklagen von 3 mm mittlere Dichten zwischen 650 und 700 kg/m³ erreicht, wobei die Spitzenwerte ebenfalls zwischen 850 und 900 kg/m³ lagen (Abb. 2). Die Dichte der Schaummittellage wurde in drei Stufen auf Zieldichten von 80, 100 und 120 kg/m³ variiert. Abhängig vom verwendeten Pressprogramm (130°C und 160°C) konnten charakteristische Unterschiede im Übergangsbereich zwischen den hochverdichteten Decklagen und der Schaummittellage festgestellt werden. Wie bereits von *Shalbafan et al (2012a und 2012b)* beschrieben, hat die Ausformung des Übergangsbereiches starken Einfluss auf bestimmte mechanische Eigenschaften. Durch die Variation der Pressbedingungen konnte gezeigt werden, dass die Eigenschaften der innovativen Platten in weiten Grenzen gezielt beeinflusst werden können.

Mit beiden Pressprogrammen lassen sich bei geringen Schaumdichten in der Mittellage hohe Dichten in der Decklage und ein steiler Dichteabfall in der Übergangsschicht zwischen Decklage und Schaumkern erreichen.

## Charakterisierung des Mittellagenschaums

Bei den verwendeten EPS Partikeln handelt es sich um marktübliche Polystyrol Beats, die werksseitig mit ca. 6% Gewichtsanteil Propan beaufschlagt wurden. Während des Pressvorgangs erweicht das Polystyrol und die kugelförmigen Beats verfließen ineinander. Das im Polymer enthaltene Treibgas kann nur zu einem geringen Teil aus der sich in Plattenmitte befindlichen Polymerschmelze austreten, da einerseits durch den hohen anfänglichen Pressdruck die Decklagen aus Feinmaterial eine gute Abdichtung bewirken, andererseits das Treibgas – wenn überhaupt – nur seitlich aus dem Spanflies austreten kann.

Wird nach der Aushärtung der Decklagen die Presse geöffnet, so kommt es zur Expansion des Treibmittels und damit zum Aufschäumen des Mittellagenmaterials. Die Schaumstruktur selbst sowie die Ausbildung des Übergangsbereiches zwischen Decklage und Schaum wird dabei von der Temperatur der aufgeschmolzenen Mittellage und der Öffnungsgeschwindigkeit der Presse beeinflusst. Beide Größen können über das Pressprogramm gezielt beeinflusst werden. Beispiele für die unterschiedliche Schaumstrukturen sind in Abb. 3 dargestellt.

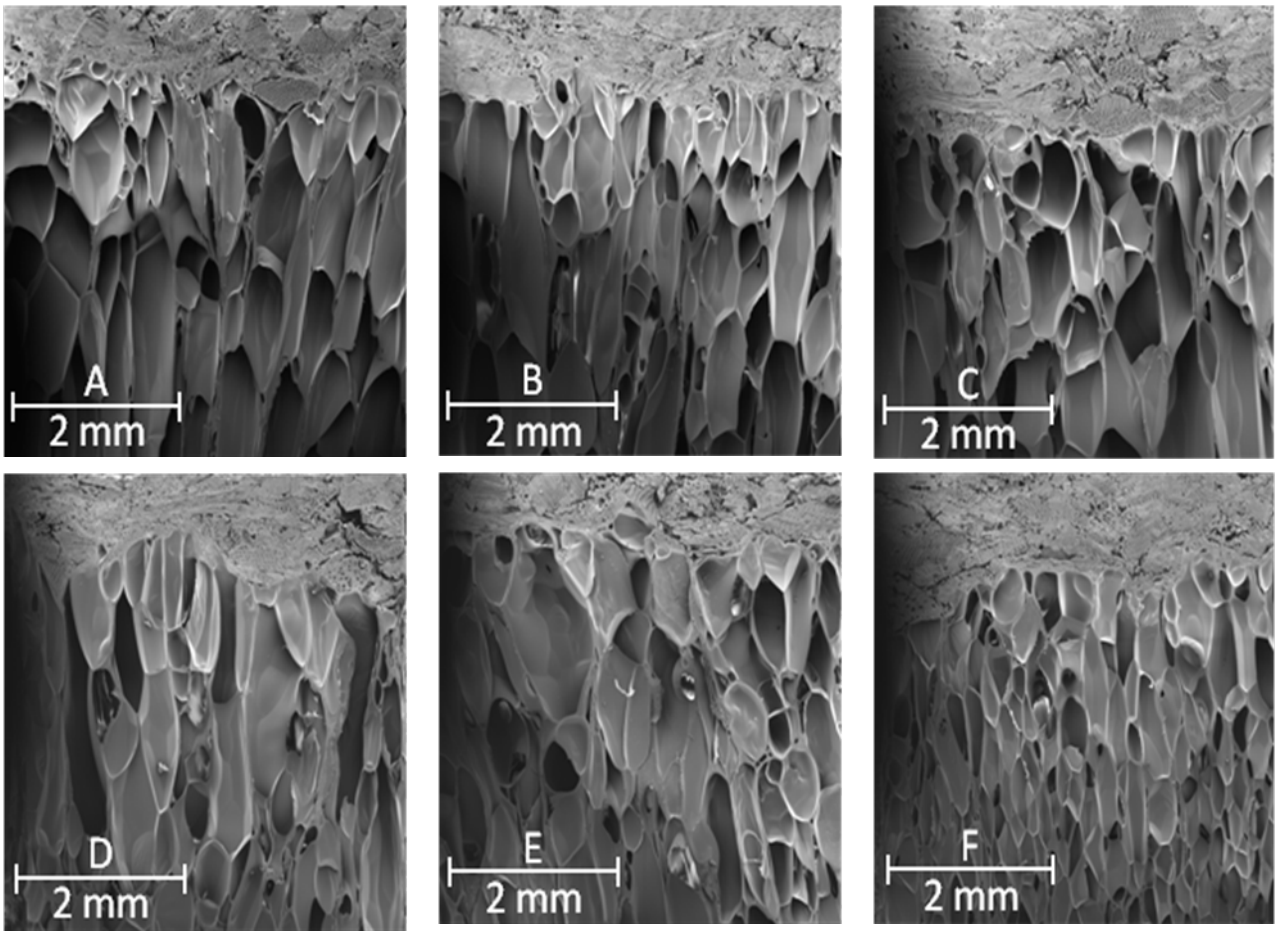


**Abb. 3 Übergangsbereich zwischen EPS-Schaum und Holzdecklage bei in-situ geschäumten Mittellagen von Schaumkern-Spanplatten; A, B und C hergestellt mit 130°C Pressprogramm, D, E und F hergestellt mit 160°C Pressprogramm**

Ein niedriges Temperaturniveau von 130°C führt bei langsamer Expansion des EPS-Schaumes zu relativ großen, starkwandigen Schaumzellen. Beim hohen Temperaturniveau von 160°C entstehen dagegen bei rascher Expansion eher kleinere Zellen mit dünnen Wandungen. Rein optisch sind keine Unterschiede an der Grenze zwischen Schaum und Holz erkennbar.

## Mechanische Eigenschaften

Die folgenden mechanischen Eigenschaften wurden für die oben beschriebenen Parameterkombinationen untersucht: Biegefestigkeit, Querzugfestigkeit (Internal bond), Schaubenauszugwiderstand (senkrecht zur Plattenoberfläche sowie aus der Kante).

### Biegefestigkeit

Die Biegefestigkeit von Sandwich-Platten wird entscheidend von der Zug- bzw. Druckfestigkeit des Decklagenmaterials in Plattenebene bestimmt. Bei den gewählten Parameterkombinationen unterschieden sich die Dicke und die Dichte des Decklagenmaterial nur unwesentlich. Im Vergleich der Biegefestigkeiten zwischen den Varianten sind deshalb auch nur marginale Unterschiede feststellbar.

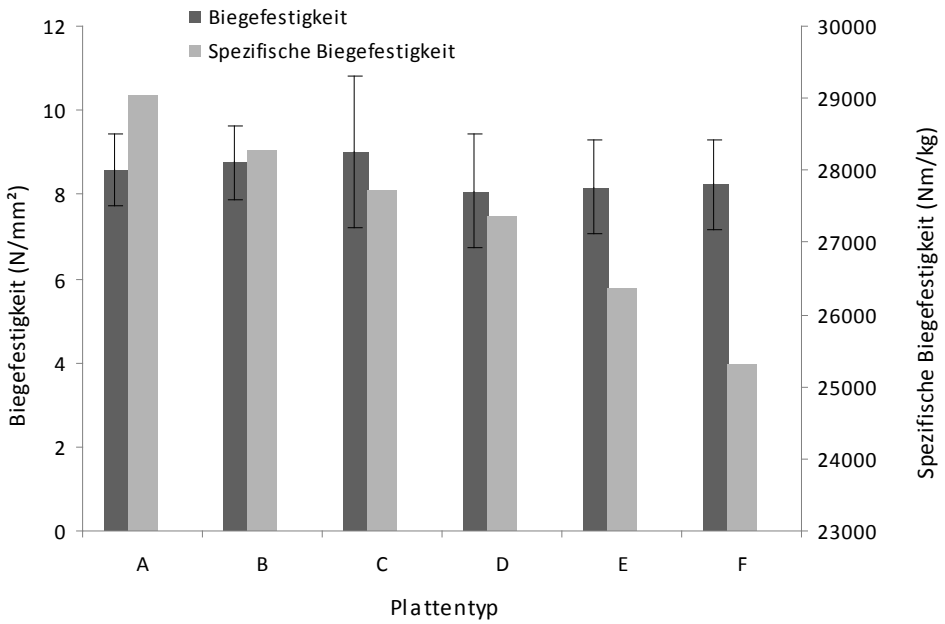


**Abb. 3 Biegefestigkeit von Spanplatten mit Schaumkern, hergestellt durch 130°C Pressprogramm mit A 80 kg/m³, B 100 kg/m³, C 120 kg/m³ Ziel-Schaumdichte, sowie hergestellt durch 160°C Pressprogramm mit D 80 kg/m³, E 100 kg/m³, F 120 kg/m³ Ziel-Schaumdichte**

Trotz der extrem niedrigen mittleren Dichten der untersuchten Platten zwischen 295 und 325 kg/m³ lagen die ermittelten Biegefestigkeiten nur knapp unterhalt der in EN 312 für P2 Platten festgelegten Grenze von 11,5 N/mm². Errechnet man eine spezifische Biegefestigkeit ($Nmkg^{-1}$) durch Division der Biegefestigkeit durch die jeweilige mittlere Dichte der Platte so ergeben sich für die untersuchten Schaumkernplatten in allen Parameterkombinationen höhere Werte als die spezifische Biegefestigkeit von 17700 $Nmkg^{-1}$ einer normgerechte P2 Platte mit 11,5 N/mm² und einer Dichte von 650 kg/m³.

## Querzugfestigkeit (Internal bond)

Bedingt durch die Belastungsrichtung hat die Qualität des Schaumes in der Mittellage und die Verbindung zwischen Decklage und Schaumkern einen entscheidenden Einfluss auf die Ergebnisse der Querzugfestigkeit. Wie aus Abb. 4 ersichtlich unterscheiden sich die Querzugfestigkeiten der bei 130°C hergestellten Schaumkernplatten (A, B, C) erheblich von den bei 160°C hergestellten Platten (D, E, F). Die bei niedrigeren Temperaturen produzierten Platten zeigen ein Versagen in der Mittellage, also in der Schaumschicht, während die bei höheren Temperaturen hergestellten Platten allesamt einen Bruch in der Grenzschicht zwischen Decklage und Mittelschicht aufwiesen. Die geringeren Querzugfestigkeiten sind hier aller Wahrscheinlichkeit nach auf weniger stark verdichteten Späne auf der Innenseite der Deckschicht bei den mit höherer Pressentemperatur hergestellten Platten zurückzuführen (siehe Abb. 2).

In allen Fällen wurde jedoch der in EN 312 festgeschriebene Wert von 0,24 N/mm² weit überschritten. Gleiches gilt für die berechneten spezifischen Querzugfestigkeiten, die im Falle einer 650 kg/m³ schweren Spanplatte bei 370 $kgm^{-1}$ liegen würde.

Da so hohe Querzugfestigkeiten für den Einsatz von Leichtbauplatten nicht erforderlich sind, kann geschlussfolgert werden, dass auch bei wesentlich niedrigeren Schaumdichten in der Mittellage noch ein akzeptabler Internal bond erzielt werden kann. Wie zuvor bereits gezeigt, hat die Schaumdichte kaum einen Einfluss auf die Biegefestigkeit.

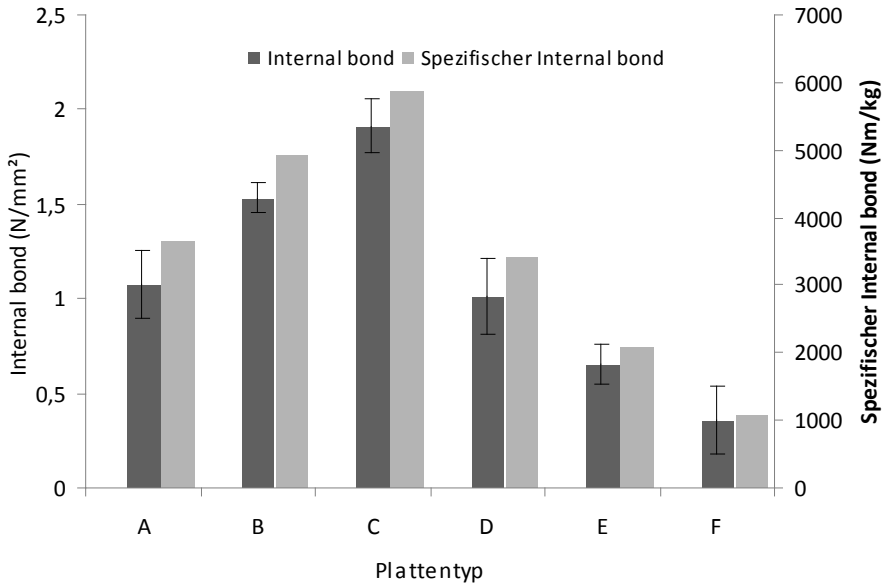


**Abb. 4 Internal bond (Querzugfestigkeit) von Spanplatten mit Schaumkern hergestellt durch 130°C Pressprogramm mit A 80 kg/m³, B 100 kg/m³, C 120 kg/m³ Ziel-Schaumdichte sowie hergestellt durch 160°C Pressprogramm mit A 80 kg/m³, B 100 kg/m³, C 120 kg/m³ Ziel-Schaumdichte**

## Schaubenauszugwiderstand

Beim Einsatz von Spanplatten zur Herstellung von Möbeln stellt der Schaubenauszugwiderstand eine wichtige Kenngröße dar, da Scharniere sicher auf bzw. an Oberflächen befestigt werden müssen und Eckverbindungssysteme in der Regel ausreichend Halt in den Mittellagen der Platten finden müssen.

Erwartungsgemäß unterscheiden sich die Schraubenauszugwiderstände bei Spanplatten mit Schaumkern je nachdem, ob die Schrauben senkrecht zur Plattenebene oder parallel zur Plattenebene aus dem Schaum ausgezogen werden.

Im Falle des Schraubenauszugwiderstands senkrecht zur Plattenebene (Abb 5, links) ergibt sich ein ähnliches Bild wie bei der Biegefestigkeit. Der Schaubenauszugwiderstand wird entscheidend von der Dichte und der Dicke der Decklagenschicht *(Johnson 1967)* bestimmt. Da sich diese bei den untersuchten Parameterkombinationen kaum ändert, waren auch beim Schraubenauszugwiderstand keine nennenswerten Unterschiede zu erwarten (Abb 5, linker Teil).

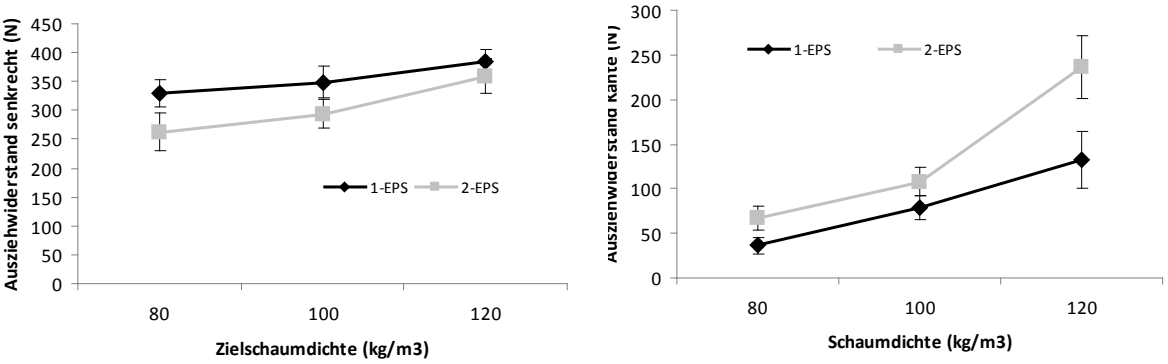


**Abb. 5 Schraubenauszugwiderstand senkrecht zur Plattenebene (links) und parallel zur Plattenebene (rechts), 1-EPS Schaumkernplatten produziert bei 130°C, 2-EPS bei 160°C**

Gänzlich anders sieht die Situation im Falle des Schraubenauszugs parallel zur Plattenebene (Abb 5, rechts) aus. Erwartungsgemäß zeigt sich hier ein sehr starker und deutlicher Einfluss der Schaumdichte. Anders als im Falle der Querzugfestigkeit zeigt hier jedoch der bei höheren Temperaturen entstehende feinzellige Schaum bessere Werte als der grobzelligere Schaum, der bei niedrigeren Temperaturen entsteht. Dies steht im Einklang mit den Ergebnissen von *Sand und Shivkumar (2003)* sowie *Gendon (2005)*.

## Physikalische Eigenschaften

Bei Holzwerkstoffen wird als wichtige physikalische Eigenschaft meist die Dickenquellung nach 2 h bzw. 24 h Wasserlagerung bestimmt.

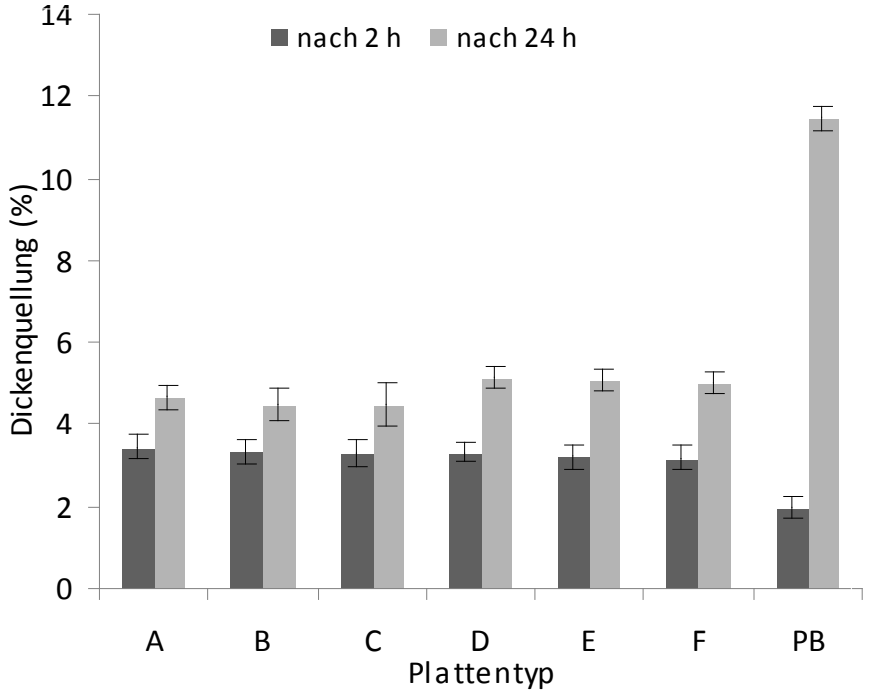


**Abb. 6 Dickenquellung nach 2 h und 24 h Wasserlagerung; Platten hergestellt durch 130°C Pressprogramm mit A 80 kg/m³, B 100 kg/m³, C 120 kg/m³ Ziel-Schaumdichte, sowie durch 160°C Pressprogramm mit Ziel-Schaumdichte: A 80 kg/m³, B 100 kg/m³, C 120 kg/m³; PB normale Spanplatte**

Vergleicht man die in Abb. 6 dargestellten Werte für die in Untersuchung eingeschlossenen Schaumkernplatten mit den Werte von konventionellen Spanplatten so erkenn man, dass die Werte für die Dickenquellung nach 2 h Wasserlagerung bei den Schaumkernplatten leicht oberhalb der Werte für normale Spanplatten, die 24 h Werte aber weit unterhalb der Werte für die normale Spanplatte liegen. Obwohl im Falle der Schaumkernplatten nur die holzhaltigen Decklagen quellen können, liegt die Gesamtquellung der Schaumkernplatten nach 2 Stunden Wasserlagerung oberhalb der der normalen Spanplatte, was dadurch erklärbar ist, dass bei der Produktion der Schaumkernplatten im Labor auf die Zugabe von Additiven verzichtet wurde. Marktübliche Spanplatten enthalten jedoch immer wachsartige Additive zur Verbesserung der Quellungseigenschaften.

Allerdings kann durch diese Additive die Wasseraufnahme allenfalls kurzfristig, nicht aber langfristig verbessert werden. Wie aus Abb. 6 ersichtlich, ist offensichtlich der aus EPS bestehende Schaumkern kaum an der Dickenquellung beteiligt. Die 24 h Werte der Schaumkernplatten liegen allesamt nur leicht oberhalb der 2 h Werte, jedoch nur etwa bei der Hälfte der Werte für konventionelle Spanplatte.

## Zusammenfassung und Ausblick

Nach einem neuartigen einstufigen Verfahren hergestellte Holzwerkstoff-Sandwichplatten mit in-situ geschäumtem Kernmaterial aus EPS lassen sich hinsichtlich ihres Aufbaus in weiten Grenzen variieren. Darüber hinaus haben die Prozessbedingungen einen maßgeblichen Einfluss auf die Ausformung der mechanischen und physikalischen Eigenschaften. Die beispielhaften Ergebnisse zeigen, dass sich durch eine Variation des Aufbaus der Platten (Dicke der Decklagen und Dichte des Schaummaterials) sowie durch die gezielte Wahl der Prozessparameter in der Heizpresse die Eigenschaften gezielt beeinflussen lassen. Bei mittleren Dichten der Sandwichplatten von etwa 300 $kgm^{-3}$ konnten Eigenschaften erzielt werden, die in der gleichen Größenordnung wie die konventioneller, etwa doppelt so schwerer Spanplatten oder sogar weit darüber lagen. Ermittelt man spezifische, dichtebereinigte Eigenschaften, so ergeben sich für die Sandwichplatten in aller Regel wesentlich verbesserte Werte.

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# XV

# 4th Joensuu forestry networking week, Joensuu, Finland (2012)

**Ali Shalbafan**
Johannes Welling

# Innovative Lightweight Wood-based Panels Produced in An Integrated Process

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## Background

Lightweight panels have been considered by furniture manufacturers because of its low density, resource efficiency and strength to weight ratio. Lightweight sandwich panels can compete with conventional wood based panels while saving 50 percent of the weight. There are two conventional ways for producing foam core sandwich panels: either assembly by gluing together of prefabricated layers or injection of liquid foam to form the core between the prefabricated facings. The lack of simultaneous production of all layers together at one time is obvious in these methods. Recent technological development presented by Hamburg University (Luedtke et al. 2008) leads to an innovative one-step process which simplifies the multi-stage process for production of foam core panels. This integrated process has been derived from a conventional production line of particleboard.

The three layered mat is formed by using resinated wood particles for the facings and expandable polystyrene (EPS) for the core layer. The mat is then hot pressed in a one-step process comprising of three consecutive stages. During the first stage, the mat is hot pressed with a specific pressure of 3 N/mm2 to form the face layers. The second stage starts with the opening of the press to the final panel thickness (19 mm) when the temperature of core materials has reached the level needed for expansion. In the third stage, the stabilization of the panel is achieved by the internal cooling of the press plates.

Our published and unpublished results show that the lightweight foam core particleboards can in the future increasingly be used to replace conventional wood-based particleboards in the furniture industry. With a proper design, structural constructions made of lightweight panels can result in weight reductions of up to 50 % compared to conventional particleboards, while still maintaining comparable strengths. Further developments in materials design processes will lead to even lighter components with strength and stiffness properties that can be optimally adapted to suit the requirements.

# Innovative Lightweight Wood-based Panels

JOENSUU FORESTRY NETWORKING WEEK

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## *Foam core Panels*

## *Introduction*

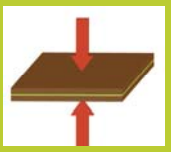
There are two conventional ways for producing foam core sandwich panels: either assembly by gluing together of prefabricated layers or injection of liquid foam to form the core between the prefabricated facings. The lack of simultaneous production of all layers together at one time is obvious in these methods.

Recent technological development presented by Hamburg University leads to an innovative one-step process which simplifies the multi-stage process for production of foam core panels. This integrated process has been derived from a conventional production line of particleboard.

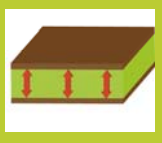
## *Method*

**1st Stage**
- Mat forming
- Closing of the press

**2nd Stage**
- Forming of the faces
- Opening of the press to the final panel thickness



**3rd Stage**
- Expansion of the core
- Stabilization and cooling



## *Conclusion*

- Lightweight foam core particleboards can in the future increasingly be used to replace conventional wood-based particleboards in the furniture industry.
- With a proper design, structural components made of lightweight panels can result in weight reductions of up to 50 % compared to conventional particleboards, while still maintaining comparable strengths.
- Further developments in materials design processes will lead to even lighter components with strength and stiffness properties that can be optimally adapted to suit the requirements.

NORTH KARELIA UNIVERSITY OF APPLIED SCIENCES

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# XVI

## 40th Annual conference of North American thermal analysis society (NATAS), Orland, Florida (2012)

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**Ali Shalbafan**
Johannes Welling
Charles Boardman

# Cone Calorimeter Analysis of FRT Intumescent and Untreated Foam Core Particleboards

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## ABSTRACT

The effectiveness of treatments of the surface layer of novel foam core particleboards were evaluated by means of Cone calorimeter tests. Foam core particleboards with variations of surface layer treatment, adhesives and surface layer thicknesses under similar processing conditions were used to produce the test specimen for the Cone calorimeter tests. Ignitability, heat release rate profile, peak of heat release rate, total heat released, effective heat of combustion, mass loss rate, gaseous emissions and specific extinction area were measured using the cone irradiance of 50 kW/m$^2$. Additional analysis of this data provided fuel composition information that could reveal the pyrolysis events of the composite boards. Thermocouples at various depths were used to provide further verification of pyrolysis events. The unprotected foam core panels generally had much higher heat release rates, somewhat higher heat of combustion and much higher smoke production due to the EPS-foam component of tested panels, whereas time to ignition and total heat release were not pronounced from the veneer treated boards. Adding the commercial FRT veneer to the face particleboard provided a dramatic improvement to the measured flammability properties. It worked sufficiently well with a 3 mm thick surface layer to improve the predicted flame spread rating of the foam core particleboards.

## INTRODUCTION

A novel technology to produce lightweight, sandwich-type composites with particleboard facing and a foam core in one single production step has been developed [1]. This type of particleboard and foam panel can be produced on standard particleboard production lines which can be adapted to the new technology some modifications of the machines. The presence of the Expandable Polystyrene (EPS) for in-situ foaming of the core material implies some restrictions in the production process. But also the fire safety of this type of innovative panels might become a crucial aspect when introducing these novel panels into the market. The cone calorimeter for evaluating flammability has gained very wide acceptance world-wide and has been considered to be especially useful for the development of new products [2, 3]. This ASTM E 1354-11a test apparatus measures the relevant reaction-to-fire parameters that have good correlations to full-scale fire behavior. The ignition time, heat release rate, total heat released, heat of combustion, mass loss rate, combustion products and specific extinction area are the main parameters measured and analyzed in this study. The need for a comprehensive investigation of fire performance of foam core sandwich panels is indicated by the limited studies available on similar thin foam core sandwich panels.

The first study in this project involved the cone calorimeter tests of samples exposed in the horizontal orientation with the conical radiant electric heater set at the irradiance 35 kW/m². By testing 19 mm-thick panels with variations in surface layer thicknesses, core foam densities, and processing temperatures, it was found that the surface layers have an important impact on the fire behavior of sandwich structures [4]. In that study, the heat release rates (HRR) for the sandwich panels were much higher than for the conventional particleboard panel. Their flammability properties improved as the surface thicknesses increased from 3 to 5 mm. However, the levels of HRR were similar to some existing wood-based panels, and thus should have at least some market use on that basis.

It is interesting that the EPS foam has thermal properties that suggest a fire retardant solution. It is stated that the polystyrene foams start to soften and shrink from 100 ˚C and melt at even higher temperatures (around 250 ˚C). Upon further heating, ignitable decomposition gases are created at about 350 ˚C. Without a flame source, temperatures above 450 to 500 ˚C lead to the ignition of the decomposition products. When exposed to a small flame, the flame retarded XPS melts away from the ignition source without itself igniting and ignition might only be observed after longer flame exposures. If the contact with the external flame stops, further burning or smoldering might not be observed. In conjunction with other combustible substances, even flame retarded polystyrene foam can burn (www.exiba.org/Properties_of_XPS.asp). Thus to avoid this burning condition the polystyrene can be kept below its decomposition temperatures via the insulation effects of either a thicker surface layer or the use of surface intumescent veneer or coating. The testing of the commercial intumescent surface layer with a high fire rating required the use of the more severe cone irradiance of 50 kW/m², which is associated with large fires and severe reaction to fire tests.

This paper reports on the in-depth study to verify this added fire retardancy mechanism. In addition to the standard flammability measures discussed in ASTM E1354, this study also utilized imbedded thermocouples at various depths in the sandwiched panels and advanced evolved gas analysis to reveal the decomposition behavior of sandwich panels with and without intumescent veneer coating. The construction of three sandwich panels with varying surface layers and the enhancement to the cone calorimeter gas analysis are described in the material and methods section. In the results and analysis section each relevant flammability feature is explained for the three sandwich panels for the exposure to irradiance at 50 kW/m² and piloted ignition. Also from this data set, the flame spread index classifications (ASTM E84) were estimated.

## MATERIAL AND METHODS

### Three Variations for Surface Layers of Foam Core Particle Boards

Basically, the foam core particleboards with a nominal thickness of 19 mm were manufactured from a three layered mat without additional gluing between the face and core layers. The resinated wood particles and urea formaldehyde resin (Kaurit 350, BASF, Germany) was used for the face layers. The expandable polystyrene (EPS, Terrapor 4, Sunpor, Austria) with a granule size of 0.3 to 0.8 mm were used as the core materials. According to the data sheet of Terrapor 4, it contains a small amount of flame retardant. Babrauskas and Parker [5] mentioned that fire retardant in foams work for very low ignition flux (<25 kW/m²) but fire performance is essentially unchanged when larger ignition sources are used. This material also contains 5.7 % pentane (by weight) as the blowing agent. Our unpublished study showed that between 2 and 3 % of the initial pentane remains in the foam cells after expansion, depending on process parameters (press temperature etc.).

The three-layered mat was then pressed in a lab-scale single opening (Siempelkamp, Germany) hot-press. The press cycle consist of three consecutive stages: pressing phase, foaming phase, and stabilization phase by the internal cooling of the press plates. The temperature of the press plates was set at 130 ˚C. The target overall density was 320 kg/m³ with a face density of 750 kg/m³ and a core density of 124 kg/m³. Nominal surface thickness was 3 mm which corresponds to the foam core thickness of 13 mm and overall thickness of 19 mm. Shalbafan et al. 2012a has described in details the pressing schedules and foaming conditions.

The two improvements utilized for this study were the use of conventional beech veneer without and with intumescent paper underneath of the veneer. The fire resistive adhesive used for veneering the samples was Firobond Ultra Adhesive (FUA) supplied from ENVIROGRAF, UK. The sandwich panels without any veneer were utilized as reference samples in this series of tests. At least two panels of each series were produced as replicates and one sample was cut out from each panel to do the fire performance test. All the samples were conditioned at 23 °C and 50 % relative humidity for at least two weeks prior to testing to meet equilibrium moisture content (EMC).

### Cone calorimeter upgrades and test procedure

The tests were carried out according to the ASTM E1354 test method with a cone calorimeter apparatus (Atlas Electrical Devices, Chicago, IL) at the Forest Product Laboratory in Madison, USA. Samples were exposed in the horizontal orientation to the irradiance 50 kW/m² upon opening the water-cooled thermal shutter and using an electric spark for piloted ignition. Prior to placing the specimen in the sample holder, four thermocouples were attached in the following manner. The exposed surface thermocouple (36 gauge Type K wire) was inserted into a slanted surface crevice formed with a razor blade. Two thermocouples (30 gauge Type K wire) were inserted in tiny long holes at the interface of the foam and particle board, with the bead situated at the sample's middle. The fourth thermocouple was taped to the backside surface at the sample's middle. These thermocouple measurements provided data to verify the insulating enhancements of the veneers. The Figure 1 shows the position of the inserted thermocouples in the cross section of the samples.

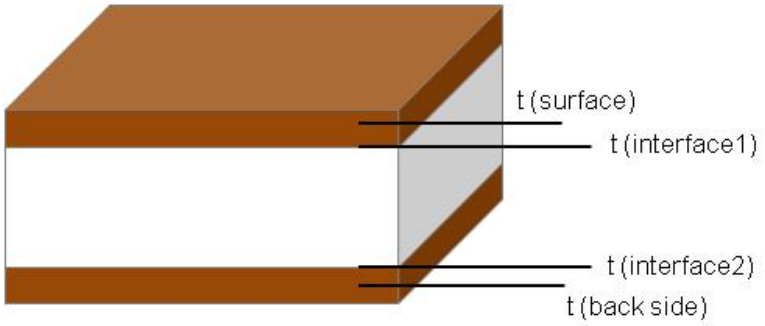


**Fig 1** The position of the thermocouples inserted in different places of the samples

The specimens were tested in the optional retainer frame with a wire grid over the test specimen. As explained earlier, some of the pentane remained in the specimen. After ignition of the surface layer, the elevated temperature eventually reaches the foam core layer. This temperature stimulates the remaining pentane in the foam to cause slight expansion of the foam during the test. To overcome excessive spalling and foam expansion that results in direct contact with the cone heater, a surface wire grid was used in all the cone tests to restrain the heated surface. Ignitability was determined by observing the time for sustained ignition of the specimen with a 4 seconds criteria for sustained ignition..

Exhaust gas composition was determined using three gas analyzers from Sable Systems (www.sablesys.com) and a relative humidity sensor from U.P.S.I. (www.upsi.fr). Oxygen was measured using the PA-10, a paramagnetic analyzer capable of resolution to 0.0001 %O2 and modified to provide even faster response by reducing internal volume of the filters. Exhaust gas to the sensor was dried using the Sable ND-2, a permeable-membrane dryer. Carbon dioxide was measured using the CA-10, a dual wavelength infra-red sensor capable of resolution to 1 ppm. The same technology was used in the CM-10A for Carbon monoxide detection. Gas was delivered to the analyzers using two pumps. The first larger pump pulls exhaust quickly to the location of the Sable equipment through a pre-filter and water-bath controlled (50 °C) water-to-air heat exchanger to provide consistent incoming air conditions. Then a sub-sample pumps pulls exhaust smoothly through the dryer and analyzers.

The relative humidity was measured using the F-TUTA.34R, a quick responding sensor placed very early in the gas sample path inside the cone calorimeter. The lines and sample location were heated with heat tape to near 50 C to avoid condensation on the lines after the ring sampler. The F-TUTA.34R provides analog signals corresponding to relative humidity and temperature. Similarly the Sable components provide analog signals, including the barometric pressure. These signals along with the type K thermocouple readings at various locations in the specimen were captured by the data acquisition system (Measurement Computing USB-1616HS) at 4 Hz. Raw signals were then time-shifted based on time-of-flight to the sensor to have all changes correspond to the mass loss signal from the cone calorimeter.

Exhaust flow rate calculations were based on Bernoulli's formula using pressure drop across the orifice, temperature of the exhaust, and various gas concentrations. Further fine tuning of the exhaust flow rate is based on matching the computed mass flow rates of depleted oxygen, carbon dioxide, and water with that determined from nearly complete combustion of pure ethylene glycol, whose fuel mass flow is measured with the weigh scale. As a basis for comparison, we have that for any incomplete hot combustion, the dynamic mass flow rate (g/s) of a fuel mixture with empirical formula $C_XH_YO_ZN_US_V$ has six equivalent calculations as derived from simple mass balances as [6],

$$\begin{aligned}
\dot{m}_{fuel} &= \left(\frac{12X+Y+16Z+14U+38V}{32(X+V)+8Y-16Z}\right)\left(\Delta\dot{m}_{O2}+\frac{32\dot{m}_s}{12}+\frac{16\dot{m}_{CO}}{28}+\frac{(32+8W)\dot{m}_{CHw}}{12+W}\right) \quad > Form\ 1\\
&= \left(\frac{12X+Y+16Z+14U+38V}{44X}\right)\left(\dot{m}_{CO2}+\frac{44\dot{m}_s}{12}+\frac{44\dot{m}_{CO}}{28}+\frac{44\dot{m}_{CHw}}{12+W}\right) \quad > Form\ 2\\
&= \frac{12X+Y+16Z+14U+38V}{9Y}\left(\Delta\dot{m}_{H2O}+\frac{9W\dot{m}_{CHw}}{12+W}\right) \quad > Form\ 3\\
&= \frac{12X+Y+16Z+14U+38V}{14U}\Delta\dot{m}_{N2} = \frac{12X+Y+16Z+14U+38V}{70V}\dot{m}_{SO2} \quad > Forms\ 4\ \&\ 5\\
&= \dot{m}_{CO2}+\dot{m}_s+\dot{m}_{CO}+\Delta\dot{m}_{H2O}+\dot{m}_{CHw}+\Delta\dot{m}_{N2}+\dot{m}_{SO2}-\Delta\dot{m}_{O2} \quad > Form\ 6
\end{aligned} \tag{1}$$

With X=2, Y=6, and Z=2 for ethylene glycol that is combusting completely, we were able to use Forms 1, 2, 3, and 6 to compare with the time derivative of the dynamic weight loss. No fine tuning of zero and span parameters for oxygen, carbon dioxide, and carbon monoxide gas analysis were needed, whereas the relative humidity sensor required minor calibration adjustments. To match up their response times from 10% to 90% levels during step changes, small digital filtering was applied to sensor data for carbon dioxide, carbon monoxide, and water vapor, and a small digital deconvolution was applied to the oxygen sensor data. Since the molar fractions of $O_2$, $CO_2$, CO, and $H_2O$ are now available and synchronized, we followed the ASTM E1354 Annex procedure for calculating the mass flow rates, respectively, of the same molecules. The soot mass flow rate is merely calculated as the smoke production rate (product of volumetric rate and extinction coefficient) divided by the specific extinction area, 8.3 $m^2/g$ , for the black smoke. Estimates of THCs, although quite small, could reasonably have w=2 in Equation 1 and their mass flow rates approximately 0.1% of the carbon dioxide mass flow rates corresponding to flaming combustion [8]. These mass flow rates are then substituted into Equation 1 and some of the different forms of Equation 1 are compared in Figure 2 showing excellent agreement for burning of glycol. The calibrations derived for glycol burning was also applied successfully to the follow-on tests of the six sandwich panels for this study.

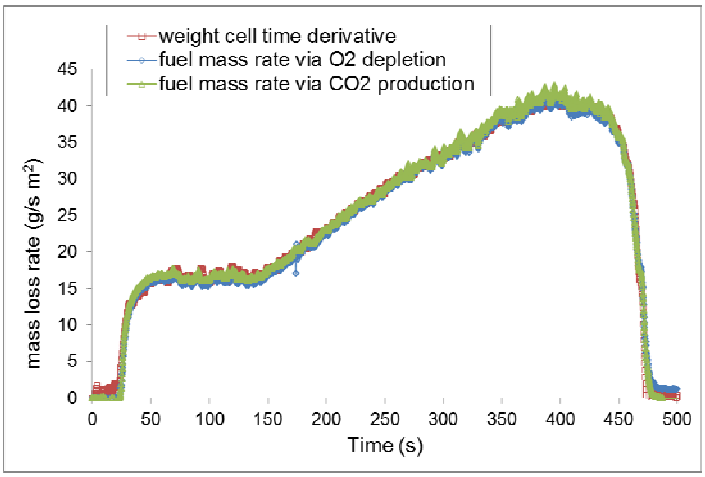


**Fig 2** Comparison of fuel mass rate between gas analysis and weight cell time derivative.

From Equation 1 we found we can derive further properties of the fuel combusted. Consider a volatile composition of fuel (tar), water vapor and carbon dioxide, $C_X{\cdot}H_Y{\cdot}O_Z{\cdot}N_US_V + mH_2O + nCO_2$. The ratio of molar carbon content of the fuel mixture to its stoichiometric molar consumption of oxygen gas is derived as,

$$r_c = \frac{X'+n}{V+X'+Y'/4-Z'/2} \cong \frac{\frac{\beta_{CO2}}{44}+\frac{\beta_s}{12}+\frac{\beta_{CO}}{28}+\frac{\beta_{CHw}}{12+W}}{\frac{\beta_{O2}}{32}+\frac{\beta_s}{12}+\frac{1}{2}\frac{\beta_{CO}}{28}+\frac{(1+W/4)\beta_{CHw}}{12+W}} \equiv \frac{8\beta_{CO2,st}}{11} \tag{2}$$

Betas are merely the mass ratio of combustion product changes to oxygen depletion mass. We note that carbon fuel loading (Equation 2) is independent of water content in any form because parameter m is factored out of Equation 2. Carbon fuel loadings calculated for hydrogen gas, methane, propane, polystyrene, carbohydrates, carbon monoxide, carbon dioxide from Equation 2, are respectively 0, 1/2, 3/5, 4/5, 1, 2, and 4 regardless of the $H_2O$ content. Therefore, the use of carbon fuel loading can assist in identifying fuel, even when combustion becomes incomplete. Suppose that during a test period, the measured water vapor, excess nitrogen gas, sulfur dioxide, and THC's are attributed only to material pyrolysis. Using Equations 1 and 2, further fuel properties are derived as,

$$\frac{Y}{X} = \frac{Y'+2m}{X'+n} = \frac{[\dot{m}_{H2O}/9+W\dot{m}_{CHw}/(12+W)]}{\frac{\dot{m}_{CO2}}{44}+\frac{\dot{m}_s}{12}+\frac{\dot{m}_{CO}}{28}+\frac{\dot{m}_{CHw}}{12+W}} \cong \frac{[\beta_{H2O}/9+W\beta_{CHw}/(12+W)]}{\frac{\beta_{CO2}}{44}+\frac{\beta_s}{12}+\frac{\beta_{CO}}{28}+\frac{\beta_{CHw}}{12+W}} \tag{3}$$

$$\frac{Z}{X} = \frac{Z'+m+2n}{X'+n} = 2+\frac{2V}{X}+\frac{Y}{2X}-\frac{11}{4\beta_{CO2,st}} \tag{4}$$

For wood, the stoichiometric net heat of combustion (kJ/g) is correlated closely as [9],

$$h_{c,st} = 13.23 r_o \tag{5}$$

$$r_o = (32X+8Y-16Z)/(12X+Y+16Z+14U+38V) \tag{6}$$

Polystyrene, $C_8H_8$, ($r_0$=3.077), has the value 12.93 instead of 13.23 in Equation 5. Indeed, carbon solid and carbon monoxide fuel has further deviations, such that the heat release due to incomplete combustion (producing C and CO from oxidizing the organic carbon) has the adjustment to Equation 5 as [9],

$$HRR = 13.23\Delta\dot{m}_{O2} - 2.54\dot{m}_{CO} + 2.48\dot{m}_s \tag{7}$$

The holocellulose, as the major component, is made up mostly alpha cellulose, mannan, and galactan that has the empirical formula, $C_6H_{10}O_5$, ($r_0$=1.185), while minor components are xylan and arabinan with a slightly different empirical formula. Its heat of combustion via Equation 5 is in agreement with the measured value for fully volatized holocellulose [9]. An empirical formula of lignin can be used as $C_9H_6O_2(H_2O)(OCH_3)_{4/3}$, ($r_0$=1.74), which also has net heat of combustion via Equation 5 in agreement with that measured for fully volatized lignin [9]. In the case of extractives, monoterpenes is the main component with empirical formula, $C_{10}H_{16}$, ($r_0$=3.294), which is consistent via Equation 5 for the net heat of combustion [9]. This also predicts that Equation 6 is linearly related to mass fractions of extractives, holocellulose, and lignin for any wood material and was established to a high correlation [9]. If any of the constituents are also charring, then its corresponding volatiles have a differing empirical composition than that of the virgin material, due to retaining the carbon into the char. As a result, the net heat of combustion of wood volatiles is not straightforward, requiring the techniques offered by the use of

Equations 1 to 6. Therefore, for all samples the composition ratios of $r_c$, Y/X, Z/X, and $r_o$ as a function of time will be discussed in the context of improving flammability performances with fire retardancy.

## RESULTS AND DISCUSSION

### Heat release rate (HRR) of panels with three surface layer variations

The potential fire hazard of a combustible material can be indicated by the heat release rates (HRR). Figure 3 shows the HRR profile, as computed with Equation 7, having the dual peak HRR profiles. The first peak is the result of ablating initially the surface exposed to a combined cone heater and flame radiance on the surface. The HRR then decreases as a result of surface charring and the thermal wave process following the ablative process. In essence the pyrolysis front develops and is decreasing in speed, and with the char density staying constant, the volatization mass rate is also decreasing. Since the volatile heat of combustion is fairly constant for initially dry wood (as shown later in Figures 6, 9, and 12 during dry portions of particle board volatization) , the HRR is also decreasing [9,10]. The HRR eventually begins to rise as a result of the thermal wave termination at the insulated rear surface, which means the sample is entering the thermally thin regime, and broadens and speed up the thin pyrolysis zones. For a surface layer sufficiently thin and backed by an insulation board such as EPS, the dual peaks in the HRR merge together into a single initial peak, such that the surface is treated as thermal capacitance that control the heating process, and thus the pyrolysis process [6]. However, since there is a second, backside surface layer of particle board, it is just a matter of time after the EPS has fully melted and charred remains of the exposed surface layer heats the backside surface layer by contact or radiation. Further volatization occurs when the backside particle board reaches its volatization temperatures after a period of heating. The glowing from the infusion of air takes over at some point, and as the material is consumed the HRR will decrease once again. More detailed measurements developed for this study is presented in later sections to explain further this pyrolysis process.

Indeed the size of a fire is correlated positively with the HRR and the HRR will in turn increase as the fire is spreading, unless the HRR can be made to decrease rapidly enough (burnout) or be kept to a low value to counter the increase in pyrolysis surface area [7]. That is, fire retardancy would serve its purpose by preventing fire growth rather than merely preventing ignition. The other factor is that the ASTM E84 test lasts 10 minutes, so that only the first 600 seconds of the cone calorimeter test is only relevant. In addition, the ASTM E84 specimen is backed by a heavy cement board that will absorb heat from the exposed specimen (the thermal wave moves on through rather than terminating), thereby drastically reducing the second HRR peak [7] and extending the period of glowing. However, there are real world fires in which the insulation backing is more the norm.

It is seen that some reduction of the HRR profile in Figure 3 is obtained with the beech veneer adhered with Firobond Ultra Adhesive by EnviroGraph (FUA) to both sides of the sandwich panel, whereas the second large peak HRR peaking at 450s is both decreased and delay and some HRRs are now observed beyond 600s. However, the use of the veneer with intumescent paper (ES/MP/DK by Intumescent Systems LTD) adhered with FUA to both sides of the sandwich panel, has decreased HRR overall and the majority of the HRRs are now greater than 600 s. The repeated tests confirmed this result. The HRR profiles that are most amenable to analytical fire growth modelling are that of exponential decay function, for predicting the flame spread rating for the ASTM E84 test method that was successful with OSB boards, treated and untreated. Since the second large HRR peak can be ignored because of the heavy backing board, the closer attention to the first peak is targeted for this exponential decay function approximation. Wood products with peak HRR around 300 $kW/m^2$ are known as Class C materials [7]. If the initial narrow peak HRR for the intumescent veneered panel is also ignored in Figure 3, then a fitted exponential decay has the PHRR lowered to 100 $kW/m^2$, ignition time increased to 55 s (using a high density veneer), and the Total heat release (THR) remaining at 117 $MJ/m^2$ , should predict a Flame Spread Index in Class A category [7]. Further investigations with targeted variations of the surface layer should have merit.

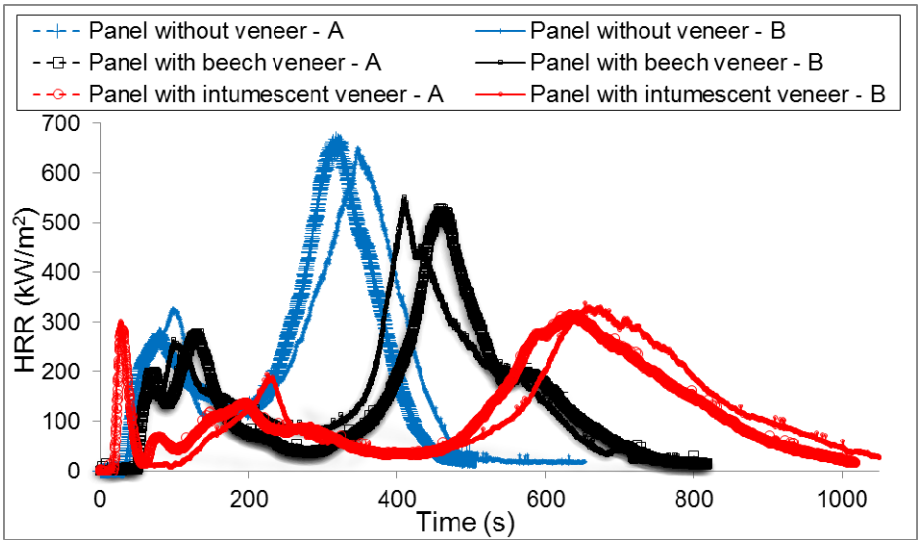


**Fig 3** Comparing sandwich panel HRR with three surface layer constructions

## Pyrolysis mechanisms of panels with three surface layer variations

The thermal conductivity of the EPS foam strongly affects the fire performances. Due to its low thermal conductivity expanded polystyrene foam acts as a protective layer underneath of the woody surface layer. This leads to an intensive heating of the surface layer. Accordingly, an increased first peak of heat release rate significantly higher than that of conventional particleboard does occur. After surface ignition (and prior to the point of PHRR at 30 kW/m²) char formation starts, and the volatile emission rate is affected by the speed of the pyrolysis front propagating into the wood-based material. While the surface layer is burning the foam core layer first melts and then starts volatizing. The foam does not char and its volatiles with its corresponding higher heat of combustion begin to be added to that of the wood volatiles. This can be detected also with thermocouples by which polystyrene decomposition is indicated when temperatures around 350 °C are reached. At this time the pyrolysis zone reaches the back face of the samples and causes so called the thermal feedback effect [3]. The second Peak HRR is due to the volatizing of the foam and the back surface layer, and also to a transition to glowing, which is seen by heat of combustion approaching 30 kJ/g or $r_o$ reaching 2.67 to correspond with pure carbon (ie. the char becomes mostly carbon, but will not combust until the air is able to penetrate after the volatiles has ceased emitting). Because of the challenge posed by the presence of the EPS foam core, a fundamental study was made of panel with three layer variations as reported here.

### *Mass loss rate, temperature profile, and volatile features of panel without veneer*

For the sandwich panel without veneer, it is seen that fuel mass rate derived from the gas analysis using Equation 1 to be in agreement with the weight cell time derivative for combustion times after ignition in Figure 4. This figure shows the dual peak feature noted for the corresponding HRR profiles. The temperature profiles in Figure 5 demonstrate the insulation capabilities of the exterior board only lasted for 100 seconds before the EPS settled at the highly degrading temperatures around 500 $^{o}$C until glowing began. The composition features shown in Figure 6 makes apparent that significant water evaporation (high Y/X and Z/X ratios) occur at the beginning and at 150 seconds. Thus during the time up to 150 seconds the free moisture moved to the back side under temperature gradient, and when the heat became available after the collapse of the EPS foam, the accumulated moisture evaporated in large amounts that was able to dilute the volatiles to cause a temporary reduction in $r_o$ (also net heat of combustion) values. The carbon loading remains close to unity, verifying that the volatiles and glowing char have carbohydrate-type empirical form. Finally the ratio Z/X goes to zero and Y/X goes to unity while $r_o$ values are reaching 2 or beyond at the time 325 seconds that indicates glowing combustion of highly carbonized char.

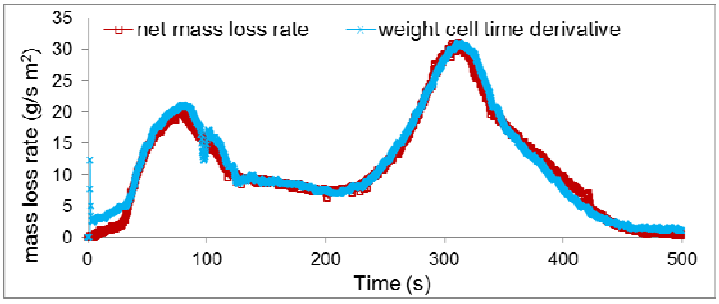


**Fig 4** Using Form 6 of Equation 1 to calculate fuel mass rate in agreement with weight cell time derivative for un-veneered samples

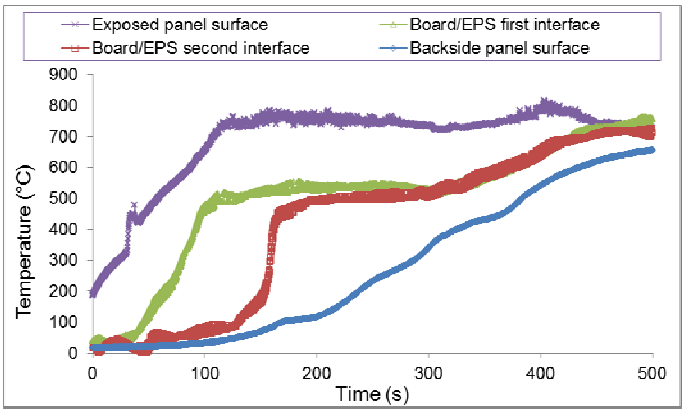


**Fig 5** Temperature measurements at various depths for un-veneered samples

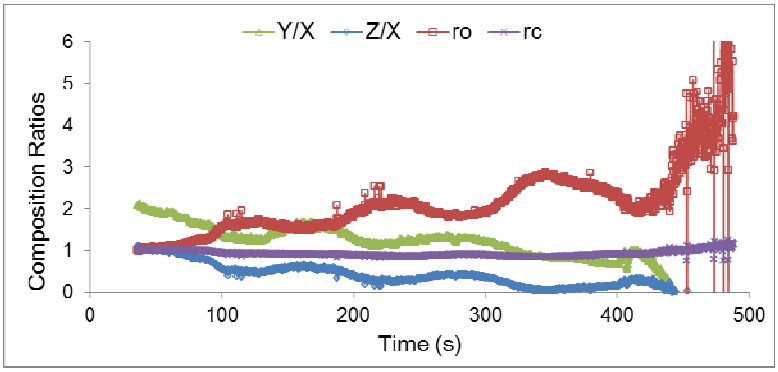


**Fig 6** Derived empirical compositions of pyrolysis for un-veneered samples

## *Mass loss rate, temperature profile, and volatile features of panel with beech veneer*

For the sandwich panel with the beech veneer we likewise get good predictions of the fuel mass rate with the gas analysis, and Figure 7 shows a triple peak feature as also seen in the corresponding HRR profile. It is seen that nearly all pyrolysis still occurred within 600 seconds corresponding to ASTM E84 test time. Temperature profiles in Figure 8 still show the EPS degrading at temperatures around 450 $^{o}$C beginning at time 150 seconds. The empirical composition of the volatiles at 150 seconds in Figure 9 possibly shows the presence of EPS volatiles (carbon loading less than one and $r_o$ peaking), while the evaporation of water that has piled up towards the backside occurred at 250 seconds (quite high values of Y/X and Z/X), and

finally the glowing combustion sets in at the time 500 seconds (Y/X approaching one, Z/X approaching zero, carbon loading slightly less than one, and $r_o$ approaching 2 and higher). However, this is not much improvement in flammability properties.

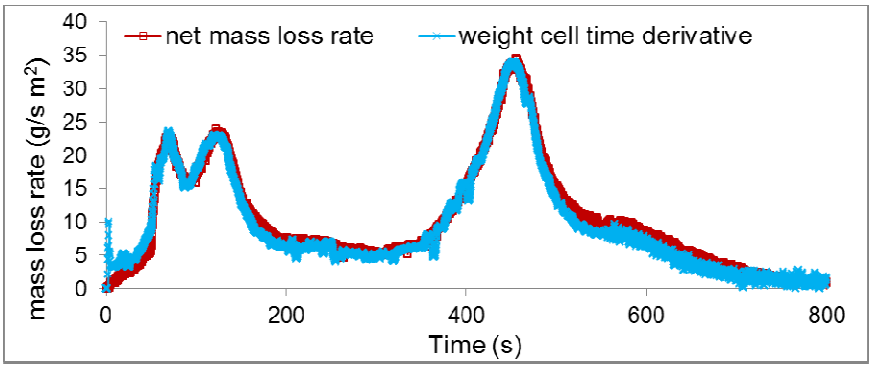


**Fig 7** Using Equation 1 to calculate fuel mass rate in agreement with weight cell time derivative for panel with beech veneer

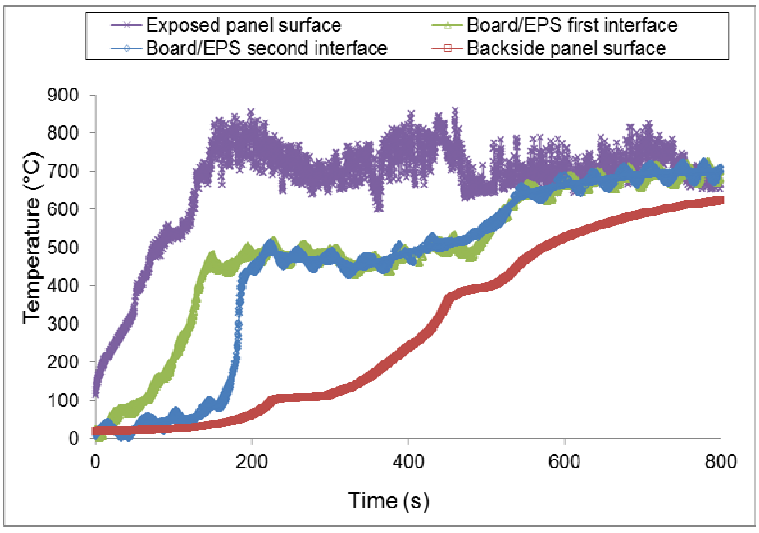


**Fig 8** Temperature measurements at various depths in the panel with beech veneer

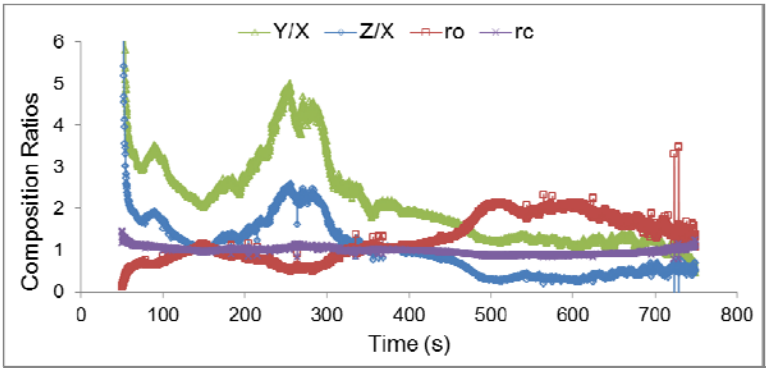


**Fig 9** Derived empirical compositions of pyrolysis for panel with beech veneer

*Mass loss rate, temperature profile, and volatile features of panel with intumescent veneer*

For the sandwich panel with intumescent veneer paper, once again good agreement of the fuel mass rate from gas analysis with the load cell time derivative is obtained in Figure 10, and it is seen that more of the pyrolysis is occurring after 600 seconds, thereby effectively reducing the HRR contributing to the ASTM E84 test environment. The temperature profiles shown in Figure 11 show that EPS remained below the degradation temperature of 350 $^{o}$C at times up to 600 seconds. In the empirical composition plots shown in Figure 12, it is apparent that glowing began around 500 seconds. It is seen from the high values of Y/X and Z/X at ratios of four and two respectively showed the moisture contribution from the intumescent paper up to 200 seconds. At 300 seconds is another incident of water evaporation from the moisture driven to the panel backside via temperature gradients. At times surrounding 200 and 400 seconds, the Y/X is about 2, and Z/X, $r_o$ and $r_c$ are around 1, all of which are closely the features of wood pyrolysis without water vapour and EPS volatiles.

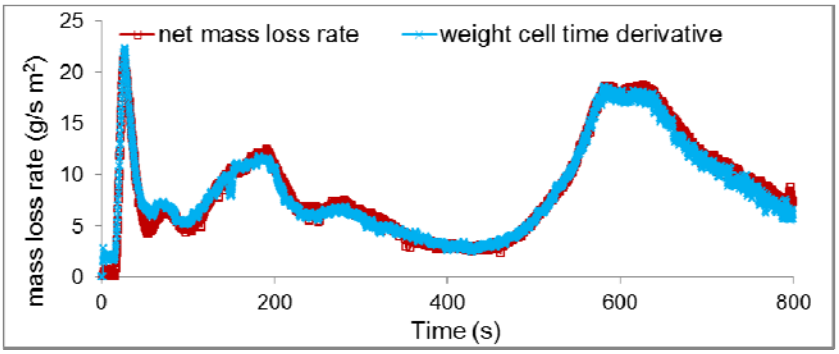


**Fig 10** Using Equation 1 to calculate fuel mass rate in agreement with weight cell time derivative for panel with intumescent veneer

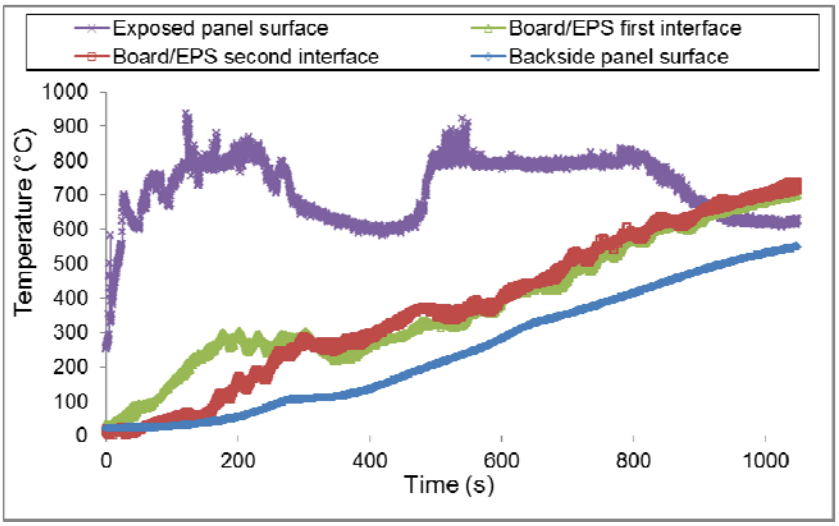


**Fig 11** Temperature measurements at various depths of the panel with intumescent veneer

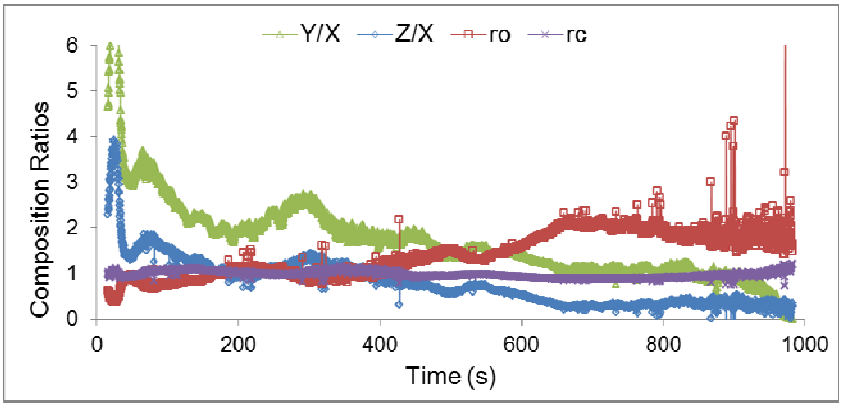


**Fig 12** Derived empirical compositions of pyrolysis for panel with intumescent veneer

## CONCLUSION

In order to assess novel sandwich panels with fire retardant improvements, advanced cone calorimetry techniques were devised to analyse flammability properties. Improved heat release rate calculations were devised. Four thermocouples attached to the specimen at the various depths were used to determine the physical state of the EPS foam core that defined softening, melting, decomposition, and ignition. A state-of-art gas analysis procedure was devised to determine composition features of panel pyrolysis, which resulted in validating the calculations of empirical composition of the volatiles as Y/X and Z/X, and of carbon loading and oxygen mass to fuel mass ratio. These various analytical procedures were used to evaluate sandwich panels that had (1) surface layer without veneer, (2) surface layer with beech veneer, and (3) surface layer with veneer-intumescent paper composite. The cone calorimeter tests at 50 $kW/m^2$ show that the veneer-intumescent paper composite protected the core EPS foam from degrading, as well as seal and dilute wood volatiles in the early stages of pyrolysis, to where it may be possible to achieve a Class A flame spread rating. Although we used the measured $O_2$, $CO_2$, CO, $H_2O$ and soot mass flow rate in determination of the pyrolysis properties, they were not presented directly in this paper, as they will be reported in a future publication in which several datasets are utilized, in contrast to the fundamental study for this work.

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# XVII

# 8th Forest-based sector technology platform (FTP) conference, Barcelona, Spain (2013)

**Ali Shalbafan**
Johannes Welling

# *Innovative Lightweight Foam Core Particleboards Produced in an Integrated Process*

***Abstract***

The European countries hold the world leadership for production volume, process and product innovations in the wood-based panel industry. In the last 20 years, the production capacity of wood based panels has been considerably increased in Europe from 32 Mill. m³ (1994) to 51 Mill. m³ (2012) (EPF, Döry). About 70% of the output volume is used for the European furniture industries as the primary consumer (EPF & Eurostat 2012) where the demand for lightweight panels is of high interest. As a general rule, wood based panels having a density less than 500 kg/m³ can be named as lightweight panels.

The primary reasons for the lightness were the design trend (thick elements with low price and weight), weight handling, transport cost and assembly for the customers. Recently the raw material availability is decreasing which results in increasing prices of raw materials (Mantau et al. 2010). The demand for wood as a renewable energy source has been also grown due to the increasing prices for fossil-based energy. This shows that the wood based panel industry has not only confronted a competition for raw materials but also faces growing prices for both materials and energy. Additionally, the customer demand for flat-pack furniture (self assembly) is also driving force for the development of light panels. In central Europe, from each two Euros spent for furniture more than one is already paid for take-away furniture (Thoemen 2008).

There have been several attempts and strategies to reduce panel density like using of light species, annual or perennial plants, less compaction of the mat furnish and etc. One of the major methods for remarkable weight reduction is using of the sandwich concept where a thick but lightweight core is covered by two thin but stiff skins. There are two conventional ways for producing foam core sandwich panels: either assembly by gluing together of prefabricated layers or injection of liquid foam to form the core between the prefabricated facings. The lack of simultaneous production of all layers together at one time is obvious in these methods. Recent technological development presented by Hamburg University and Thünen Institute (Luedtke et al. 2008) leads to an innovative one-step process which simplifies the multi-step process for the production of foam core panels. This integrated process has been derived from a conventional production line of particleboard.

In this novel process the three layered mat, consist of resinated wood particles in the surface layers and expandable polystyrene granulate (EPS) as the core layer, are hot pressed. The press cycle was performed as follows: 1) the specific pressure was increased from 0 to 3 MPa (0 to 435 psi) during the first 10 seconds and maintained for the compaction and curing of the faces until the core materials reached the activation temperature; 2) the specific pressure was then decreased from 3 to 0 MPa (435 to 0 psi) with opening of the press to the final panel thickness (19 mm) to allow core expansion; 3) for stabilization of the panel the

press temperature was decreased to allow cooling until the temperature of the EPS material reached the glass transition temperature.

Our published and unpublished results based this novel process show that the lightweight foam core particleboards can in the future increasingly be used to replace conventional wood-based particleboards in the furniture industry. With a proper design, structural constructions made of lightweight panels can result in weight reductions of up to 50 % compared to conventional particleboards, while still maintaining comparable strengths. Further developments in materials design processes will lead to even lighter components with strength and stiffness properties that can be optimally adapted to suit the requirements.

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# Innovative Foam Core Particleboard Produced in an Integrated Process

Barcelona, 11-13 March 2013
FTP-c8

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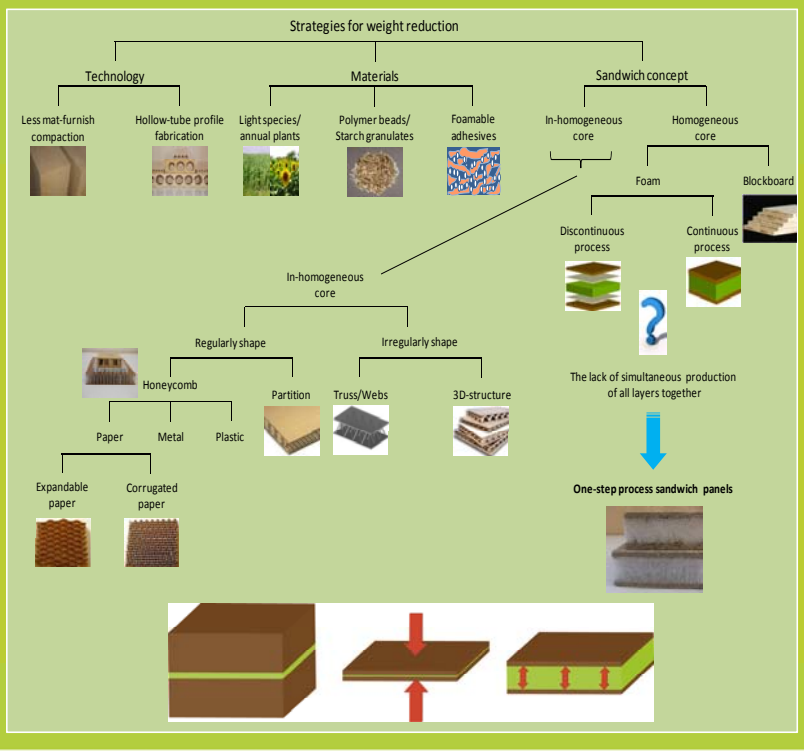
## *Foam core Particleboard*

## *Background*

The various strategies applied for weight reduction are much dependent on the final panel application. Thus, it is hard to generalize the selection criteria for weight reduction. Nevertheless, all of the strategies used for the reduction of panel density during recent decades can be segregated in three major groups; technology, materials and sandwich concept.

Recent technological development presented by Hamburg University leads to an innovative one-step process which simplifies the multi-stage process for production of foam core panels. This integrated process has been derived from a conventional production line of particleboard.




## *Outlooks*

- The future for foam core particle board looks bright indeed which can be used to replace conventional wood-based particle boards in the furniture industry .
- Final performance of foam core particle board is significantly dependent on the quality of surface layers, face-core interface and foam cells configurations.
- The most significant findings to be revealed from the experiments are that the panel properties can be varied in wide ranges to obtain panels which fulfill minimum requirements set by industrial users.
- With a proper design, structural components made of lightweight panels can result in weight reductions of up to 50 % compared to conventional particleboards, while still maintaining comparable strengths.

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Sincerely yours,

Ali