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# Effects of Agglomeration and Pressing Process on the Properties of Flat Pressed WPC Panels

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**ABSTRACT:** This study discusses the influence of agglomeration process, press type and press parameters, on the physical and mechanical properties (water absorption (WA), thickness swelling (TS), internal bond strength, module of elasticity, and module of rupture) of flat pressed wood–plastic composite panels. Additionally, the effects of coupling agent and polymer's melt flow rate on panel properties are investigated. The compounding of the raw materials is done using a heating cooling mixer and a die ring agglomerator (DRA). Test panels are made using a laboratory scale single-daylight press, an industrial single-daylight press, and an industrial scale continuous double belt press (DBP). The best results were obtained using the DRA and the continuous DBP, with 24 h WA and TS values of below 1%, and a modulus of elasticity of more than 4500 N mm$^{-2}$. © 2013 Wiley Periodicals, Inc. J. Appl. Polym. Sci. 129: 3710–3717, 2013

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## INTRODUCTION

Wood–plastic composites (WPC) are usually manufactured into rod-shaped profiles like terrace planks by extrusion, or into 3-dimensionally structured form parts by injection molding. In addition to these techniques, flat pressing technology can be considered as a promising alternative for manufacturing large-dimensioned panels, as slit-die extrusion is limited in width, thickness, and output rate. Dimensions of flat pressed WPC panels resemble more those of wood-based panels with a thermoset as an adhesive, such as particleboard and medium density fiberboard (MDF), so that new application fields of WPC could be discovered in future, particularly when elevated moisture resistance is required.

Apart from dimensions, process parameters like temperature, duration of hot pressing, and the essential need of active cooling are different from thermoset-based panel production. Furthermore, only little lateral expansion of the wood-furnish mat takes place at least in particleboard pressing, while in WPC panel production the frictional forces between the particles are annihilated by the liquid flow of the molten polymer.[1] Similar to wood-based panel production, trimming waste and production reject can be re-used as raw material, as no decrease of panel properties has to be expected.[2]

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 panels. In this case, the material is heated twice and cools down between the first and the second step. Lu et al.[3] proposed that wood particles are more easily dispersed and additives are more evenly distributed using a two-step process. 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 (e.g., Wolcott,[1] Krzysik and Youngquist,[4] Gil,[5] Boeglin et al.,[6] Pecina et al.,[7] Sellers et al.,[8] Balasuriya et al.,[9] Teixeira et al.,[10] Philipp,[11] Fuentes Talavera et al.,[12] Chaharmahali et al.,[13] and Ayrilmis and Jarusombuti[14]). Alternatively, the wood particles, polymer and, if required, additives can be compounded in a first step by using an extruder, a heating cooling mixer (HCM), an internal mixer, or a die ring agglomerator (DRA). Besides a better dispersion of the raw materials there are more advantages of a pre-compounding: (1) Outsourcing of formulation development, material procurement, and quality management to a supplier; (2) Easier transport and storing of WPC-compound in comparison to voluminous and moisture sensitive wood particles, due to the increased bulk density and the encapsulation

of wood particles in a hydrophobic polymer matrix. On the other hand, the additional process step causes additional costs. The use of wood-plastic granulates for WPC panel manufacture has been reported in scientific studies by Vos,[15] Falk et al.,[16,17] Balasuriya et al.,[9] Clemons and Ibach,[18] Chaharmahali et al.,[19] Gardner et al.,[20] and Benthien et al.[21]

As in conventional wood-based panel production, the flat pressing of WPC panels can be done, in principle, in a continuous or discontinuous way. Examples of WPC panel production in a continuous double belt press (DBP) have been reported by Maué,[22] Dominik,[23] Gardner et al.,[20] and Benthien et al.[21] On the other hand, the company Boise Cascade, USA, established a multi-daylight concept for industrial WPC panel production in 2003.[24,25] After a change of ownership this production plant is now operated by NewWood Manufacturing Incorporated, Elma, Washington, USA. Overall, flat pressing of WPC is only little established on an industrial scale, so far. It can be hypothesized that, similar to the situation in WPC extrusion, product properties do not only depend on the raw materials used, but also on production techniques and process parameters. While most of the work on flat pressed WPC published so far focuses on raw materials, only little is known about the influence of the process itself on product performance. The motivation of the present article is to provide scientifically based knowledge on this dependency. In particular, it is, therefore, the aim of the present article to illustrate and discuss the influence of the agglomeration and pressing process on the performance of WPC panels. Such knowledge is essential to assess the potential of flat pressing WPC technology, and to support decisions on the set-up of new industrial production lines.

This work is a continuation of a previous paper evaluating raw material effects on panel properties.[26] That paper does also include a comprehensive literature review on flat pressed WPC. In addition, the impact of fire retardants on fire performance and other properties of WPC panels produced in the same lab under similar conditions as described in the present paper has been published by Ayrilmis et al.[27–29] And finally, a last paper of this series describing effects of surface reinforcement on the mechanical behavior of flat pressed WPC panels is going to be published shortly by Schmidt et al.[30]

## EXPERIMENTAL

### Raw Material

For manufacturing the WPC granulates, two different soft wood flours (WF) from commercial sellers were used. In the following, wood flour from LA.SO.LE, Percoto, Italy, (CB 15 E) will be named as WF1 and wood flour from JELU-Werk, Rosenberg, Germany, (Jeluxyl WEHO 500S) as WF2. For WF1, the main sieve fraction was found between 0.3 and 0.8 mm and for WF2 between 0.1 and 0.3 mm. The used polypropylene types were PP1 (HC 205 TF, Borealis Polyolefine GmbH, Schwechat, Austria) and PP2 (Moplen HP 500V, Basell Polyolefine GmbH (LyondellBasell Industries), Wesseling, Germany). The melt flow rate (MFR) was 4 g 10 $min^{-1}$ (230°C 2.16 $kg^{-1}$) for PP1 and 120 g 10 $min^{-1}$ (230°C 2.16 $kg^{-1}$) for PP2. Polymer densities were 0.905 g $cm^{-1}$ (PP1) and 0.910 g $cm^{-1}$ (PP2). In order to combine the advantages of a low MFR polymer (high mechanical strength) with those of a high MFR polymer (high viscosity), a mixture of PP1 (50%) and P2 (50%) was used. This polymer mixture will be called PP3 in the following. Additionally, a recycled polyethylene (PE1) with a MFR of 0.4 g $min^{-1}$ (190°C 2.16 $kg^{-1}$) was provided by Dr. Schürmann Kunststoffe, Upahl, Germany. As a coupling agent (CA) maleated polypropylene (MAPP) from Integrate NE 542013, Equistar, Lyondell-Basell Industries, USA, if included, was mixed to the polymer and wood material during the agglomeration or mixing process. The WPC granulates were prepared using a HCM (Reimelt Henschel MischSysteme GmbH, Germany) and a DRA (Palltruder®, Pallmann Maschinenfabrik GmbH & Co. KG, Zweibrücken, Germany). The HCM process was controlled by power consumption and process temperature: subsequently to the increase of power consumption (rising toughness of the mixture due to polymer plastification), the rapid increase of temperature was defined as criteria to finish the heating step and start the cooling step (50°C). If these criteria cannot be obtained from the process chart, the cooling process was started when reaching a temperature of 195°C.

### Panel Manufacture

The WPC panels were produced using a single-daylight press in laboratory scale, a continuous DBP in industrial scale (Techno-Partner Samtronic (TPS) GmbH, Göppingen, Germany) and a single-daylight press in industrial scale (Dr. Schürmann Kunststoffe GmbH, Upahl, Germany).

**Laboratory Scale.** For manufacturing the test panels in laboratory scale, a computer-controlled laboratory hot press was used which is typically used for the manufacturing of thermoset-bonded wood-based panels. The press was operated in plate position control mode. Test panels in laboratory scale had a size of 42 cm × 38 cm with a target thickness of 10 mm. The WPC granulate was scattered on a silicon paper covered aluminum caul plate. A pressing frame was used to prevent lateral yielding of the raw material during pressing. When aiming for low densities (∼ 0.8 g $cm^{-3}$) a disposable polyurethane (PU) frame was used, while for higher target densities (>1.0 g $cm^{-3}$) the PU frame was substituted by an aluminum frame. Pictures of theses frames can be found in the work by Ayrilmis et al.[29] Panel manufacturing for determining the influence of agglomeration process, MFR, and CA (influence of agglomeration process, MFR and CA) were arranged with the pressure restricted to a maximum of 700 N $cm^{-2}$, a pressing temperature of 190°C and a pressing time of 500 s. After hot pressing, low density panels (∼ 0.8 g $cm^{-3}$) were transferred to a second press and passively cooled down under moderate pressure to room temperature, while keeping the panel thickness constant by spacing strips (referred to as off-line cooling, cf. Benthien and Thoemen[26] and Benthien et al.[21]). Alternatively, high target density panels (>1.0 g $cm^{-3}$) were cooled inside the hot press (in-line cooling). Three replicate panels were manufactured for each condition. Similar conditions were applied when manufacturing panels for determining the influence of the pressing process used (influence of pressing temperature and process). Aiming to determine the influence of pressing temperature on panel properties (influence of pressing temperature and process), the pressure was restricted to a maximum of 47 N $mm^{-2}$ and platen temperature

was 170, 190, and 210°C, respectively. Studying the effects of granulate type on the pressing process (effects of granulate type on the pressing process), platen temperature was 210°C and hot pressing were arranged at two pressure levels: during the first 1300 s the maximal pressure was restricted to 47 N $cm^{-2}$ and for the subsequent 600 s restricted to 1125 N $cm^{-2}$. After hot pressing the panels were cooled in-line. The temperature in the middle layer was recorded by thermocouples.

**Double Belt Press.** Using the DBP, WPC granulates were mechanically scattered onto the prolonged lower belt of the DBP, plasticized inside the themper zone of the press, and afterwards cooled passing a cooling zone. Due its conception as demonstration press, the production width was 1.2 m, while such presses can be configured up to 3.2 m for industrial production. For the system used, panel thickness was limited to a maximum of 12 mm. Thicker panels can be manufactured by equipping such a press with a high-pressure module (Combi-Press, TPS) or gas-stream pre-heating module (Jetstream, TPS) to enable the heat transfer into the WPC granulates.

**Industrial Single-Daylight Press.** For the trails in the industrial single-daylight press, WPC granulates were scattered manually into an aluminum pressing frame which was fixed on the lower caul plate. The material was then hot-pressed and subsequently cooled inside another press, following the plant's typical procedure of the plant where plastic boards are usually manufactured. Panel plane dimensions were equally to those of plywood (2.44 m × 1.22 m), while panel thickness can be varied between 10 and approximately 22 mm.

### Panel Properties

Physical and mechanical properties were obtained referring to the technical specifications CEN/TS 15534. Water absorption (WA) and thickness swelling (TS) tests were implemented according to EN 317, but with water submersion times of 24, 168, and 672 h. While immersion time of 672 h (28 days = 4 weeks) was according to CEN/TS 15534, 24 h (1 day) and 168 h (7 days = 1 week) of immersion were chosen to describe the progress (long-tern versus short-term) of TS and WA. Specimens' dimensions were 50 mm × 50 mm. When reaching immersion time, samples were taken out of the water (20°C) and dried with a paper towel before measuring thickness and weight. TS and WA are expressed as a percentage of the initial value for thickness and weight. As an important characteristic for wood-based panels, internal bond (IB) strength was measured following EN 319. Specimens' dimensions were 50 mm × 50 mm. Samples surfaces were sanded and glued on plywood blocks with PU adhesive. After conditioning at 20°C and 65% relative humidity, the tensile strength perpendicular to the plane direction were determined. The main modification was that 10 mm deep grooves were inserted in plane direction into the sample sides to compensate for the high IB levels and poor glueability of WPC specimens, so that the rupture does no longer occur at the interfaces between the specimen and the plywood test blocks. The good correlation between results of such modified internal bond tests with results obtained from samples without grooves has been demonstrated by Thoemen et al.[31] Modulus of elasticity (MOE) and rupture (MOR) were determined according to EN 310. Samples 250 mm long and 50 mm wide were applied for third point loading test. Load-deflection data for the calculation of MOE were recorded at 10 and 40% values of failure load.

### Data Treatment

It has been shown by Benthien and Thoemen[26] that the physical and mechanical properties of WPC panels strongly depend on the specimen's density. Due to the inevitable variation of density in both laboratory and industry scale test panels, a normalization procedure was required so that measurements could be compared at the same density level. By applying a linear regression (least square method) to each data series representing one formulation, it was tested whether a correlation between density and measured values could be assumed on a significance level of 99%. If significance was given the property values were normalized to a defined density (e.g., 0.85 g $cm^{-3}$). If a linear relation could not be assumed, mean values were used for the further data analysis without normalization.

### Statistical Analysis

A single factor analysis of variance (ANOVA) was conducted using the analysis tool of Microsoft Excel to evaluate the effects of pressing temperature respectively pressing process on the physical and mechanical properties of the test panels. The null hypothesis (no effect) was accepted if the *P*-value exceeds the predefined significance level at $\alpha = 0.01$.

## RESULTS AND DISCUSSION

### Influence of Agglomeration Process, Melt Flow Rate, and Coupling Agent

Figure 1 illustrates the influence of MFR and CA on WA and TS after 24, 168, and 672 h submersion in water. The compounding of wood flour and polymer to WPC granulate was made using a HCM and a DRA. Figure 2 shows the results for bending properties (MOE, MOR) and IB strength, respectively, for the same material and process conditions.

A direct comparison of these results with literature values is difficult. There are only few studies conducted on flat pressed WPC panels and much less on panels applying pre-compounded raw materials as feedstock. Nevertheless, provided bending properties of panels with wood flour contents of 50% are in the range of the results presented here: Vos[15] gave values for MOE of 1650 N $mm^{-2}$ and MOR of 11.7 N $mm^{-2}$, Balasuriya et al.[9] gave values for MOE of 2200–3400 N $mm^{-2}$ and MOR of 17–24 N $mm^{-2}$ and Gardner et al.[20] MOE of approximately 2000 N $mm^{-2}$ and approximately MOR of 35 N $mm^{-2}$. Regarding WA, Vos[15] mentioned values of 1.58% after 24 h of immersion and Clemons and Ibach[18] values of 7% after 336 h of immersion. For PE-based dry-blended industrial scale made flat pressed WPC panels (single-daylight) with a WF content of 50%, dimensions of 4 × 8 feet (1.22 m × 2.44 m), a thickness of 7/16 inch (11 mm), and a density of 52 lb./$ft^3$ (0.83 g $cm^{-3}$), properties were given according to ASTM D-1037 as 254,265 psi (1753 N $mm^{-3}$) MOE, 2594 psi (17.9 N $mm^{-3}$) MOR, 210 psi (14.48 N $mm^{-3}$) IB strength, and less than 1% TS.[32]

Test panels bonded with PP1 (MFR 4) and agglomerated using a HCM show already high values for WA (48.3%) and TS

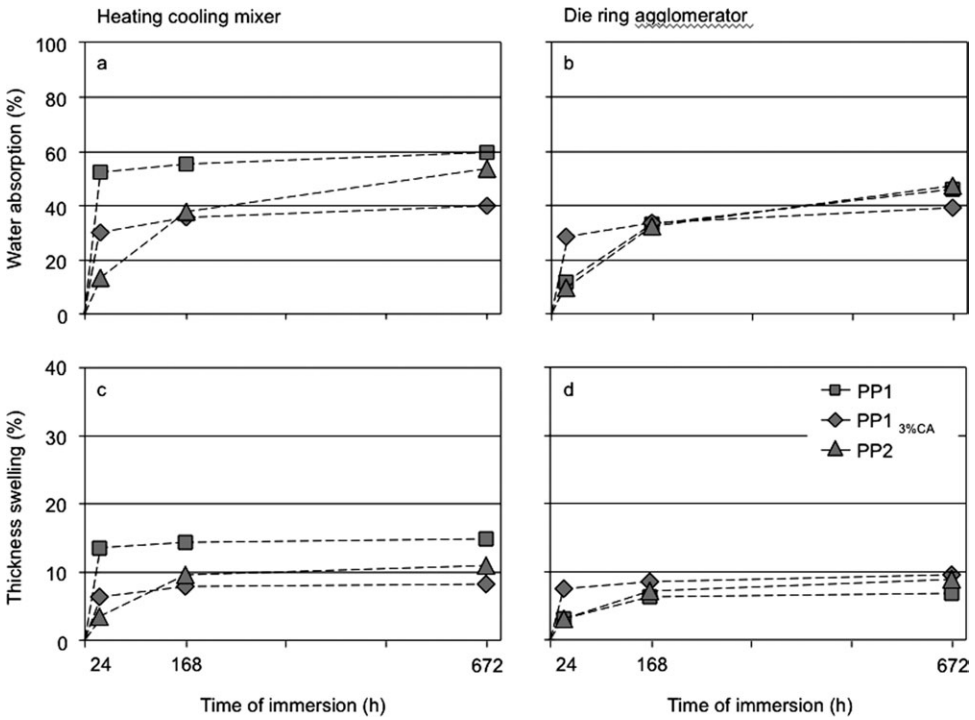


**Figure 1.** Influence of agglomeration process, MFR, and CA on WA and TS after 24, 168, and 672 h of submersion in water. Raw material: WF1. Wood flour content: 70% (wt/wt). Press properties: 190°C, 700 N $cm^{-2}$, 500 s. Standard deviation: ± 2.3–11.4% (WA), ± 0.5–2.5% (TS). Panel densities were normalized to 0.85 g $cm^{-3}$.

(13.7%) after 24 h of submersion in water, while the further increase of these values after 672 h of water submersion turned out to be comparative small, with $WA_{672h} = 56.0\%$ and $TS_{672h} = 15.0\%$, respectively. When adding 3% CA to the PP1-formulation, WA and TS decrease considerably. In comparison to the use of a low MFR polymer (PP1; MFR 4) as matrix material, the usage of a high MFR polymer (PP2; MFR 120) results in an obvious short-term waterproofing ($WA_{24h} = 9.5\%$;

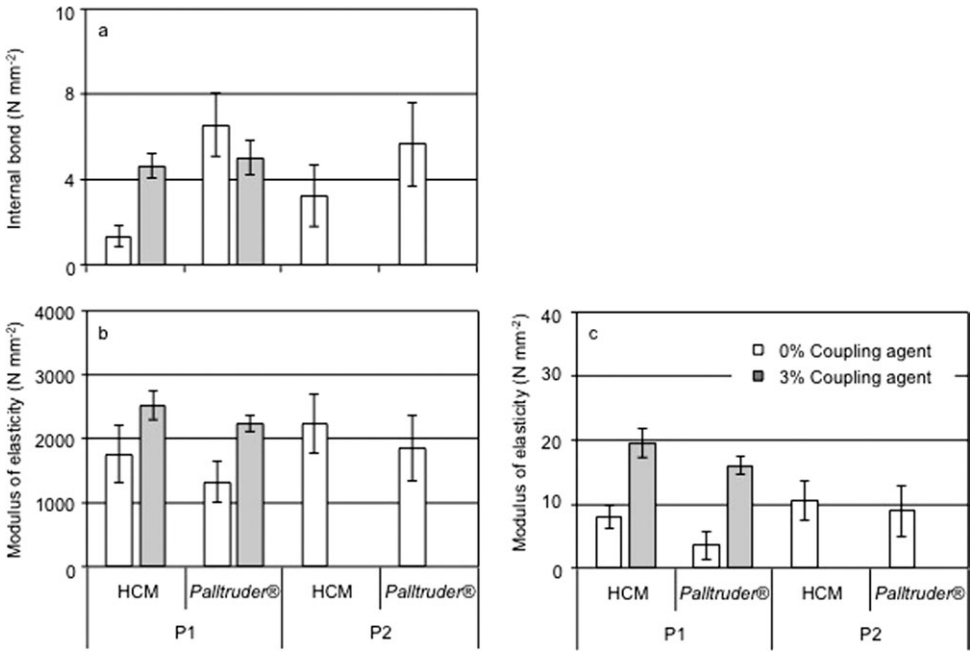


**Figure 2.** Influence of agglomeration process, MFR, and CA on internal bond (IB), modules of elasticity (MOE), and modules of rupture (MOR). Raw materials: WF1. Wood flour content: 70% (wt/wt). Press properties: 190°C, 700 N $cm^{-2}$, 500 s. Panel densities were normalized to 0.85 g $cm^{-3}$. HCM = heating cooling mixer, DRA = die ring agglomerator.

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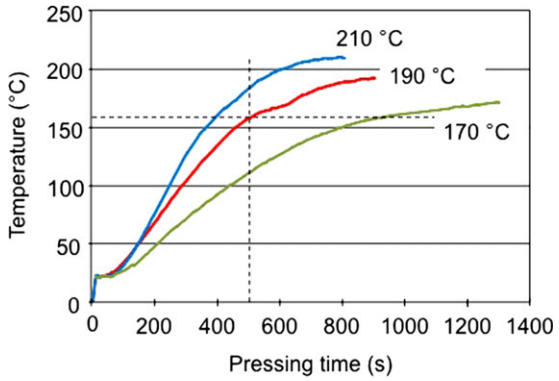


**Figure 3.** Temperature in panel's middle layer for pressing temperatures of 170, 190 and 210°C. Raw materials: WF1, PP1 (DRA). Wood flour content: 50% (wt/wt). Specific pressure: 47 N $cm^{-2}$. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

$TS_{24h} = 3.6\%$). After 672 h of submersion in water, values reach nearly the level of samples that were made using PP1. Such a short-term prevention against water penetration causes a temporary inhibited swelling, comparable to the pursued effect of wax admixture in conventional particleboard or MDF production.

Looking at the influence of the agglomeration technique it is obvious that the physical properties of panels, bonded with 3% CA equipped PP1, are nearly on the some level as PP2-bonded samples, whereas PP1-bonded samples without the addition of CA show better physical properties for panels made of a DRA granulate. This effect may be explained by more intensive internal material shear and kneading movements in the DRA compared to a HCM. The use of the HCM technique requires the use of a low viscosity polymer or the addition of a CA to ensure the encapsulation of wood particles into the polymer matrix.

An increase of IB strength (Figure 2) was achieved when using DRA granulate instead of HCM granulate. Focusing on HCM granulate for panel manufacturing, the use of a high MFR polymer (PP2) leads to an increase of IB strength in comparison to PP1. This effect is not observed using a DRA for compounding. The addition of a CA into a PP1-formulation increases the IB strength for HCM based samples, whereas this value decreases when adding the same CA to the DRA granulate.

Looking at MOE and MOR within each raw material formulation, properties of samples made using HCM granulate exceed those, which were made of DRA granulate. The use of CA or a low MFR let properties improve. The contrary effect for IB strength and bending properties due to the use of a HCM or a DRA granulate may be explained by the characteristic granulate structure: The orientation of the wood particles in the globular structure of a DRA granulate is maintained during scattering and pressing process, while a HCM granulate is more voluminous and the wood particles are not orientated in spherical structures, so that the wood particles are able to orientate parallel to the panel plane during pressing. Due to this orientation, IB strength may be lower for panels made from HCM granulate, but the horizontal alignment of the wood particles may cause a higher bending strength at the same time. The preparation of microphotographs would be helpful to demonstrate the difference in wood particle orientation between the DRA and the HCM in future. Basically, the use of CA or high MFR polymer causes higher mechanical properties, because a more intensive bounding between the polymer and the wood particles is given, so that forces can be transferred more homogeneously. The consideration of CA as a variable showed that its addition is not advantageous inevitably: TS and WA were not improved when using ring die agglomerated CA-improved granulates for panel manufacturing and IB strength was found decreased for these elaborations.

### Influence of Pressing Temperature and Process

Figure 3 illustrates the temperature development in the middle layer of test panels during manufacture in the laboratory press. The temperature is recorded by thermocouples placed into the material during scattering. The hot-pressing process was stopped after 1300 s (170°C), 900 s (190°C), and 800 s (210°C), which were approximately the times to reach the target temperature of 160°C in the middle layer. Table I shows the influence of reached middle layer temperature on physical and mechanical properties. A consistent increase of mean values of all properties for increasing temperature can be observed. However, this increase of properties is relatively moderate and probably would not justify the extra costs going along with an increase of process temperature.

Additionally to properties of panels manufactured in laboratory scale, properties of panels made using a DBP in industrial scale are presented in Table I. Comparing these results with properties of panels made in laboratory scale at 210°C (800 s), a considerable increase of properties was achieved. The increase of physical properties was 31% (WA) and 33% (TS) and of mechanical properties 44% (MOE) and 49% (MOR). The reason for this increase is not obvious, but it may be hypothesized that the nip rolls installed for calibrating the WPC panels to target thickness do cause a repetitive compaction and hence a kneading of the material, which results in a tighter contact between the wood particles and the polymer.

In addition to the results discussed before, raw material formulations WF1/PE1 and WF2/PP1 were manufactured to WPC panels using a continuous DBP, a single-daylight press (both in industrial scale) and a laboratory press. For the most properties a significant influence of pressing process was found (Table II). Focusing on MOE and MOR, panel properties are nearly at the same level, when using a DBP or laboratory single-daylight press. Using a single-daylight press in industrial scale, lower bending properties were achieved. It was shown by varying press type (continuous and single-daylight) and scale (laboratory and industrial) that results from laboratory scale test are not inevitable transferable when increasing manufacturing scale. In particular, a change in press type may result in increased properties while the reason can only be hypothesized.

### Effects of Granulate Type on the Pressing Process

The more intensive friction and kneading movements in a DRA let the granulate appear differently in comparison to those made using a HCM. DRA granulate has a globular structure

**Table I.** Results of Statistical Analyze (ANOVA) Concerning the Influence of Press Temperature in the Middle Layer (Alternative Hypothesis) on Physical and Mechanical Panel Properties (170°C, 1300 s; 190°C, 900 s; 210°C, 800 s)

| Press technology | Double belt process | Laboratory press | | | | | Significance |
|---|---|---|---|---|---|---|---|
| Press temperature | 210 °C | 170 °C | 190 °C | | 210 °C, | | level |
| Press time | – | 1300 s[a] | 900 s[a] | 500 s[a] | 800 s[a] | *P*-value | at $\alpha = 0.01$ |
| Water absorption (%) after submersion time | | | | | | | |
| 24 h | 0.9[b] ± 0.0 | 1.4 ± 0.1 | 1.3[c] ± 0.1 | 2.1 ± 0.2 | 1.1 ± 0.1 | <0.01 | s. |
| 168 h | 1.9[b] ± 0.1 | 3.4 ± 0.4 | 3.1 ± 0.2 | 5.7 ± 0.4 | 2.9 ± 0.6 | 0.02 | n.s. |
| 672 h | 4.3[b] ± 0.2 | 6.4 ± 0.6 | 6.4 ± 0.2 | 8.2 ± 0.7 | 6.4 ± 0.8 | 0.05 | n.s. |
| Thickness swelling (%) after submersion time | | | | | | | |
| 24 h | 0.4[b] ± 0.3 | 0.6[c] ± 0.8 | 0.6[c] ± 0.2 | 1.3[d] ± 0.6 | 0.6[c] ± 0.2 | 0.98 | n.s. |
| 168 h | 1.0[b] ± 0.3 | 1.3[c] ± 0.7 | 1.5[c] ± 0.2 | 2.2[d] ± 0.5 | 1.7[c] ± –0.7 | 0.43 | n.s. |
| 672 h | 1.8[b] ± 0.5 | 2.2[c] ± 0.7 | 2.3[c] ± 0.2 | 5.4[d] ± 0.3 | 2.6 ± 0.5 | <0.01 | s. |
| Internal bond (N mm$^{-2}$) | – | 5.1 ± 0.9 | – | 3.6[d] | 5.8 ± 0.5 | – | – |
| Module of elasticity (N mm$^{-2}$) | 4567[b] ± 158 | 2953 ± 78.5 | 3149[c] ± 38.9 | 2929 ± 87 | 3161 ± 52.0 | <0.01 | s. |
| Module of rupture (N mm$^{-2}$) | 46.5[b] ± 2.0 | 28.0 ± 1.5 | 30.4[c] ± 0.5 | 18.3 ± 1.9 | 31.3 ± 0.8 | <0.01 | s. |

[a]Required press time to achieve press temperature in the middle layer; [b]Average value (1.03 g cm$^{-3}$); [c]Average value (1.01 g cm$^{-3}$); [d]Average value (0.93 g cm$^{-3}$).
n.s. = not significant; s. = significant
Raw materials: WF1; PP1 (die ring agglomerator). Wood flour content: 50%. Specific press pressure: 47 N cm$^{-2}$ (170°C, 1300 s; 190°C, 900 s; 210°C, 800 s), 700 N cm$^{-2}$ (190°C, 500 s). Panel densities were normalized to 1.03 g cm$^{-3}$.

while HCM granulate grains are more jagged and have a wider size distribution. Due to its specific structure, the kind of granulate effects the pressing process. Consequently, each granulate type requires an adapted pressing program.

Figure 4 shows the pressing diagrams recorded during manufacturing test panels from a DRA granulate and a HCM granulate. It was found that a HCM granulate needs longer times to reach target thickness and temperature in the middle layer. Further on, in the second part of the pressing program higher pressure was needed to compact the raw material in comparison to a DRA granulate. This effect was also observed manufacturing panels using the industrial DBP.

The different structure of the two granulates can be utilized for explaining the difference in core layer heating. The voluminous characteristic, the inhomogeneous particle size, and the less intensive agglomeration of the raw materials of HCM granulate

**Table II.** Results of Statistical Analyze (ANOVA) Concerning the Influence of Press Technology (Alternative Hypothesis) on Physical and Mechanical Panel Properties

| | | Double belt press | Single-daylight press | Laboratory press | *P*-value | Significance level at $\alpha = 0.01$ |
|---|---|---|---|---|---|---|
| WF1/PE1 | Water Absorption (%) after submersion time | | | | | |
| | 24 h | 2.4[a] ± 0.1 | 1.4 ± 0.1 | 1.4 ± 0.1 | <0.01 | s |
| | 168 h | 4.0 ± 0.1 | 2.9 ± 0.1 | 3.2 ± 0.2 | <0.01 | s |
| | 672 h | 7.5 ± 0.1 | 5.8 ± 0.2 | 6.3 ± 0.3 | <0.01 | s |
| | Thickness Swelling (%) after submersion time | | | | | |
| | 24 h | 1.3[a] ± 0.1 | 1.0 ± 0.2 | 1.1[a] ± 0.2 | 0.01 | n.s. |
| | 168 h | 2.2[a] ± 0.2 | 1.8 ± 0.3 | 1.9 ± 0.1 | 0.03 | n.s. |
| | 672 h | 3.8[a] ± 0.4 | 2.8 ± 0.4 | 2.7 ± 0.2 | <0.01 | s |
| | Module of elasticity (N mm$^{-2}$) | 2072[a] ± 52 | 1732[a] ± 47 | 2047[a] ± 67 | <0.01 | s |
| | Module of rupture (N mm$^{-2}$) | 19.6[a] ± 0.6 | 18.2[a] ± 0.5 | 20.1 ± 0.2 | <0.01 | s |
| WF2/PP1 | Module of elasticity (N mm$^{-2}$) | 3404[b] ± 152 | 2731[c] ± 116 | 3350[d] ± 90.8 | <0.01 | s |
| | Module of rupture (N mm$^{-2}$) | 31.4[b] ± 2.7 | 30.4[c] ± 1.0 | 29.9[d] ± 1.6 | 0.01 | n.s. |

n.s. = not significant, s. = significant; [a]1.07 g cm$^{-3}$; [b]1.04 g cm$^{-3}$; [c]1.1 g cm$^{-3}$; [d]1.08 g cm$^{-3}$.
Raw materials were compounded using a die ring agglomerator. Wood flour content: 50%. Panel densities were normalized to 1.07 g cm$^{-3}$.

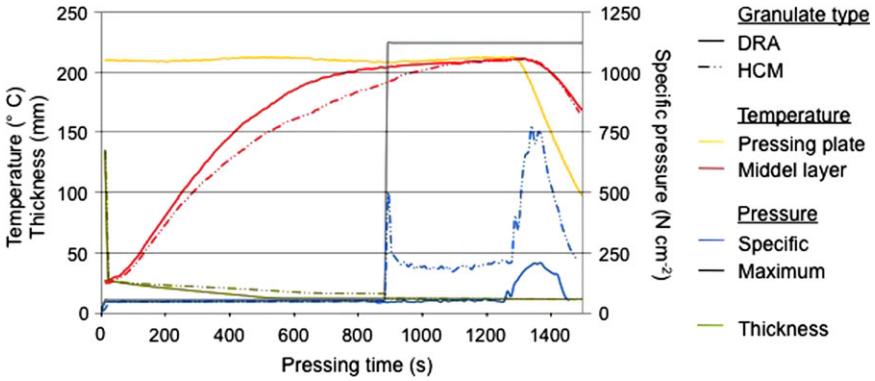


**Figure 4.** Pressing diagram for a DRA and a HCM granulate. Raw materials: WF1, PP3. Wood flour content: 70%. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

result in lower heat transfer rates. Due to the insulation effect of the air between the compound particles, the polymer plasticizes later and target thickness cannot be achieved as quickly as for a DRA granulate. Consequently, in the second pressing step a higher pressure is needed do compact the granulate.

## CONCLUSION

It was the aim of the present article to illustrate and discuss how agglomeration and pressing process influence the performance of WPC panels. In addition, the effects of MFR and CA were studied. For this purpose, wood particles and polymers were agglomerated in a HCM or in a DRA, respectively. The granulates were then processed into test panels using a single-daylight press in laboratory scale, a DBP and a single-daylight press, both in industrial scale. It was found that panel properties increased when using a high MFR polymer, or if a CA was added. This is in particular the case for HCM compounding since less intensive internal material shear and kneading movements using this technique can be compensated. A better processability was found for DRA granulates because its higher bulk density allows a quicker heat up of the material in the press and the required pressing pressure was lower. The increase of pressing temperature from 170 to 210°C results in a decreased pressing time because the heat transfer and the melt temperature in the middle of the panel were reached quicker. A PE- and a PP-based WPC granulate were processed to WPC panels using a continuous DBP, an industrial single-daylight press and a single-daylight press in laboratory scale. It was found that the physical properties reached nearly all the same level, while the MOE for industrial single-daylight pressing was found to be significantly lower. In sum, agglomeration and pressing process were found to strongly affect the properties of flat pressed WPC panels. However, these variables need to be considered in context with the characteristics of the raw material used. As the addition of a CA was found to be needed when low MFR polymers and wood flour are compounded with a HCM, that fact does not apply for high MFR polymers or ring die agglomeration. Likewise, superior mechanical properties of samples made on the DBP can be interpreted as an adventitious combination of raw materials and agglomeration and pressing process. Finally, in respect to the relatively high prices of virgin polymer and virgin wood flour, properties of WPC panels will be a result of economically available raw materials and processing equipment applied in commercial practice. The feasibility of industrial-scale WPC panel manufacture was demonstrated in this study for both, the continuous and cyclic pressing process. This implies that the production of WPC panels could be realized immediately so that the market for low maintenance, high durable and high water resistance composite materials could be enriched by large dimensioned plate-shaped WPC panels which are able to discover new fields of application.

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