

## EFFECTS OF ALTERNATIVE RAW MATERIALS AND VARYING RESIN CONTENT ON MECHANICAL AND FRACTURE MECHANICAL PROPERTIES OF PARTICLE BOARD

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Particle boards were produced from different types of wood particles, *i.e.* spruce, recovered particles, willow, poplar, and locust. Effects of raw material, as well as varying resin content on mechanical and fracture mechanical properties were investigated. For the analysis of mechanical properties, specific fracture energy, stress intensity factors, and the industrial European standard methods internal bond strength according to EN 319 and bending strength according to EN 310 were used. The total fracture energy was measured, and the stress intensity factor was calculated by means of data achieved through finite element simulations. Results of the fracture energy analysis were compared to internal bond strength (IB) and bending strength. While IB and the modulus of elasticity (MOE) showed a high variability, data scattering for fracture energy tests and modulus of rupture (MOR) were smaller, which are due to significant differences between the resin contents of the various board types.

*Keywords:* Bending strength; Internal bond strength; Particle size; Plantation raw material; Resin; Specific fracture energy; Stress intensity factor

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### INTRODUCTION

Providing a continuous raw material supply at low raw material costs is an increasing challenge for the forest products industry (Youngquist 1999; Sellers 2000). Worldwide, a growing number of industrial plants processing forest products are facing raw material shortages; some of them even operate below 50 % of their capacity (Setunge *et al.* 2009). Nowadays, approximately 95 % of the lignocellulosic material that is used for particleboard (PB) production is wood from forests (Ghalehno *et al.* 2010). The capacity extension and parallel decreasing availability of forest based wood material for the PB production raises the question of alternative resources. The list of tested raw materials for PB production is widespread. Among these are bagasse (Youngquist *et al.* 1997; Nikvash *et al.* 2010), straw (Dai *et al.* 2004), flax sieves (Heslop 1997; Papadopoulos and Hague 2003), bark (Nemli *et al.* 2009; Pedieu *et al.* 2009), bamboo (Rowell and Norimoto 1988), cotton (Alma *et al.* 2005; Guler and Ozen 2004), hemp

(Nikvash *et al.* 2010), and various others. The main problem with these natural raw materials is their periodic availability. Additional problems arise from different surface characteristics, such as an increased wax content, which results in a reduced mechanical performance.

Studies dealing with wood material from plantations (*e.g.* eucalyptus, *Pinus radiata*, poplar, willow, and locust) showed that these resources have favorable characteristics such as rapid growth rates, short harvesting cycles, continuous availability, and low cost. Naturally grown poplar wood is used for the manufacture of numerous wood-based products. The wood of poplar species has relatively low density and a diffuse porous structure (Balatinecz *et al.* 2001). Especially in the United States and in Canada, indigenous poplar sources were rapidly tapped by industry due to the increasing costs of softwood. The utilization possibilities of hybrid poplar are the same as those for indigenous poplar wood. Additionally, hybrid poplar has the advantage of improved quality traits due to genetic modification. According to Berjan (2000) and Dinus (2000), plantation poplar has a high potential to be a major source of wood fiber in the future. From the perspective of the wood based panel industry, plantation poplar shows inferior properties in comparison to native poplar, due to strength reduction and extractives (Bendtsen *et al.* 1981; Kretschmann *et al.* 1998).

Balatinecz *et al.* (2010) describe the usage of willow and poplar as an alternative resource for the particle board production. The material tests (EN 319) revealed values which are in the range of the standard requirements and predestine these raw materials for industrial usage. Both species are well-suited as PB materials because of their good bonding characteristics and compressibility (Geimer and Crist 1980). Another alternative raw material for PB manufacturing is locust, produced on plantations. Weight-reduced particleboards (raw materials: willow and black locust) were produced and tested by Kowaluk (2009) and showed promising results, especially for the willow species.

The chemical composition of poplar and willow is characterized by a high content of polysaccharides and low lignin content (Balatinecz *et al.* 2010). Mullins and McKnight (1981) reported an almost extractive-free wood basis. In their paper, the pH-value of poplar is reported to be in a range of 5.8 to 6.4, causing no reactions with resins such as urea formaldehyde or with preservatives. In contrast to that, Nemli *et al.* (2004) manufactured particleboards from black locust and noted that the tannin contents reduce bonding properties. Besides these factors, especially silica, phenol and some oxidants have been reported to have a positive effect on mechanical properties.

The resin content is one of the main components affecting the board performance. In the particle board production process, increasing the resin content is used as the first possibility to respond to board strength variation (Dunky and Niemz 2002): the internal bond strength increases significantly with a raised resin content (Lehmann 1970). Similar tendencies can be seen with the bending strength as it rises with increased resin content.

Testing wood based panels by means of bending strength gives information about the bending stress of the specimen. However, specimens in bending tests usually fail due to the tension in the bottom face layer. Therefore, the tensile strength of the surface layers has the greatest influence on the bending strength (BS). In comparison, the internal bond strength (IB) provides information about the tensile strength perpendicular to the surface layers and separates the specimen mostly in the middle layer. The IB depends on the raw

material, the resin content, the bulk density, and the vertical density profile, and is affected by different process parameters. Nevertheless, the strength value resulting from IB tests only gives information on the bond strength. No additional values, such as Young's Modulus or the fracture energy, can be derived from the IB test procedure. Therefore, the IB test is unsuitable for studying the effects of inhomogeneous resin distribution, particle size, morphology, and orientation (Geimer 1981; Wang and Lam 1999). In contrast, fracture energy concepts – although mechanically more challenging – promise a higher yield of information concerning material characteristics and the separation process of the two specimen halves. The essential factors in the fracture mechanical analysis are the presence of cracks and the crack growth. The first energetic fracture concept, including the determination of the energy necessary for crack growth, was developed by Griffith (1920).

One approach to the analysis of wooden material, based on a method called “corrected compliance” by Gagliano and Frazier (2001) uses a double cantilever beam (DCB) specimen geometry. Thereby, a load is applied and the testing procedure continues until a load drop of 3% occurs due to the formation of cracks. When failure occurs, the cross head speed is stopped and the crack length is quantified on both sides of the specimen. This procedure is continued until total failure of the DCB specimen takes place. For the analysis, a load displacement curve of each load cycle is plotted over the crack length, and a fitted equation is generated, using the failure values of the testing procedure. The fitted curve enabled the calculation of the fracture energy [ $\text{J/m}^2$ ]. Further investigations using double cantilever beam specimen for solid wood and bonding analysis were performed by Šernek (2002), Liswell (2004), and Veigel *et al.* (2010). One of the main problems with this testing procedure is the measurement of the crack length (Eckmann 2007). The determination of the crack length in terms of wood and wood based panels is difficult, as a lot of micro cracks occur (Frühmann *et al.* 2002). Parallel measurements at the front and the back of the specimen do not allow a complete crack determination.

Another approach to testing wood and wood based panels with non-linear elastic fracture mechanics (NLEFM) is the wedge splitting experiment, developed and patented by Tschegg (1986). Earlier studies using the wedge splitting method for testing particle boards (*e.g.* Ehart *et al.* 1996; Sinn *et al.* 2008), forcing the specimen to fail only through opening the sample in Mode I. Here, no loading and unloading cycles were necessary; only the load-displacement curve was recorded. The fracture energy  $G_f$  then was simply determined by integration of the load displacement curve.

The objectives of this study were (1) to compare five different raw materials for the particleboard production and (2) to analyze the effect of varying resin content in the raw material groups on mechanical properties. In addition (3), three different types of mechanical testing (*i.e.* internal bond strength, bending strength, and fracture testing by means of the double cantilever-I-beam test) were compared, as the data quality was assumed to differ significantly when using different testing procedures.

## MATERIALS AND METHODS

### Design of Experiment

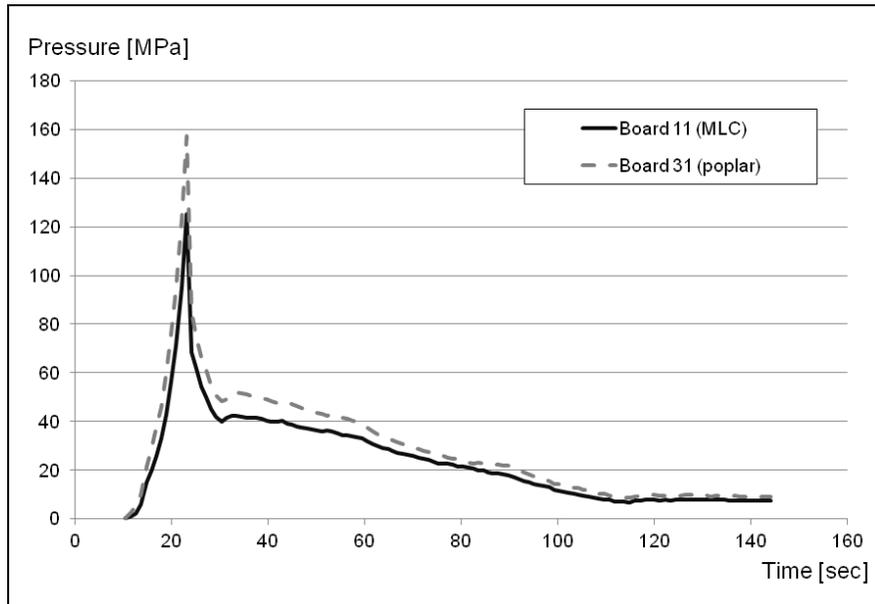
Wood particles were prepared by means of a laboratory knife ring flaker (willow, *Salix sp.*, poplar *Populus sp.*, locust *Robinia pseudacacia L.*), an industrial knife ring flaker (spruce), and an industrial hammer mill (recovered particles). The settings of the knife ring flaker were kept constant to generate the same particle shape. In the following, the particles were dried at 103°C to a moisture content of approximately 2.5 %. The experimental variables were:

- 5 raw material types (standard particles (spruce), recovered particles, willow, poplar, and locust)
- 3 resin content gradations (*i.e.* 5.6%, 7.0%, 8.4% UF E05)
- 4 replications per board

The resin used was a urea formaldehyde resin (Dynea Prefere 10F152). This resin has a solids content of 66.0% to 66.8%, a pH value of 9.0 to 10.0, and a density of 1.29 g/mL.

### Particleboard Manufacture

All panels were prepared in the laboratory. Boards were manufactured as single layer boards to exclude variations in particle distribution. The particles had a moisture content of 2.1% for poplar and particle board (PB) particles, 2.3% for willow, and 2.4% for recovered particles and locust. After drying, the particles were stored in airtight plastic containers and then used in the laboratory without any further treatment.



**Fig. 1.** Two selected press power curves, showing a middle layer (MLC) and a poplar press cycle

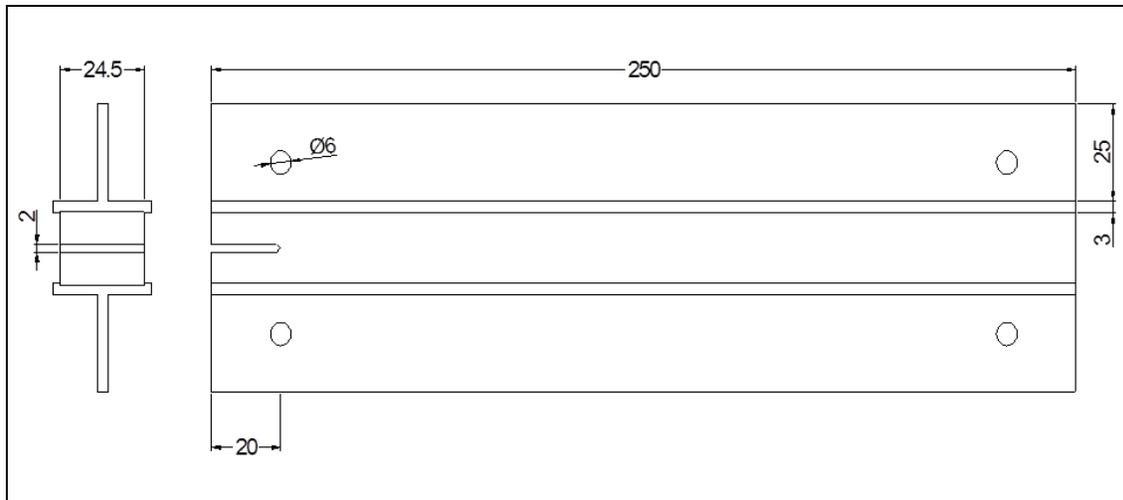
To prepare the panel mat, the wood furnishes were weighed out to a target board density of 600 kg/m<sup>3</sup> and placed in the Ploughshare® GMP batch mixer (Lödige). The resin was weighed to a mass of 5.6%, 7.0%, and 8.4% dry resin per the oven dry weight of wood and then applied using an air pressure air-atomizing nozzle. In this study, no wax or catalyst was used. After blending, the wood particles were manually strewed into a 50.0 cm x 69.0 cm box to form the mat. The mat was then directly placed in a single-opening laboratory hot-press.

The plate temperature was regulated to be 200 °C, and the pressure was applied according to the press power curve shown in Fig. 1, yielding a final board thickness of 14 mm with a press factor of 9.3 s/mm after reaching the maximum pressure. Hence, the pressing time per board was 145 s. After pressing, the boards were conditioned at 25 °C and 65 % relative humidity (RH).

### Specimen Preparation

Sample sets for double cantilever I-beam (DCIB) testing, internal bond strength (IB) testing, and bending strength (BS) testing were gained from the laboratory produced particleboards. The specimens were stored for several weeks in a standard climate 20 °C/65 % RH, until the equilibrium moisture content was reached.

The DCIB specimens had a length of 250 mm and a width of 24.5 mm (Fig. 2). Before further processing, the density of each specimen was determined by means of dimensional and gravimetric measurements. A notch of 20 mm depth was sawn into the middle layer parallel to the panel surfaces using a band saw (saw kerf-thickness 2 mm). Two braces were glued to each of the specimens with a fast-curing cyano-acrylate adhesive (Loctite 431, Henkel). To guarantee a direct load application in the middle layer, metallic T-beams were used as braces, which appear as an “I” in combination with the specimen. This leads to the name of the new testing procedure – double cantilever I-beam test (DCIB).



**Fig. 2.** Geometry of double cantilever I beam (DCIB) specimen. All dimensions in mm

The IB analysis was performed according to EN 319 (1993). The IB specimens (50 mm x 50 mm) were taken from a position parallel and next to the DCIB samples from the same boards. Before testing, the IB specimen were bonded to aluminum braces using the same cyano-acrylate resin (Loctite 431, Henkel) as with the DCIB specimen.

Bending strength (BS) specimens with dimensions of 50 mm x 330 mm were cut from particleboards parallel to DCIB specimen. The material testing was performed according to EN 310 (1993). After cutting, the specimens were tested without further treatment.

### Fracture Energy Testing

The fracture tests, using the DCIB specimen, were performed on a Zwick/Roell Z100 universal testing machine equipped with a 2.5 kN load cell. To test the fracture energy, a tensile load is applied perpendicularly to the middle layer area, which leads to fracture in Mode I.

The specimens were clamped into fasteners with pins, and a load was applied at the notched end of the specimen, leading to stresses in the specimen. The tip of the initial notch was at half distance of the connection line between the upper and the lower pin borehole to permit a direct force application (see Fig. 2). The cross head speed was chosen to be 1 mm/min. After reaching a force drop of 50 % of the maximum load, a progressive increase of the cross head speed up to 10 mm/min was applied. The test was stopped after a maximum displacement of 50 mm or a remaining force of 5 N. These settings guaranteed a testing period of maximally 3 minutes.

The fracture energy was calculated by a simple integration of the area below the load-displacement curve (Fig. 3). The results reflect the fracture work necessary to split the specimens into two parts. According to Hu and Wittmann (1992), the specific fracture energy  $G_f$  is the energy applied in stable or quasi-stable fracture of a notched specimen which is averaged over the fracture area. Relating the separation area to the fracture work, the specific fracture energy (J/m<sup>2</sup>) can be calculated according to Equation 1,

$$G_f = \frac{1}{(L-a)B} \int_0^{z_{\max}} F(dz) \quad (1)$$

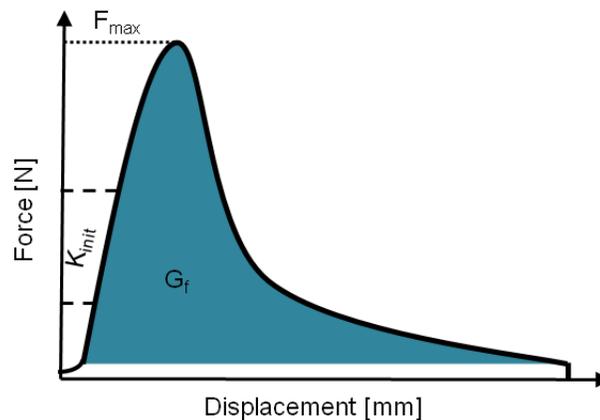


Fig. 3. Load-displacement curve of Double Cantilever I-Beam testing

where  $F$  is the applied force,  $z$  is the displacement at the loading point,  $a$  is the initial crack length, and  $L$  and  $B$  are the total length and the width of the specimen.

Tabulated formulas for stress intensity factors are based on the assumptions of isotropic materials and simple geometries. In order to determine the critical stress intensity factor  $K_{Ic}$  under Mode I, considering the composite DCIB-specimen, material tests were performed and the data was used for a finite element simulation using the ABACUS® software. The problem was reduced to a two-dimensional plain strain model. The J-Integral stress intensity factor algorithm from Abaqus® was used to derive Equation 3 from a number of simulations with an adjustable isotropic modulus of elasticity of the board. The relative error between the FEM-simulation and Equation 2 is less than 0.5 % for  $3.165 < \frac{k_{init}}{b} < 1100$ .

$$K_{Ic} = F_{max} \left[ (6.568E-05) + (2.082E-7) \cdot \frac{k_{init}}{b} + (-1.498E-10) \cdot \left( \frac{k_{init}}{b} \right)^2 + (5.253E-14) \cdot \left( \frac{k_{init}}{b} \right)^3 \right] \quad (2)$$

Hereby,  $F_{max}$  reflects the maximum applied load,  $k_{init}$  is the initial slope, and  $b$  is the specimen width.

### Internal Bond Strength Testing

The determination of the internal bond strength according to EN 319 (1993) was performed on a Zwick/Roell Z020 universal testing machine. The specimen were tested until failure with a continuous crosshead speed of 0.5 mm/min. Failure occurred within  $60 \pm 30$  s after applying a pre-force of 20 N. The internal bond strength ( $f_t$ ) was calculated according to equation (3) by dividing the maximum load  $F_{max}$  by the cross section ( $a \cdot b$ ) of the specimen.

$$f_t = \frac{F_{max}}{a \cdot b} \quad (3)$$

### Bending Strength Testing

Flat-wise three-point bending tests were performed in correspondence to EN 310. Samples with dimensions of 330 mm length,  $b = 50$  mm width, and  $t = 14$  mm thickness were tested using a Zwick/Roell Z100 universal testing machine with a crosshead speed of 7.5 mm/min. The specimen thickness leads to a free span length  $l_1$  of 280 mm. To exclude layering effects of face layer and bottom layer, each second specimen was tested upside down. Specimen failure occurred within  $60 \pm 30$  s after an applied pre-force of 10 N. The determination of the modulus of elasticity  $E_m$  according to EN 310 is given in Equation 4.

$$E_m = \frac{l_1^3 (F_2 - F_1)}{4bt^3(a_2 - a_1)} \quad (4)$$

$F$  generally describes the force increase in the linear elastic part of the force-bending diagram.  $F_1$  is the force at 10% of the maximum load, while  $F_2$  reflects 40%. The variables  $a_1$  and  $a_2$  describe the bending progression corresponding to  $F_1$  and  $F_2$ . The bending strength was calculated as described in equation 5.

$$f_b = \frac{3F_{\max}l_1}{2ab^2} \quad (5)$$

## RESULTS

### Effect of Resin Content on Strength Properties

The results of the mechanical testing, divided into particle and resin content groups, are presented in Fig. 4. For the statistical analysis, a one-way analysis of the variance (ANOVA,  $p < 0.05$ ), followed by a post hoc multiple  $t$ -test with the Bonferroni procedure was performed using SPSS®. The Bonferroni procedure was used, as no variance homogeneity was found and the sample number was unequal.

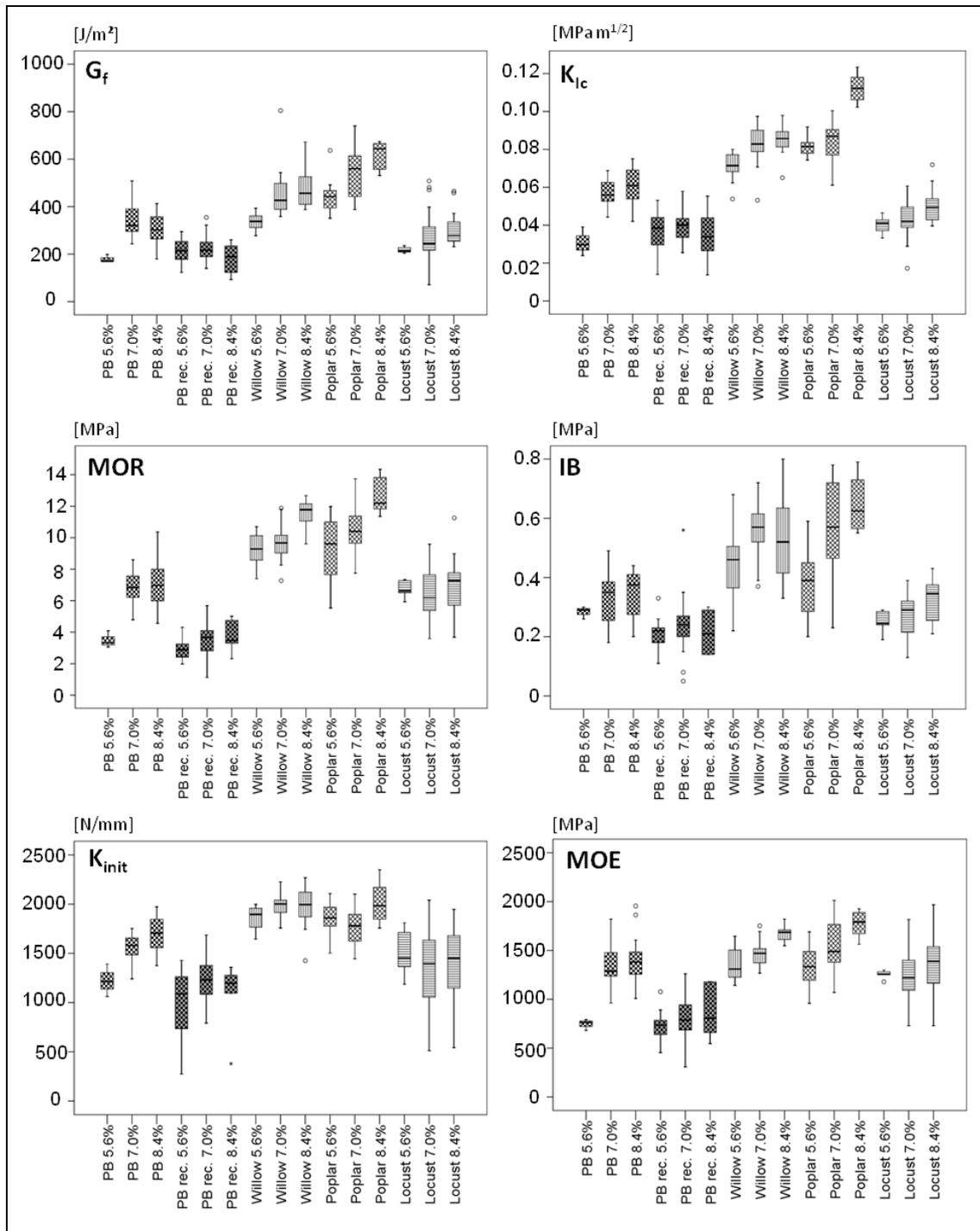
In Table 2, the specifications of the specimen are presented. The number of test specimen varied greatly, which is due to material failure during the specimen preparation. The target density was 600 kg/m<sup>3</sup>; however, the measured values were generally lower.

**Table 2.** Characteristic Data of the Tested Particleboards

Raw material	Resin content	Abbreviation	N	Density [kg/m <sup>3</sup> ]
Industrially produced particles	5.6 %	PB 5.6 %	6	522.5 ±26.3
Industrially produced particles	7.0 %	PB 7.0 %	23	568.4 ±19.0
Industrially produced particles	8.4 %	PB 8.4 %	16	579.7 ±29.3
Recovered particles	5.6 %	PB rec. 5.6 %	15	603.6 ±18.2
Recovered particles	7.0 %	PB rec. 7.0 %	33	581.4 ±45.2
Recovered particles	8.4 %	PB rec. 8.4 %	6	531.4 ±72.3
Willow	5.6 %	Willow 5.6 %	16	569.9 ±15.4
Willow	7.0 %	Willow 7.0 %	23	601.0 ±29.9
Willow	8.4 %	Willow 8.4 %	15	585.3 ±19.7
Poplar	5.6 %	Poplar 5.6 %	16	592.5 ±35.6
Poplar	7.0 %	Poplar 7.0 %	24	571.2 ±20.4
Poplar	8.4 %	Poplar 8.4 %	8	598.8 ±23.4
Locust	5.6 %	Locust 5.6 %	8	582.5 ±8.5
Locust	7.0 %	Locust 7.0 %	39	571.0 ±32.1
Locust	8.4 %	Locust 8.4 %	16	617.0 ±46.0

The specific fracture energy ( $G_f$ ), determined by the DCIB test procedure, shows significant differences between the raw materials, as well as the resin contents (RC). PB 5.6% RC differed significantly from PB 7.0% RC and PB 8.4% RC. In the PB rec. group, no significant difference between the resin content groups was found. Willow showed the same tendencies as PB: the willow 5.6% RC group lies considerably lower than the willow 7.0% RC group and the willow 8.4% RC group, while the latter do not differ

greatly. Within the poplar group, no significant difference can be found. Locust, in contrast, showed the same significant arrangement as PB and willow.



**Fig. 4.** Results of: specific fracture energy  $G_f$ , stress intensity factor  $K_{Ic}$ , modulus of rupture MOR, internal bond strength IB, initial slope  $K_{init}$ , and modulus of elasticity MOE, for laboratory produced particleboards

Besides the total fracture energy, the stress intensity factor  $K_{Ic}$  was measured. This value gave similar results as  $G_f$ . The results for PB and willow are the same as for  $G_f$  discussed above: the PB 5.4% RC group differed perceptibly from the other two resin content groups. No significant differences between the resin content groups were found for PB rec. and locust. For poplar, the 5.6% RC and 7.0% RC were rather similar, while the 8.4% RC group lay significantly higher.

The analysis of the internal bond strength values only showed significant differences between the resin content groups for the poplar group. For the other raw material types, no effect was measurable. Analyzing poplar more closely, one finds that the 5.6% RC group differed markedly from poplar 7.0% RC and poplar 8.4% RC, while the last two groups were relatively equal.

The bending strength (*i.e.* the MOR) showed the same characteristics as  $G_f$ : the PB 5.6% RC group was significantly different from the other PB groups. For PB rec., no significant differences were found. Willow, in contrast, had highly different values for willow 8.4% RC than for willow 5.6% RC and willow 7.0% RC, while both lower groups did not show any differences. For poplar, significant differences were found for poplar 8.4% RC, which is similar to the findings of willow.

The modulus of elasticity also showed significant differences for PB 5.6% RC as opposed to the other two groups, between which no significant difference was found. For PB rec. and locust, no significant differences were found between the resin content groups, while both willow and poplar showed large differences between 5.6% RC and 8.4% RC.

### Comparison of Three Mechanical Testing Procedures

The bending strength, the internal bond strength, the specific fracture energy, the stress intensity factor, the initial slope of fracture tests, and the modulus of elasticity are six different parameters used to describe material characteristics. The coefficient of variation (CV) is a relative spread and therefore used to compare unequal systems with different units of measure. In Table 3, the CV is used to compare the testing systems with data gained from mechanical testing of the five different particle board types (*i.e.* PB, PB rec. willow, poplar, and locust).

**Table 3.** Comparison of Mechanical Testing Systems by Means of Coefficient of Variation

	$G_f$	$K_{init}$	$K_{Ic}$	IB	MOR	MOE
PB	17.7 %	11.7 %	17.7 %	19.1 %	17.9 %	14.1 %
PB rec.	28.0 %	28.6 %	31.0 %	31.4 %	26.8 %	26.0 %
Willow	17.1 %	7.9 %	10.2 %	23.2 %	10.1 %	8.6 %
Poplar	14.9 %	9.3 %	8.2 %	25.1 %	14.7 %	12.8 %
Locust	20.7 %	23.0 %	16.6 %	21.0 %	19.6 %	14.7 %
Average	19.5 %	16.1 %	16.7 %	24.0 %	18.8 %	15.2 %

For PB and PB rec., the CV did not differ much between the testing systems. The comparison by means of the willow data showed the lowest numbers for  $K_{init}$  and MOE.  $K_{Ic}$  and MOR performed with the same quality, while IB displayed the poorest data. For

poplar, the scatter was lowest for  $K_{init}$  and  $K_{Ic}$ , while  $G_f$ , MOR, and MOE were in the same range. Once again, IB had the highest values. Analyzing locust, it is evident that only  $K_{Ic}$  and MOE had lower values, while the other four groups were on the same level.

The last row shows the average values for the CV. Overall,  $K_{init}$ ,  $K_{Ic}$ , and MOE performed with the lowest values, while MOR and  $G_f$  showed values in the same range. In contrast, the internal bond strength shows the highest average numbers for the coefficient of variation, which indicates high scattering.

## DISCUSSION

### Raw Material Type vs. Mechanical Characteristics Determined by Means of Fracture Energy Testing

Standard wood chips used for particle board production have better mechanical characteristics compared to particle boards manufactured from recovered wood chips. The poor performance of PB manufactured from recovered wood chips can be explained by the high density and material variation of these particles. Furthermore, the geometry of the recovered particles, when inspected visually, was highly inhomogeneous.

In contrast, poplar and willow exhibited the best mechanical characteristics in all resin content groups. It seems that the densification of the fiber mat during the pressing process has a positive impact on the material characteristics. This positive effect using plantation grown poplar and willow is due to the low density of the raw material. Locust reveals material characteristics in the same range as standard, green particles. The increased resin content does not yield significantly better mechanical values, which is due to the acidic surface of locust. The good performance of poplar can be traced back to the outstanding densification characteristics. The effect of better performance using poplar in comparison to industrial PB chips and locust chips has also been described by Kowaluk *et al.* (2011). Especially for locust, the acidic surface leads to a different resin and hardening behavior.

### Resin Content

Comparing the results from the mechanical tests in relation to varying resin content, it can generally be stated that increasing resin content has an improving effect on the board characteristics (see Fig. 3), which is in sound accordance with Dunky and Niemz (2002) and Lehmann (1970). A continuous increase of the mechanical performance with increasing resin content can be achieved with the raw materials willow, poplar, locust, and in most cases PB (aside from the  $G_f$  values, which fall with rising resin content) based on mean values. The values of PB rec. rise between 5.6 % and 7.0 % resin content, after which they fall again for IB and fracture testing related results. This leads to the conclusion that the resin content has a negligible effect on particle boards manufactured from recovered particles.

Comparing the results from the non-linear elastic fracture mechanics approach, it was shown that the  $G_f$  of poplar was almost twice as high as that of PB rec. The high fracture energy of poplar can probably be explained by the bridging effect. This effect was not visible for PB rec., as the cubic structure made particle rotation or bridging effects impossible. On the other hand, bridging of particles was observed during testing

for willow, PB, and locust specimen. The comparably cubic structure of recovered particles did not even yield higher  $G_f$  values when the resin content was increased. In general, the surfaces of the failed specimen were characterized by roughness and cracks which follow the orientation of bigger particles. Ehart *et al.* (1996) reported mean values of 240 J/m<sup>2</sup> for particle board middle layers using the fracture energy concept in combination with the wedge-splitting-method. These findings lie between our measured data of PB for 5.6 % RC and 8.4 % RC and confirm our data.

Analyzing resin content effect on  $K_{Ic}$ , the tendencies are similar to those for  $G_f$ . Using  $K_{Ic}$ , it was, in some cases, possible to find significant differences between resin content in raw material groups. Differences were found for willow 5.6% RC and poplar with a resin content of 8.4%.

The internal bond tests showed no significant differences at all. The imprecise data of the IB method is in this case due to the high scattering in the testing procedure. One study, performed by Kowaluk *et al.* (2011), showed IB values for laboratory produced particleboard with industrially produced face layer particles and 8% UF RC of 0.51 MPa, 0.47 MPa for willow with a RC of 8.0% in the middle layer and 0.24 MPa for locust with a RC of 8.0%, respectively. The presented IB values for willow and locust are slightly higher than values reported by Kowaluk *et al.* (2011). On the other hand, the IB values of particleboards containing only industrially produced particles were significantly higher in our study. Similar tendencies can be found for bending strength testing. Kowaluk *et al.* (2011) found MOR values for particle boards made from industry particles of 7 MPa, which fits in the gap between PB 7.0 % RC and PB 8.4 % RC. The same can be stated for willow values of 12.5 MPa, and the locust values of 9.5 MPa, which is slightly higher than our data. While the MOR yields data of high precision, the high scatter of the MOE data makes a significant differentiation impossible. However, both evaluation methods yield the highest values for poplar with a RC of 8.0 %, which is the same as  $K_{init}$  of poplar with a RC of 8.0 %.

### Comparison of Mechanical Testing Systems

The comparison of mechanical testing systems by means of coefficient of variation (CV) showed the poorest characteristics for the internal bond strength in comparison to the other procedures.  $K_{init}$  and MOE both use data of the slope of the linear elastic part of the load displacement curve. The CV numbers of the  $K_{init}$  are generally lower than those of MOE. Only the test results for locust have much higher values for  $K_{init}$ . The analysis of  $G_f$ ,  $K_{Ic}$ , and MOR showed that all these testing systems work equally well. The CV numbers of the stress intensity factor  $K_{Ic}$  were lowest for the raw material types willow, poplar, and locust. Thus, the most precise material determination can be performed with a stress intensity factor analysis.

### CONCLUSION

On basis of the results described above and the information from literature, the results can be summarized as follows:

1. The densification potential of the particles (poplar and willow), as well as surface characteristics (locust) have an important impact on board strength.
2. The resin content has an intense effect on willow, poplar, and locust. An effect of increasing resin content on the mechanical properties of boards made from recovered particles could not be determined.
3. Results for the IB strength test showed that this standard test method is designed for quality assessment and production control of wood based panels. If panels meet the threshold mark for different applications, sound bonding in the middle layer can be assumed. However, the IB test does not provide additional information relative to the mechanical properties and does not reflect structural differences of the panels due to the high scattering, which limits the possibility of further data analysis.
4. Regarding the method of fracture energy calculation using DCIB specimen geometry and data analysis by means of the fracture energy concept as described by Stanzl-Tschegg *et al.* (1995), a significant distinction of different board types is possible. Using stress intensity factor values for the board evaluation made the statistic distinction of the board characteristics even more precise. Bending strength also yields high quality data and is sufficient for the analysis of board characteristics. However, the data could not be differentiated as precisely as with fracture energy testing.
5. The validation of the mechanical testing procedures by means of the coefficient of variation showed poor numbers for internal bond strength. In contrast, fracture and bending values exhibited a low scatter and basically similar trends.

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