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The mechanical properties of densified VTC wood relevant for structural composites

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Abstract The mechanical properties of densified wood relevant for structural composites were studied. Low density hybrid poplar (*Populus deltoides* × *Populus trichocarpa*) was densified using the viscoelastic thermal compression (VTC) process to three different degrees of densification (63, 98, and 132%). The modulus of rupture (MOR) and the modulus of elasticity (MOE) of the control (undensified) wood and of the VTC wood were determined. The bonding performance of the control and VTC wood, using two phenol-formaldehyde (PF) adhesives, was studied. Four different 3-layer composites were also prepared from undensified and VTC wood, and tested in four-point bending. The results showed that the bending properties of the VTC wood (MOR and MOE) were significantly improved due to the increased density. The bonding performance of VTC wood with PF adhesives was comparable with or better than in the case of the control wood. Increased density of the face layers in the 3-layer VTC composites was advantageous for their mechanical performance.

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Mechanische Eigenschaften von verdichtetem VTC Holz als Ausgangsmaterial für Verbundwerkstoffe für tragende Zwecke

Zusammenfassung Die für tragende Verbundwerkstoffe relevanten mechanischen Eigenschaften von verdichtetem Holz wurden untersucht. Das Holz der Hybridpappel (*Populus deltoides* × *Populus trichocarpa*), einer Holzart mit geringer Dichte, wurde mit viskoelastischer thermischer Verdichtung (VTC) in drei verschiedenen Graden (63, 98, und 132%) verdichtet. Die Biegefestigkeit und der Elastizitätsmodul einer Referenzprobe und des VTC Holzes wurden bestimmt. Das Verklebungsverhalten mit Phenolformaldehyd (PF)-Harz einer Referenzprobe und des VTC Holzes wurden untersucht. Vier verschiedene dreilagige Schichthölzer wurden aus unverdichtetem und aus VTC Holz hergestellt und anschließend im 4-Punkt-Biegeversuch geprüft. Die Biegefestigkeit und der Elastizitätsmodul des verdichteten Holzes wurden durch die Verdichtung signifikant verbessert. Das Verklebungsverhalten des VTC Holzes mit PF-Harz war vergleichbar oder besser als das der Referenzprobe. Die erhöhte Verdichtung der Deckschicht des dreilagigen VTC Schichtholzes wirkte sich vorteilhaft auf die mechanischen Eigenschaften aus.

1 Introduction

The "green revolution" has increased public awareness regarding the efficient utilization of timber, and the protection of forest lands, particularly of old growth forests. As a result, a shift in the available resource base has occurred, from old-growth mature forests to intensively managed, short-rotation, forest plantations. Many species of trees are now grown in plantations where conditions are manipulated to encourage the rapid growth of the trees. Unfortunately, the demand for certain types of wood products cannot be adequately met with this kind of wood material, because of their low density and mechanical properties which do not allow them to be used as structural products.

The poor mechanical properties of low-density wood can be modified and improved by various combinations of compressive, thermal and chemical treatments. Wood can be compressed in the transverse direction (i.e. densified) under conditions that do not cause significant damage to the cell wall. The densified wood products thus obtain increased strength, stiffness and hardness.

Over the years, various methods of wood densification have been reported (Seborg et al. 1945, Inoue et al. 1993, Dwianto et al. 1999, Navi and Girardet 2000, Blomberg and Persson 2004). Recently, Kamke and Sizemore (2005) developed a method for wood densification using a viscoelastic thermal compression (VTC) process. The VTC process uses elevated steam pressure to achieve conditions above the glass transition temperature (T_g) of wood, which enables the production of high density products without destroying its micro-cellular structure. The product, viscoelastic thermal compressed wood (VTC wood), is intended to be used as a component in an engineered composite material such as sandwich composites.

Sandwich composites are extensively used in structural applications. They consist of two thin faces with high stiffness and high strength, and a core with low density and low stiffness. The faces are usually made of carbon fibres, a glass fibre composite, or metals, and the core is typically made of aluminium or of non-metallic honeycombs, end-grain balsa wood, or closed-cell polymer foams such as polyvinyl chloride or polyurethane (Gdoutos et al. 2001). Wood-based sandwich panels can also be found. Plywood-faced sandwich (PSW) panels with low-density fibreboards for use as wood-based structural insulated walls and floors have also been developed (Kawasaki et al. 2006). The development of the VTC process has enabled the development of a novel wood-based composite with low-density (undensified) wood in the core, and high-density VTC wood (densified) for the faces of the composite (Kamke and Sizemore 2005). The high-density VTC wood faces resist in-plane and bending loads, whereas the low-density core stabilizes the facings and carries the shear loads.

The aim of this paper is to examine the relevant mechanical properties of VTC wood, and to demonstrate that it can be used for the production of structural composites. The manufacturing of composite products from VTC wood requires adhesive bonding. The process of densification, and the various methods which are used to achieve stabilization, changes the anatomical structure of VTC wood. The high strain which occurs in the VTC process deforms the cell lumen and drastically reduces the total lumen volume, although the cells deform without fracture of the cell walls (Kutnar et al. 2008). The surface chemistry and surface free energy of VTC wood may also be altered. Consequently, the gluing effectiveness of VTC wood can be affected. The objective of the study was therefore also to determine the bonding performance of VTC wood with commercial structural adhesives. Furthermore, novel wood-based composites, called 3-layer VTC composites, were prepared and tested in order to determine their relevant structural properties.

2 The viscoelastic thermal compression of wood

As viscoelastic materials, amorphous polymers of wood can behave as viscous fluids and as linear elastic solids. The behaviour depends on the temperature and moisture, and on the time of exposure to the inducing conditions. The VTC process takes into account these viscoelastic properties. Hence the first stage of the VTC process is the softening of the cell wall by raising the wood components, by heat and humidity, to or above their T_g. When T_g is reached, rapid vapour decompression is induced, which causes the mechano-sorption effect (Grossman 1976). Rapid movement of water out of the wood cell wall occurs. The cells can transfer stress and resist strain, and the polymer molecules are able to deform under the applied load without cleaving. The density of the wood is then increased by compression. Since the polymer molecules within the cell wall are stretched, relaxation of the remaining stress has to be induced. The temperature of the process is therefore increased, which increases the molecular motion and assists stress relaxation. During this high temperature treatment, some thermal modification of the cell wall occurs. Cooling of the wood below T_g, and increasing its moisture content (MC), is the final step in the VTC process.

Whereas the VTC process softens the cells prior to compression, the VTC wood densification is achieved without cell wall fractures. The densification is due to the reduction of void spaces in the cellular structure of the wood. In general, the increase in density is in the range of between approximately 25% and approximately 500%, though preferably within the range of between 100 and 200%. High density and an unfractured cellular structure result in a wood product of high strength and dimensional stability (Kamke 2006).

The VTC process was designed to utilize rapidly-grown, low-density, wood species. In spite of this it can also be applied to any wood species of different densities and MC. Since during the VTC process, the movement of moisture is essential, thin wood components are better suited, since thinner wood components lose moisture more rapidly and uniformly. The thickness of the wood components should typically be within the range between 3 and 12 mm, prior to compression. The MC of the wood prior to the VTC process can be greater than the fibre saturation point, but a content of about 15 to 30% is preferred.

3 Materials and methods

3.1 The VTC process

Low density hybrid poplar (*Populus deltoides* × *Populus trichocarpa*) was densified using the VTC process. Three degrees of densification (63, 98, and 132%) were applied, following the procedure described by Kutnar et al. (2008). The obtained VTC wood with different degrees of densification had the same thickness, 2.5 mm. Prior and after the VTC process the specimens were conditioned in a controlled environment at a temperature of 20 °C and a relative humidity of 65%. At equilibrium, the control specimens achieved a MC of 12%, whereas the VTC specimens achieved a MC of 7%. This was due to the chemical changes in the wood components which occurred during the VTC densification process that reduced the hygroscopicity of the wood.

3.2 The bending properties of VTC wood

The control and VTC wood specimens were tested in bending to failure. In all cases, the test span was 100 mm, and the load was applied at the midpoint in 3-point bending. The loading rate was 3 mm/min (Fig. 1a). The testing parameters were density, modulus of rupture (MOR), and modulus of elasticity (MOE).

3.3 The bond strength of VTC wood in longitudinal tensile shear

A phenol-formaldehyde (PF) adhesive (Georgia Pacific Resins, Inc.) with a viscosity of 330 mPa s designed for OSB panels (adhesive A), and a plywood PF adhesive (Fenolit Borofen B-407/45) (adhesive B) with a viscosity of 360 mPa s, were used to bond the control and VTC wood specimens. The specimens were bonded in a hot-press for 6 min at 150 °C, using 155 $g\,m^{-2}$ adhesive coverage and a pressure of 700 kPa. All of the bonded specimens were conditioned in the controlled environment at a temperature of 20 °C and at 65% relative humidity. The joints bonded with adhesive A were tested six months after bond-

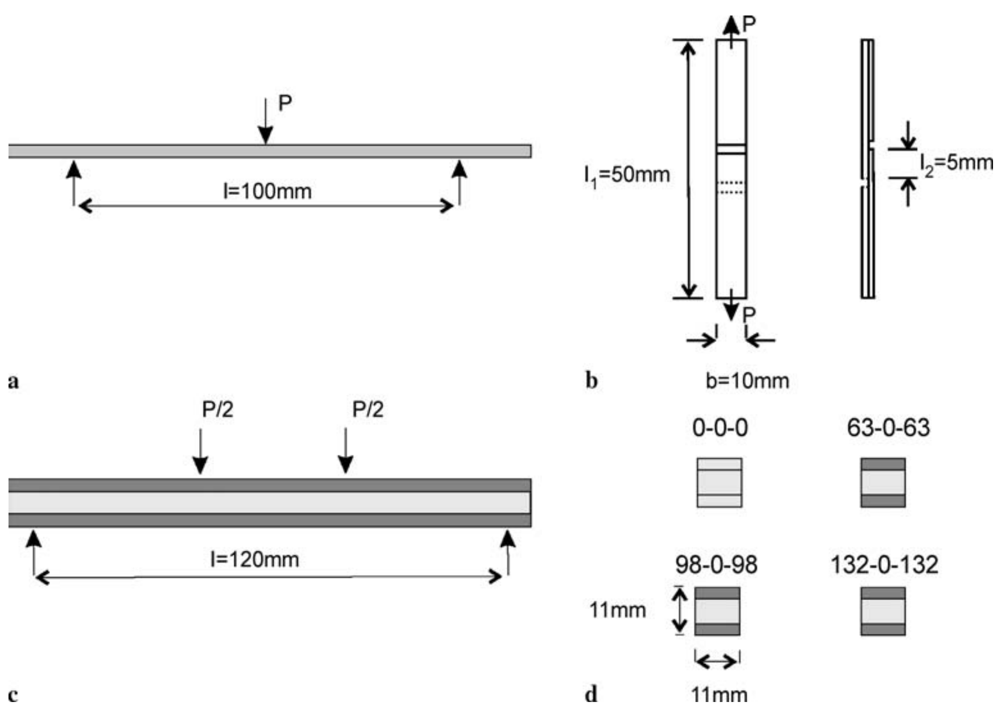


Fig. 1 The geometry of the test specimens. **a** Specimens for the 3-point bending tests of the control and VTC wood; **b** Specimens for the tensile shear test of adhesive bond; **c** Specimens for the 4-point bending tests of the 3-layer composites; **d** Composition (transverse view) of the four different 3-layer composites (0 – the control wood; 63 – the VTC wood with a 63% degree of densification; 98 – the VTC wood with a 98% degree of densification; 132 – the VTC wood with a 132% degree of densification)

Abb. 1 Form der Prüfkörper. **a** Referenz- und VTC Prüfkörper für den 3-Punkt-Biegeversuch; **b** Prüfkörper für die Zugscherprüfung der Verklebung; **c** Prüfkörper des dreilagigen Schichtholzes für den 4-Punkt-Biegeversuch; **d** Aufbau der vier verschiedenen, dreilagigen Schichthölzer (0 – Referenzprobe, 63 – VTC Holz mit 63% Verdichtung, 98 – VTC Holz mit 98%Verdichtung, 132 – VTC Holz mit 132% Verdichtung) ing, whereas the joints bonded with adhesive B were tested a week after bonding.

3.3.1 The lap joint testing method

Shear strength was used to evaluate the adhesive bond performance of the test specimens ($n = 6$), which were prepared in accordance with the requirements of the European standard EN 302-1 (2004). However, some modifications were made due to the reduced dimensions of the tested specimens. Strips of width $b = 10$ mm and length $l_1 = 50$ mm were cut from bonded assembly. Flat bottomed cuts of 2.5 mm wide were made in the bonded sections across the grain, so that an overlap of width $l_2 = 5$ mm was defined in the middle section (Fig. 1b).

The mechanical testing was performed on a Zwick/Roell Z100 universal testing machine using testXpert II software. The tensile force was increased until the test specimen failed. The rate of load increase was set to 1 kN/min, which ensured that the specimens failed within 60 ± 30 s after the beginning of the test. As well as the load needed to cause failure, the percentage of wood failure was also observed visually, to the nearest 10%.

3.4 Manufacture of the VTC composites

Four different 3-layer laminated composites were manufactured (Fig. 1d and Table 1). The 3-layer control composites (0-0-0) were manufactured from undensified wood. The outer laminas were 2.5 mm thick, whereas the core was 6 mm thick. The 3-layer VTC composites (63-0-63, 98-0-98, 132-0-132) were manufactured from densified and undensified wood. The VTC wood laminas were placed in the two outer layers, and a 6 mm thick piece of undensified wood was placed in the core layer. Both of the outer layers were cut out from the same VTC specimen, with dimensions 170 mm × 60 mm × 2.5 mm. Eight replicates of each 3-layer composite were prepared by using 155 g m^{-2} of PF adhesive (adhesive A) for bonding. The adhesive was cured in a hydraulic hot-press at 150 °C and 700 kPa for six minutes. After pressing, the specimens were returned to the controlled environment with a temperature of 20 °C and 65% relative humidity.

3.4.1 Four-point bending tests of the 3-layer composites

Four-point bending tests were performed in order to evaluate the behaviour of the 3-layer composites ($n = 8$), since these sandwich composites (with strong and stiff facings, and lightweight cores) are mostly used in structures which are predominantly loaded in flexure. The test specimen, with dimensions 160 mm × 11 mm × 11 mm, was placed in the aforementioned Zwick/Roell Z100 universal testing machine. The span length was 120 mm, and the two loading points were set to divide the span into three equal sections, each of length 40 mm (Fig. 1c). The loading rate was 5 mm/min. The bending force was increased until the test specimen failed or a deflection of 12 mm was reached. The deflection at mid-span was measured. The load–deflection curve was recorded, and the MOE and MOR were determined. After testing, the failure pattern was examined.

4 Results and discussion

4.1 Bending properties of the VTC wood

The results of the bending test showed that the VTC process significantly influenced the MOE and MOR of the wood (Table 2). The increase in the MOE and MOR of the VTC wood was approximately proportional to the increase in density. In the case of the VTC wood with 63% degree of densification, the MOE increased by 37% in comparison with the control undensified wood, whereas in the case of the VTC wood with 98 and 132% degrees of densification, the MOE increased by 84 and 129%, respectively. Similarly, the MOR of the VTC wood with 63, 98, and 132% degrees of densification increased by 32, 66, and 102%, respectively, in comparison with the control undensified wood. Similar improvements in the mechanical properties due to the VTC process have been previously observed (Kamke 2006). The results regarding the MOE and MOR of the densified wood showed that the VTC process is a very promising method for the improvement of the poor mechanical properties of low-density wood. The VTC processing of wood provides an opportunity for fast-growing low-density wood to be used in structural applications.

Table 1 Description of the composition of the manufactured 3-layer composites (average values)
Tabelle 1 Technische Daten der produzierten dreilagigen Schichthölzer (Mittelwerte)

Composite	Core thickness [mm]	Core density at MC = 0% [g cm^{-3}]	Face thickness [mm]	Face density at MC = 0% [g cm^{-3}]
0-0-0	6	0.330	2.5	0.330
63-0-63	6	0.330	2.5	0.552
98-0-98	6	0.330	2.5	0.676
132-0-132	6	0.330	2.5	0.792

Table 2 Bending test results for the control and VTC wood specimens with different degrees of densification
Tabelle 2 Ergebnisse der Biegeversuche der Referenzproben und des VTC Holzes verschiedener Verdichtungsgrade

Specimen	Density at MC = 0% [g cm^{-3}]	MOR [MPa]	MOE [GPa]
Control 0%	0.331	76	8.7
VTC 63%	0.552	101	12.0
VTC 98%	0.676	126	16.0
VTC 132%	0.792	154	19.9

4.2 The shear strength of the adhesive bond

The results of the lap-shear tests showed that VTC wood can be satisfactorily bonded with either of the two commercially available PF adhesives used in the study (Table 3). The undensified as well as densified wood specimens bonded with adhesive A exhibited similar bond strength. The multiple range test with the 95% LSD procedure showed that there were no statistically significant differences in the shear strength of the adhesive A bond among test specimens. Wood failure was around 50%, except for the VTC 132% specimens, where it was 80%. Performance of adhesive B was comparable to the performance of adhesive A. However, the percentage of wood failure was higher in the case of adhesive B. In summary, it can be stated that the lap-shear bonding performance of densified VTC wood with the PF adhesives used in the study is comparable or better than in the case of the control undensified wood.

4.3 The laminated VTC composites

A series of four-point bending tests were performed on 3-layer composites made from VTC and from control wood. The MOE and MOR of the test specimens were determined from the obtained load-deflection data. A typical example of a load-deflection curve for each type of tested 3-layer composite is shown in Fig. 2.

Table 3 Comparison of the shear strength of the bonded control specimens and the VTC specimens, with the two investigated PF adhesives (A and B) (the standard deviation is shown in parentheses)
Tabelle 3 Scherfestigkeit der verklebten Referenzproben und der VTC Proben unter Verwendung zweier unterschiedlicher PF-Harze (A und B) (Standardabweichung in Klammern)

Specimen	Adhesive A		Adhesive B	
	Shear strength [MPa]	Wood failure [%]	Shear strength [MPa]	Wood failure [%]
Control 0%	5.55 (0.28)	50	6.92 (1.18)	95
VTC 63%	5.75 (1.08)	45	5.47 (0.69)	100
VTC 98%	6.31 (0.42)	50	7.72 (0.53)	90
VTC 132%	6.30 (0.87)	80	8.84 (0.83)	95

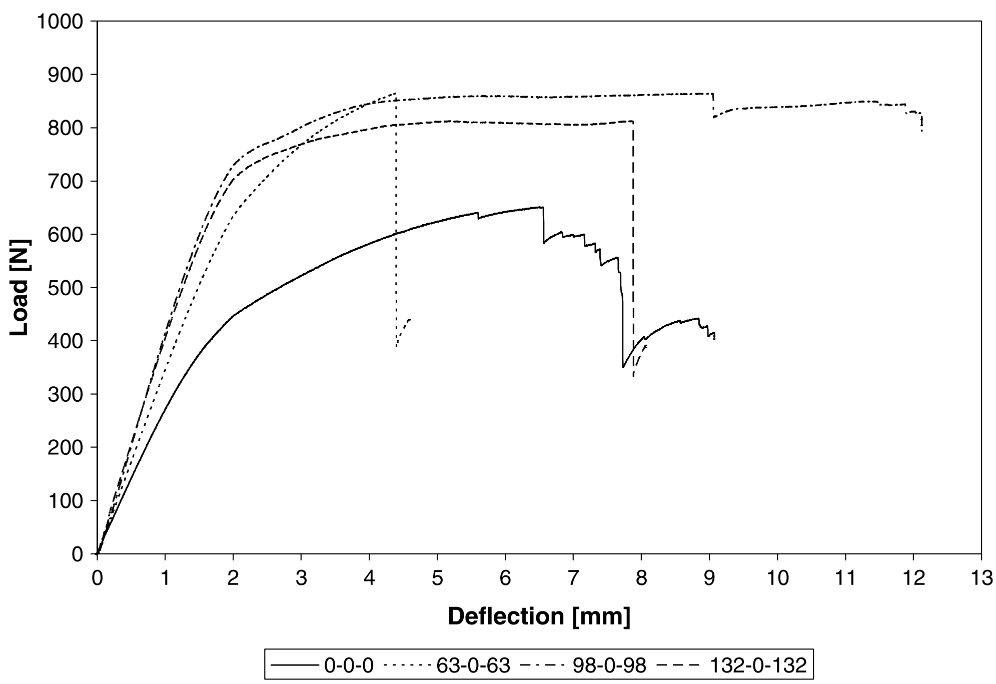


Fig. 2 Load–deflection curves of the 3-layer control and VTC composites obtained in the four-point bending tests
Abb. 2 Last-Verformungs-Diagramm der dreilagigen Referenzprobe und des dreilagigen VTC Verbundwerkstoffes im 4-Punkt-Biegeversuch

The average values and standard deviations for the MOE and MOR of the 3-layer composites are presented in Table 4. The MOE values ranged from 7.19 to 9.82 GPa for the control composites (0-0-0). In the VTC 63% composites (63-0-63), the values ranged from 9.31 to 12.3 GPa, whereas in the VTC 98% composites (98-0-98) they ranged from 9.94 to 12.9 GPa. In the VTC 132% composites (132-0-132) they ranged from 10.4 to 13.4 GPa. The results of a statistical analysis (an LSD procedure with a 95% confidence level) showed that the MOE significantly varies between the composites, except for the comparison between 98-0-98 and 132-0-132 composites. A comparison between the control 3-layer composites and the 3-layer VTC composites indicated a significant increase in the MOE. The improvement was due to the higher density of the face layers that increased the stiffness of the VTC densified wood.

The MOR results corresponding to each tested specimen are shown in Table 4. The MOR values for the 3-layer composites ranged from 55.9 to 75.8 MPa for the 0-0-0, from 62.0 to 89.3 MPa for the 63-0-63, from 72.1 to 98.2 MPa for the 98-0-98, and from 71.0 to 94.9 MPa for the 132-0-132 composites. Statistically significant differences in the MOR were obtained when the control 3-layer composite was compared with all the 3-layer VTC composites, whereas the MOR did not statistically vary among the 3 layer VTC composites.

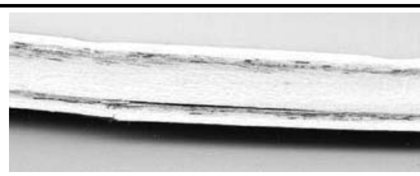
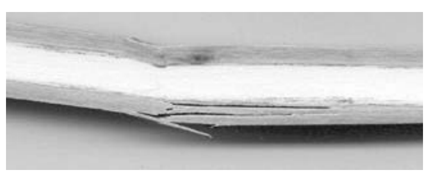
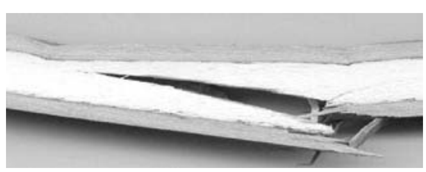
It should be remembered that the only difference between the 3-layer VTC composites was the density of the face layers, whereas the density of the core layer was constant.

Table 4 Average values of the MOE and MOR of different wood-based composites according to composite type and density (the standard deviation is shown in parentheses)
Tabelle 4 Durchschnittswerte der Biegefestigkeit und des Elastizitätsmoduls verschiedener Holzwerkstoffe getrennt nach Art des Holzwerkstoffes und der Dichte (Standardabweichung in Klammern)

Composite	Density [g cm^{-3}]	MOE [GPa]	MOR [MPa]
0-0-0	0.33**	8.2 (0.85)	64.0 (5.91)
63-0-63	0.43**	10.3 (0.90)	80.8 (9.33)
98-0-98	0.49**	11.8 (0.91)	82.8 (8.79)
132-0-132	0.54**	12.1 (1.01)	87.0 (8.06)
Solid wood, yellow poplar*	0.42***	10.9	–
LVL*	0.52***	13.8	–
PSL*	0.59***	13.8	–
LSL*	0.64***	10.3	-

* Data from Janowiak and Bukowski (2000) for yellow poplar and composites made from it.
** Mass and volume based on 0% MC.
*** Mass based on oven-dry weight and volume based on 12% MC.

Table 5 Failure types obtained in the 4-point bending tests of the 3-layer composites
Tabelle 5 Brucharten des dreilagigen Schichtholzes im 4-Punkt-Biegeversuch

Type of failure	Appearance	Failure pattern
Failure 1		Initial crack in the bottom layer, which propagates into the bond-line, where failure is by loss of cohesion between the bottom and the middle layers.
Failure 2		Failure in the bottom layer, the failure extends towards the bond-line, where failure of the adhesion between the adhesive and the wood between the bottom and middle layers occurs.
Failure 3		Failure starts in the bottom layer, and propagates through the bondline and into the middle layer.
Failure 4		Failure initiates and remains inside the bottom layer.
Failure 5		Compression inside the top layer.

Consequently, the increase in MOE and MOR was not proportional to the increase in the density of the face layer. Kamke (2006) tested three-layer VTC composites with VTC wood in the face layers and a piece of untreated wood, of the same species and original thickness, in the core layer. The obtained MOE was compared with the MOE values for undensified specimens. The increase in MOE for the three-layer composite was 2 to 3 times greater than the corresponding increase in mean density of the composite.

The MOE of the 3-layer VTC composites was compared with values corresponding to commercially-produced structural composite lumber (SCL) materials like laminated veneer lumber (LVL), parallel strand lumber (PSL), and laminated strand lumber (LSL). These composites are limited in mechanical performance, based on the mechanical properties of the wood components that they contain. Janowiak and Bukowski (2000) compared the MOE values of solid wood yellow poplar and several composites made from it (Table 4). The production of LVL and PSL materials increased the MOE by 26%, whereas LSL decreased it, when compared to solid wood. Application of VTC wood in the face layers in the 3-layer VTC composites increased the MOE by 25, 44, and 48% (depending on the level of densification), when compared to the 3-layer control composite (0-0-0). In addition, the MOE values of 3-layer VTC composites are comparable to those corresponding to commercially existing SCL. This means that the VTC process offers the possibility of manufacturing structural wood composites from non-structural timber species.

Since the MOR of the 3-layer composites is thought to be influenced by the failure pattern, the failure of each of the tested specimens was investigated. Each specimen was monitored during testing and after testing, the failure pattern of each specimen was carefully examined. Five failure groups were determined based on the results of these observations. The descriptions of each failure group and example photographs are presented in Table 5.

Due to different face properties, the 3-layer composites exhibited different failure patterns. Monitoring of the specimens during testing demonstrated that failure always began at a point coincident with one of the loading points, and propagated towards the middle of the specimens. In some cases, the failure area remained in the bottom face layer, whereas in others it stopped in the interphase region, and in some it propagated into the core. In the case of some specimens the break was instantaneous, whereas in other test specimens many cracks appeared in the bottom face layer, before final failure. In a few specimens a crack was observed in the upper face layer beneath the loading point, since the compressive strength of the specimen was reached. Table 6 summarises the number of obtained failure patterns for all of the tested 3-layer composites.

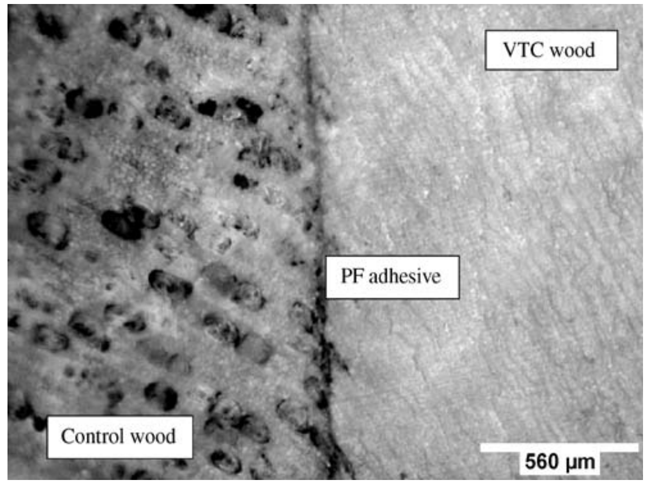


Fig. 3 Cross-sectional view of the bonded untreated wood and of VTC wood with a 132% degree of densification. The adhesive is clearly distinguishable from the wood; the dark regions indicate the presence of the PF adhesive. The specimen was embedded with polymerized linseed oil, and polished using abrasive diamond disks

Abb. 3 Querschnittsansicht der geklebten Verbindung von unbehandeltem Holz und VTC Holz (132% Verdichtung). Der Klebstoff ist deutlich erkennbar. Die dunklen Bereiche zeigen das Harz. Die Probe wurde in polymerisiertes Leinsamenöl eingebettet und dann mit diamantbeschichteten Schleifscheiben poliert

The obtained results provided important information about the bonding of the control wood to the VTC wood. In the 3-layer VTC composites the failure group named Failure 1, i.e. failure by loss of cohesion of the adhesive between bottom and middle layer, did not occur. Failure 2 occurred frequently in the VTC composites, particularly in the 132-0-132 composites. In the case of Failure 3, the crack found a weak spot in the bond-line and extended into the core, whereas in Failure 4 the crack did not even reach the bond line. Regarding the observed failure patterns, it can be stated that bonding of the VTC wood to the untreated control wood is not problematic, although penetration of the adhesive is mainly into the control wood (Fig. 3). Due to closed micro-cellular structure of the VTC wood (particularly with 132% degree of densification), the majority of the PF adhesive penetrated into the cell lumens of the control wood. The adhesive followed the path of least resistance.

Table 6 Number of obtained failure patterns with regard to composite type

Tabelle 6 Anzahl der Brucharten nach Tabelle 5 getrennt nach den Prüfkörpertypen

	0-0-0	63-0-63	98-0-98	132-0-132
Failure 1	1	0	0	0
Failure 2	1	3	1	6
Failure 3	3	4	1	2
Failure 4	2	1	5	0
Failure 5	1	0	1	0

Hence the effective penetration of the PF adhesive differs significantly among the control wood and VTC wood test specimens. Surface related phenomena such as surface inactivation, which can lead to poor bonding (Sernek et al. 2004), was not an issue in the VTC process. The VTC process was accomplished in a pressurized system; so there was little potential for the migration of extractives to the surface (Kamke 2006), and, as well as this, the surface of the wood was protected during the VTC process from contaminations that could interfere with bonding.

5 Conclusion

The VTC process increased the density of wood without cell wall fractures, so the strength and stiffness of the wood material increased as well. The improved mechanical properties make it possible for the VTC wood to be used in structural composites. Effective bonding of the VTC wood, which is crucial for the manufacturing of wood-based composites, can easily be achieved, as has been demonstrated by this study. The PF adhesive bond strength of the densified VTC specimens is similar or better than that of the control (undensified) specimens. Four different 3-layer composites from undensified wood and VTC wood were manufactured and tested in four-point bending tests. The results showed that the MOR and MOE of the 3-layer VTC composites were significantly improved due to the increased density of the VTC wood in the face layers of the 3-layer composites. These results confirmed the validity of the assumption that low-density wood species can be successfully used for the production of structural wood-based composites, if they are densified by means of the VTC process.

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