Herstellung von Holzfaserdämmstoffen auf Laub- und Nadelholzbasis mit dem Fokus auf der Fasercharakterisierung, sowie der Ermittlung der physikalischen, mechanischen und biologischen Eigenschaften

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vorgelegt von

Arne Andreas Paul Imken (M. Sc.)

geboren am 01.07.1991 in Bremen

Göttingen, 01.06.2022

1. Gutachter: Prof. Dr. Carsten Mai

2. Gutachter: PD Dr. Markus Euring

3. Gutachter: Prof. Dr. Ursula Kües

Weitere Mitglieder der Prüfungskommission

Prof. Dr. Alireza Kharazipour

Prof. Dr. Christian Brischke

Tag der Disputation: 01.09.2022

Vergessen alle Tage, vergessen jede Nacht
Wo bin ich gewesen, was hab ich gemacht
Wie hat das begonnen, wann fing das an
Wo bin ich gewesen, was hab ich getan

Ich weiß es nicht Lindemann

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Abstract

The objective of this work was to investigate the use of hardwood fibres for the production of wood fibre insulation materials in order to provide a broader range of raw materials against the background of ecological forest conversion and the current problems and regression of softwood monocultures.

In order to work on the objective, different hardwood fibres, blends of hardwood and softwood fibres and, as a reference, softwood fibres were first characterised and analysed with the help of a scanner-based system. It was found that the hardwood fibres are shorter than the softwood fibres and contain distinctly more dust particles. The fibre blends with at least 50 % softwood fibres showed a fibre length distribution between that of the pure hardwood and softwood fibres. It was concluded that pure hardwood fibres were unlikely to be suitable for use in wood fibre insulation materials and fibre blends with a minimum of 50 % softwood fibres were recommended.

In the further course of this work, wood fibre insulating materials were then produced on a laboratory scale from the previously characterised fibres and have been tested for their physical and mechanical properties, as well as for their flammability. It was found that the fibres of different hardwood tree species are differently suitable for the production of wood fibre insulating materials. Individual properties were found for the different tree species. For example, wood fibre insulating materials made from alder fibres have a very high water absorption potential. Wood fibre insulating materials made from oak fibres have an increased thermal conductivity, while those made from birch fibres have a reduced mechanical strength. The best results were achieved with wood fibre insulating materials made from beech fibres, which have comparable properties to wood fibre insulating materials made from softwood fibres. Wood fibre insulating materials made from fibre blends with a content of at least 20 % softwood fibres also show comparable properties to wood fibre insulating materials made from softwood fibres.

Finally, the susceptibility of hardwood-based wood fibre insulation materials to mould fungi was tested. For this purpose, different fibre blends and softwood fibres were tested. With increasing hardwood content, the susceptibility to mould fungi also increased.

In summary, it could be shown in the course of the investigations that wood fibre insulation materials can be produced from hardwood fibres. In order to achieve comparable properties to those out of softwood fibres, the use of beech fibres or fibre blends with a proportion of at least 20 % softwood fibres is recommended.

Zusammenfassung

Das Ziel dieser Arbeit bestand in der Untersuchung des Einsatzes von Laubholzfasern für die Herstellung von Holzfaserdämmstoffen (HFDS), um vor dem Hintergrund des ökologischen Waldumbaus und der aktuellen Problematik und Regression der Nadelholzmonokulturen eine breitere Rohstoffpalette zur Verfügung stellen zu können.

Für die Bearbeitung der Zielstellung wurden zunächst verschiedene Laubholzfasern, Mischungen dieser mit Nadelholzfasern sowie letztere in Reinform als Referenzmaterial mit Hilfe eines scannerbasierten Systems charakterisiert und analysiert. Die Analyse hatte zum Ergebnis, dass Laubholzfasern kürzer sind als jene des Nadelholzes und zudem deutlich mehr Staubpartikel enthalten. Die Fasermischungen mit einem Nadelholzanteil von mindestens 50 % ergaben eine Faserlängenverteilung zwischen denen des Reinmaterials aus Laub- bzw. Nadelholz. Daraus ließ sich zunächst schlussfolgern, dass sich reine Laubholzfasern möglicherweise nicht für den Einsatz in HFDS eignen und Fasermischungen mit einem minimalen Nadelholzanteil von 50 % zu empfehlen sind.

Im weiteren Verlauf dieser Arbeit sind aus den zuvor charakterisierten Fasern HFDS im Labormaßstab produziert worden, welche auf ihre physikalischen und mechanischen Eigenschaften, sowie auf ihre Brennbarkeit getestet wurden. Die Eigenschaftscharakterisierung führte zum Ergebnis, dass sich die Fasern verschiedener Laubbaumarten unterschiedlich gut für die Herstellung von HFDS eignen. Es zeigten sich für die verschiedenen Baumarten individuelle Eigenschaften. So wies Dämmstoffmaterial aus Erlenfasern ein sehr hohes Wasseraufnahmepotential auf, wohingegen bei solchem aus Eichenfasern gefertigtem eine erhöhte Wärmeleitfähigkeit festgestellt werden konnte. Bei HFDS aus Birkenfasern waren die mechanischen Festigkeiten reduziert. Die besten Ergebnisse erzielten HFDS aus Buchenfasern, welche vergleichbare Eigenschaften zu auf Nadelholz basierten HFDS aufwiesen. Auch HFDS aus Mischmaterial mit einem Nadelholzanteil von mindestens 20 % zeigten vergleichbare Eigenschaften zu HFDS aus Nadelholzfasern.

Abschließend wurde die Anfälligkeit von HFDS auf Laubholzbasis gegenüber Schimmelpilzen geprüft, wofür verschiedene Fasermischungen sowie Nadelholzfasern getestet wurden. Mit steigendem Laubholzanteil stieg auch die Anfälligkeit gegenüber Schimmelpilzen.

Zusammenfassend konnte im Zuge der Untersuchungen gezeigt werden, dass HFDS aus Laubholzfasern hergestellt werden können. Um vergleichbare Eigenschaften zu solchen aus Nadelholzfasern zu erzielen, wird der Einsatz von Buchenfasern oder Mischmaterial mit einem Nadelholzanteil von mindestens 20 % empfohlen.

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1 Einleitung

Am 30.03.2022 hat das Bundesministerium für Wirtschaft und Klimaschutz die Frühwarnstufe des Notfallplans Gas ausgerufen. Dieser Schritt ist erfolgt, da Russland mit der Einstellung der Gaslieferung droht (Bundesministerium für Wirtschaft und Klimaschutz 2022). Besonders betroffen von diesem Schritt wäre Deutschland, das 55 % seiner Gaszufuhren aus Russland importiert (Habeck 2022).

In der Europäischen Union (EU) sind Gebäude für 40 % des gesamten Energieverbrauchs verantwortlich. Dabei werden im Wohnsektor 67 % der Energie zum Heizen verwendet (Bosseboeuf 2015). Für ihre Heizenergie nutzen fast die Hälfte der Deutschen Erdgas als Energieträger (Bundesministerium für Wirtschaft und Klimaschutz 2019). Eine Einsparung von Gas durch eine verbesserte Gebäudedämmung bietet dabei neben einer größeren Unabhängigkeit von Gaslieferungen Russlands ebenfalls Vorteile im Kampf gegen den Klimawandel. Bei der UN-Klimakonferenz in Paris im Dezember 2015 haben sich 197 Staaten darauf geeinigt, die Erderwärmung im Vergleich zum vorindustriellen Zeitalter auf deutlich unter 2 °C zu begrenzen mit Anstrengungen für eine Beschränkung auf 1,5 °C (United Nations 2015).

Laut Umweltbundesamt zählt der Dämmstandard der Gebäude zu den wichtigsten Stellschrauben, die den persönlichen CO_2-Ausstoß bestimmen (Bilharz 2014). Energie, die auf Grund eines hohen Dämmstandards gar nicht erst verbraucht wird, ist die Energie, welche sich am leichtesten einsparen lässt.

Im Jahr 2019 sind in Deutschland insgesamt 38,5 Millionen Kubikmeter Dämmstoffe verwendet worden. Dabei entfallen 48 % auf fossile Rohstoffe, 43 % auf mineralische Rohstoffe und 9 % auf nachwachsende Rohstoffe, wobei Holzfasern im Bereich der nachwachsenden Rohstoffe den größten Anteil ausmachen. Für die Zukunft wird eine weiterhin positive Absatzentwicklung für Dämmstoffe auf Basis nachwachsender Rohstoffe erwartet. Bereits von 2010 bis 2019 hat sich der Anteil von Holzfaserdämmstoffen (HFDS) in Deutschland von 1,25 auf 2,03 Millionen Kubikmeter erhöht (Sprengard et al. 2014; Fachagentur Nachwachsende Rohstoffe 2021).

Der steigende Einsatz nachwachsender Rohstoffe für die Gebäudedämmung ist vor dem Hintergrund der Nachhaltigkeit ein wichtiger Faktor. Die Nachhaltigkeit ist der wichtigste Grundsatz der deutschen Forstwirtschaft und wurde bereits vor über 300

Jahren von Hans Carl von Carlowitz in der Schrift *Sylvicultura oeconomica* erwähnt (Carlowitz 1713). Verholzte Pflanzen als Quelle für HFDS binden während ihres Wachstums atmosphärischen Kohlenstoffdioxid durch Photosynthese. Da bei der Herstellung von HFDS typischerweise weniger CO_2 freigesetzt wird, als das Holz vorher gespeichert hat, kann man sogar von einem negativen Kohlenstoffdioxid-Fußabdruck sprechen (Lawrence et al. 2013). Diese positiven Eigenschaften werden durch die lange Haltbarkeit von HFDS von bis zu 60 Jahren noch weiter verstärkt, da die während dieser Zeit nachwachsenden Wälder ihrerseits auch wieder CO_2 binden (Paulitsch und Barbu 2015). Eine weitere Verbesserung der Kohlenstoffspeicherung besteht durch die Kaskadennutzung von Holz, wobei HFDS eine wichtige Rolle einnehmen können, indem diese beispielsweise aus zuvor höher veredelten Vollholzwerkstoffen hergestellt und nach ihrer Nutzungsdauer wiederum energetisch genutzt werden (Wiprächtiger et al. 2020).

Der Klimawandel hat weltweit Auswirkungen auf die Waldökosysteme. Dabei sind vor allem Nadelholzbestände von der anhaltenden Dürre und Insektenkalamitäten betroffen (Paczkowski et al. 2021). Deutschland hat zwischen 2018 und 2020 einen Anfall von 160 Millionen Kubikmetern Schadholz zu verzeichnen, das sind fast vier Prozent des gesamten Holzvorrates (Bundesministerium für Ernährung und Landwirtschaft 2020). Betroffen waren fast ausschließlich künstlich gepflanzte Nadelholz-Monokulturen. Mit Hilfe des ökologischen Waldumbaus sollen Diese wieder in stabilere Misch- und Laubwälder umgewandelt werden. Dabei gibt es bereits nennenswerte Fortschritte. Zwischen 2002 und 2012 hat die mit Nadelholz bestockte Fläche in Deutschland um 267.220 Hektar abgenommen, während in der gleichen Zeit die mit Laubholz bestockte Fläche um 315.368 Hektar zugenommen hat. Nach wie vor ist die Fichte mit 1,2 Milliarden Kubikmeter Holzvorrat die Baumart mit dem größten Anteil in Deutschland. Ihr folgen Kiefer (0,8 Mrd. m^3), Buche (0,6 Mrd. m^3) und Eiche (0,4 Mrd. m^3). Weitere Baumarten sind meistens zu Gruppen zusammengefasst und spielen als Reinsortimente keine tragende Rolle. (Bundesministerium für Ernährung und Landwirtschaft 2012). Dieser Waldumbau kann aber auch zu Problemen führen. So ist die holzverarbeitende Industrie in Deutschland vor allem in den Bereichen Holzwerkstoffe, Bauholz und Sägeschnittholz auf Nadelholz spezialisiert (Fritz et al. 2006). 2015 sind 9 Millionen Kubikmeter Waldholz in Deutschland für die Holzwerkstoffindustrie genutzt worden. Davon waren nur 1,7 Millionen Kubikmeter Laubholz (DHWR 2016). Durch

den bereits erfolgten und weiterhin laufenden Waldumbau kommt es zu einem erhöhten Anfall an Laubdurchforstungsholz, welches als potenzielles Substitut für das Nadelholz in der Industrie zur Verfügung steht.

Der Einsatz von Laubhölzern für die Produktion von HFDS wurde bislang noch nicht weitreichend erforscht. Es gab drei Untersuchungen an Holzfaserdämmstoffen aus Buchen- und Birkenfasern im Nassverfahren (Bartholme et al. 2009; Brombacher 2015; Sable et al. 2015). Des Weiteren wurden Dämmstoffe aus Buchen- und Eichenfasern im Trockenverfahren untersucht (Eichhorn 2017). Darüber hinaus wurden zwei Untersuchungen der Dämmeigenschaften von Buchen- und Pappelfasern durchgeführt (Heinrich und Hering 2004; Barth 2021). Die zuvor erwähnten Untersuchungen führten zu kontroversen Ergebnissen. So ermittelte Brombacher (2015), dass die verwendeten Buchenfasern keine negativen Auswirkungen auf die Platteneigenschaften hatten und äquivalent zu Nadelholzfasern verwendet werden können. Auch Sable et al. (2015) stellten in ihrer Untersuchung dar, dass es möglich ist Holzfaserdämmplatten aus Birkenfasern zu produzieren und zu verwenden. Heinrich und Henning (2004) sowie Barth (2021) konnten für Fasern der Baumarten Fichte, Kiefer, Buche und Pappel keinen holzartenspezifischen Einfluss auf die Wärmeleitfähigkeit feststellen. Auch Bartholme et al. (2009) und Eichhorn (2017) konnten zwar herausstellen, dass sich sowohl Buchen- als auch Eichenfasern für die Herstellung von HFDS eignen, jedoch stellten sie auch ungünstigere Eigenschaften (geringere Festigkeiten, erhöhte Wasseraufnahme, höhere Wärmeleitfähigkeit) verglichen mit solchen aus Nadelholzfasern fest. Betont wurden diese Ergebnisse noch durch einen Versuch von Eichhorn (2017), in dem der Anteil von Nadelholzfasern in HFDS stufenweise durch Buchenholzfasern ersetzt wurde, wobei die Festigkeiten mit steigendem Buchenholzfaseranteil herabgesetzt wurden.

1.1 Zielsetzung

Resultierend aus den einleitenden Aspekten bestand das übergeordnete Ziel dieser kumulativen Dissertation in der Erarbeitung eines nachhaltigen und wirksamen Lösungsansatzes zur Abmilderung der bereits eingetretenen und sich weiter verschärfenden Rohholzverknappung der Nadelholzsortimente. Dafür sollte der Einsatz von Laubhölzern für die Produktion von HFDS geprüft und folgende Forschungsfragen geklärt werden.

1. Können Laubholzfasern zur Produktion von HFDS eingesetzt werden?
2. Gibt es anhand einer Charakterisierung der verschiedenen Faservarianten bereits erkennbare Unterschiede?
3. Wie wirkt sich eine mathematische Fraktionierung der Fasern aus?
4. Wie wirkt sich eine Beimischung von Laubholzfasern zu Fichtenfasern auf die Eigenschaften der produzierten HFDS aus?
5. Unterscheiden sich die Eigenschaften der HFDS aus verschiedenen Laub- und Nadelholzfasern?
6. Wirkt sich der Einsatz von Laubholzfasern auf feste HFDS-Platten anders aus, als auf flexible Holzfaserdämmmatten?
7. Wie wirken sich die Faserlänge und die Porosität auf die physikalischen und mechanischen Eigenschaften aus?
8. Verändert der Einsatz von Laubholzfasern die Anfälligkeit gegenüber Schimmelpilzen?

In einer ersten Veröffentlichung (Kapitel 3) sind dafür Laubholz- und Nadelholzfasern mittels dem scannerbasierten FibreShape System analysiert und charakterisiert worden. Neben den Reinsortimenten wurden dabei auch Fasermischungen aus Laub- und Nadelholzfasern und fraktionierte Fasersortimente charakterisiert.

In einer nachfolgenden Veröffentlichung (Kapitel 4) sind aus den zuvor charakterisierten Fasern sowohl druckfeste als auch flexible HFDS produziert und auf ihre physikalischen und mechanischen Eigenschaften, sowie auf ihre Brennbarkeit getestet worden. Dafür sind sowohl die Reinsortimente aus Laub- und Nadelholz, als auch die Mischsortimente aus Laub- und Nadelholzfasern genutzt worden.

Die dritte Veröffentlichung (Kapitel 5) erweitert die erfolgten Untersuchungen der zweiten Veröffentlichung um weitere Reinsortimente aus Laub- und Nadelholzfasern, aus denen ebenfalls HFDS produziert wurden und deren mechanischen und technologischen Eigenschaften, sowie die Brennbarkeit getestet worden sind. Darüber hinaus wurden in dieser Veröffentlichung für weiterführende Analysen Computertomographie-Aufnahmen erstellt.

In der abschließenden Veröffentlichung (Kapitel 6) dieser Dissertation sind die Anfälligkeiten einiger ausgewählter HFDS-Varianten aus den vorangegangen beiden Veröffentlichungen gegenüber Schimmelpilzen im Rahmen eines Methodenvergleiches zweier verschiedener Schimmelpilztests evaluiert worden.

1.2 Quantifizierung der Autorenschaft

Die Promotionsordnung der Graduiertenschule für Forst- und Agrarwissenschaften (GFA) vom 07.02.2022 schreibt vor, dass bei Publikationen mit mehreren Autorinnen oder Autoren die Beiträge des Doktoranden deutlich abgrenzbar und bewertbar sein müssen (GFA 2022). Hierzu wird heutzutage üblicherweise eine Matrix in Anlehnung an Clement (2014) genutzt, welche die Arbeitsanteile der jeweiligen Autoren in den verschieden gewichteten Bereichen Idee, Arbeit, Schreiben und Verwaltung quantifiziert.

Tabelle 1: Quantifizierung der Autorenschaft in Anlehnung an Clement (2014).

Ideen (30 %)	**Arbeit (30 %)**	**Schreiben (30 %)**	**Verwaltung (10 %)**	**Beitrag (100 %)**
Versuchskonzeption, Versuchsplanung, Interpretation der Daten	Versuchsdurchführung, Datenerhebung und -analyse	Artikelentwurf, inhaltliche Überarbeitung, Begutachtung der Endfassung	Erschließung von Ressourcen und Gewährleistung der wissenschaftlichen Integrität	

Darüber hinaus ist der Mindestbeitrag eines Autors in Formel 1 nach Clement (2014) geregelt. Wobei n für die Anzahl der Autoren an einer Publikation steht.

Formel 1: Mindestbeitrag eines Co-Autors an einer Publikation (Clement 2014).

$$Mindestbeitrag\ (\%) = \frac{(0{,}5 * 100)}{n}$$

Zu Beginn der Kapitel 3 bis 6 wird nach Tabelle 1 unter Berücksichtigung des Mindestbeitrages in Formel 1 die Autorenschaft der jeweiligen Publikation quantifiziert.

2 Theoretischer Hintergrund

2.1 Holzfaserdämmstoffe

Holzwerkstoffe ist der Überbegriff für eine große Anzahl verschiedener Produkte. Die Gemeinsamkeit liegt in der Zerlegung von Holz und dem anschließenden erneuten Zusammenfügen der entstandenen Teile. Häufig werden für das Zusammenfügen Klebstoffe eingesetzt, außerdem können weitere Zusatzstoffe hinzugefügt werden (Niemz und Wagenführ 2012).

Neben Vollholz-, Furnier-, Span- und Verbundwerkstoffen gibt es die Faserwerkstoffe. Hierzu zählen neben mitteldichten und harten Faserplatten auch die HFDS. Nach DIN EN 13171 müssen HFDS zu mindestens 80 % aus Holzfasern bestehen. Neben Holzfaserdämmstoffen gibt es auch noch weitere Wärmedämmstoffe. Diese lassen sich nach der Herkunft der zugrundeliegenden Rohstoffe in organische und anorganische Dämmstoffe einteilen. Zu den Anorganischen zählen alle Dämmstoffe auf mineralischer Basis, wie beispielsweise Mineralwolle, Schaumglas, Blähton und Naturbims. Unter den organischen Dämmstoffen gibt es auf fossiler Basis beispielsweise expandiertes Polystyrol oder Polyesterfasern und auf nachwachsender Basis Flachs, Kokosfasern und Holzfasern (Reyer et al. 2002). HFDS zeichnen sich durch eine höhere Umweltverträglichkeit gegenüber Steinwolle oder expandiertem Polystyrol aus (Schulte et al. 2021).

Für die Herstellung von HFDS wird in der Regel Industrieholz und anfallendes Restholz verwendet. Dieses wird zunächst zu Hackschnitzeln und anschließend mit Hilfe verschiedener Zerfaserungsverfahren weiterverarbeitet. Dabei ist der Sklerenchymanteil für die Faserstoffausbeute entscheidend. Dieser ist beim Nadelholz deutlich höher als beim Laubholz. Daneben spielen die hohe Verfügbarkeit und die besonders gut geeignete Faserqualität entscheidende Rollen, weshalb aktuell fast ausschließlich Nadelholz verwendet wird (Deppe und Ernst 1996; Holzmann 2012).

Es gibt verschiedene Zerfaserungsverfahren, sowohl physikalische als auch chemische. Heutzutage wird in der Praxis üblicherweise das Defibratorverfahren nach Asplund mit einer rotierenden (Rotor) und einer feststehenden (Stator) Mahlscheibe genutzt. Dabei werden die Hackschnitzel thermisch mit Wasserdampf bei 150 bis 190 °C und einem Druck von 8 – 12 bar vorbehandelt. Durch die hydrothermische Behandlung plastifiziert die Mittellamelle der Zellen. Anschließend lassen sich die Hackschnitzel im

Defibrator mit relativ geringem Energieaufwand zerfasern, so dass Thermo-Mechanical-Pulp-Fasermaterial entsteht (Krug 2010; Niemz und Wagenführ 2012).

Nach der Zerfaserung erfolgt die Vliesbildung entweder im Nass- oder Trockenverfahren. Da das Nassverfahren deutlich energieintensiver und durch die Abwasserbelastung umweltschädlich ist, wird heutzutage meistens das Trockenverfahren genutzt (Newman 2013; Drewer et al. 2013; Paulitsch und Barbu 2015). Das Trockenverfahren benötigt nur etwa 60 % der Energie im Vergleich zum Nassverfahren. Weitere Vorteile des Trockenverfahrens sind die um die Hälfte reduzierten benötigten Zusatzstoffe, eine höhere Festigkeit, eine geringere Wärmeleitfähigkeit und eine größere Diffusionsoffenheit gegenüber dem Nassverfahren (Gebhardt 2012).

Im Trockenverfahren werden die Fasern direkt nach dem Aufschlussprozess auf die für die Beleimung notwendige Restfeuchte getrocknet. Die Beleimung findet meistens in einer Blowline mit 4 - 5 % polymeren Diphenylmethandiisocyanat (pMDI) statt (Vangronsveld et al. 2010). Anschließend werden die beleimten Fasern gestreut und die Aushärtung erfolgt über ein Dampf-Luft-Gemisch (Niemz und Wagenführ 2012).

Neben den formstabilen und druckbelastbaren Holzfaserdämmplatten gibt es auch noch flexible Holzfaserdämmmatten (Abbildung 1). Diese werden mit Hilfe von Kunstfasern beispielsweise Bikomponentenfasern (Biko-Fasern) hergestellt. Dafür sind massebezogen 6 – 9 % üblich. Diese werden nach der Fasertrocknung beigemischt und in einem Durchströmungstrockner mit Temperaturen von 70 – 180 °C durchströmt. Dabei werden die äußeren Materialschichten der Zweikomponenten-Kunstfasern erweicht, wodurch es zu einer Vernetzung des Fasergemisches kommt (Brombacher 2015).

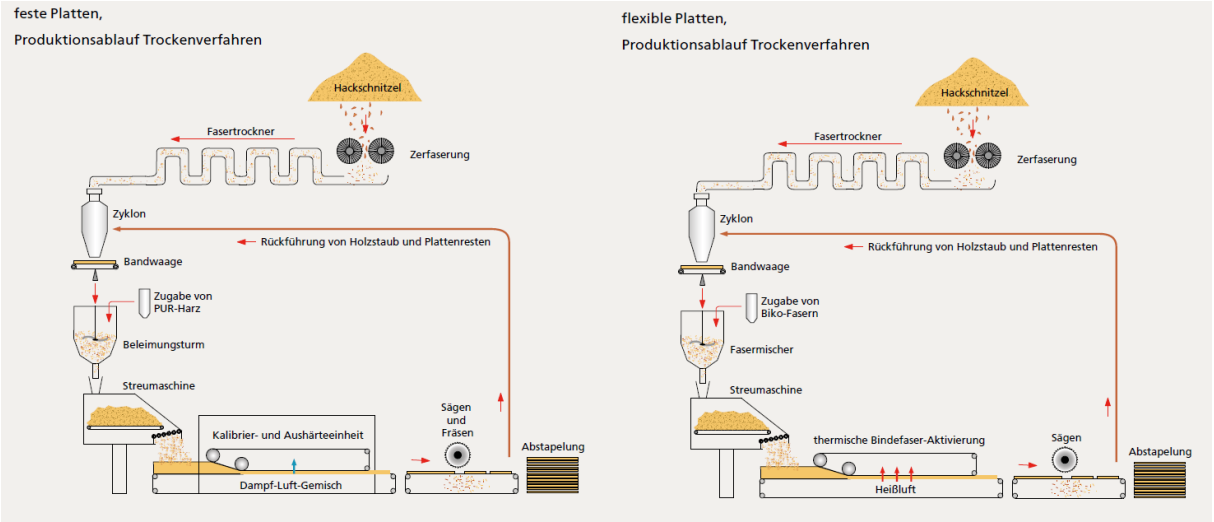

Abbildung 1: Produktionsablauf für druckfeste Platten im Trockenverfahren (links). Produktionsablauf für flexible Platten im Trockenverfahren (rechts) (VDNR 2021).

2.2 Vergleich zwischen Laub- und Nadelholz

Das Nadelholz ist entwicklungsgeschichtlich älter als das Laubholz und hat einen einfacheren Aufbau (Abbildung 2). Je nach Definition bilden auf der mikroskopischen Strukturebene nur zwei bis drei Zelltypen das Nadelholzgewebe. Zu 90 – 95 % besteht es aus Tracheiden, zu 4 – 10 % aus Parenchymzellen und bei manchen Nadelhölzern noch zu 1 % aus Harzkanälen. Dabei übernehmen die Tracheiden als axial ausgerichtetes Grundgewebe sowohl Festigungs- als auch Leitungsfunktionen. Die Parenchymzellen sind sowohl axial als auch radial angeordnet und dienen zur Speicherung. Die Harzkanäle sind, falls vorhanden, ebenfalls radial und auch axial angeordnet und dienen zur Harzausscheidung (Hering 2008; Wagenführ und Wagenführ 2012; Frommhold 2013).

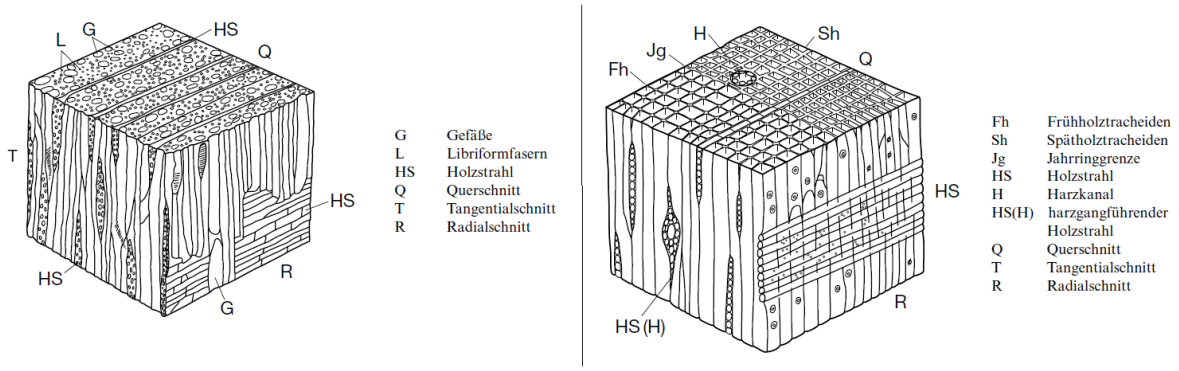

Abbildung 2: Schematische Darstellungen eines Laubholzwürfels (links) und eines Nadelholzwürfels (rechts) nach (Wagenführ 1989).

Das entwicklungsgeschichtlich jüngere Laubholz hat einen komplexeren Aufbau (Abbildung 2). Hauptsächlich kommen hier Libriformfasern (50 – 60 %) vor. Hinzu kommen Parenchymzellen (10 – 30 %) und Tracheen (20 – 40 %). Die ebenfalls vorkommenden Tracheiden liegen als sogenannte Gefäßtracheiden oder vasizentrische Tracheiden vor. Beim Laubholz werden im Gegensatz zum Nadelholz das Leitungs- und Festigungsgewebe differenziert. Die Gefäße dienen zur Wasserleitung, während Libriformfasern für die nötige Festigung sorgen. Die Parenchymzellen übernehmen wie beim Nadelholz die Speicherfunktion (Hering 2008; Wagenführ und Wagenführ 2012; Frommhold 2013).

Die verschiedenen Zelltypen unterscheiden sich auch deutlich in Länge und Durchmesser (Abbildung 3). Die Tracheiden der Fichte können eine Länge von bis zu 4,8 mm erreichen, während die Libriformfasern der Buche nur eine Länge von bis zu 1,3 mm erreichen können. Der Durchmesser ergibt sich aus Lumen und Zellwand, wobei er primär durch das größere Lumen bestimmt wird. Dabei gibt es Unterschiede zwischen Früh- und Spätholz. Das Frühholz bildet vor allem weitlumige Zellen mit dünnen Zellwänden für Leitungsfunktionen, während das Spätholz englumige Zellen mit dickeren Zellwänden für eine Stützfunktion bildet. Dieser Unterschied zwischen Früh- und Spätholz wirkt sich beim Nadelholz auf die Tracheiden aus, welche Leitungs- und Stützfunktion vereinen. Beim Laubholz wirkt sich dieser Unterschied auf die Tracheen aus, welche die Leitungsfunktion übernehmen. Daher ergibt sich dieser deutliche Unterschied zwischen Früh- und Spätholz beim Laubholz auch nur bei ringporigen Laubhölzern, die ihre Gefäße vor allem im Frühjahr bilden. Bei zerstreutporigen Laubhölzern werden das ganze Jahr über gleich viele Gefäße gebildet, die mehr oder weniger den gleichen Durchmesser aufweisen. So erreicht das Lumen der Fichte im Frühholz bis zu 45 µm und im Spätholz bis zu 22 µm. Der Gefäßdurchmesser der ringporigen Esche erreicht im Frühholz 350 µm und im Spätholz 130 µm. Bei der zerstreutporigen Buche erreicht der Gefäßdurchmesser im Früh- und Spätholz 85 µm (Wagenführ 2007).

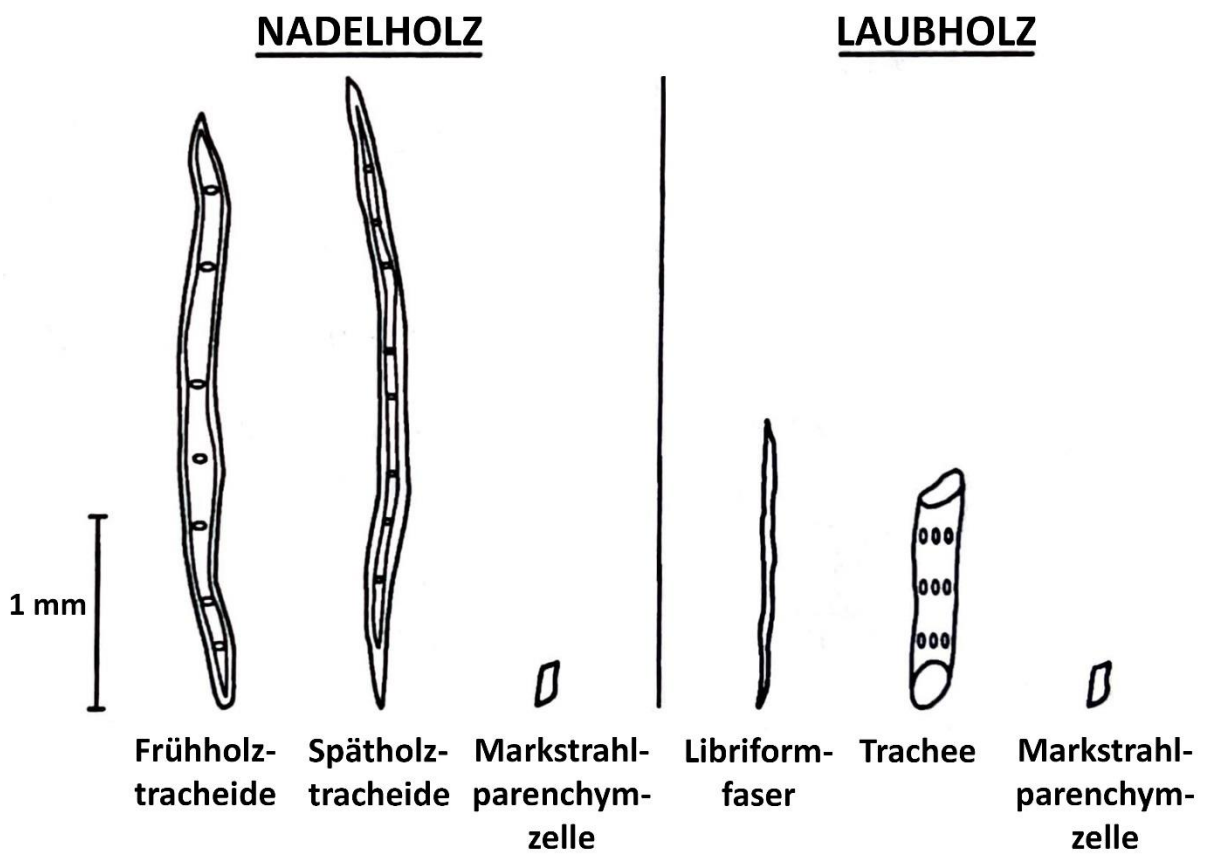

Abbildung 3: Größenverhältnis von unterschiedlichen Zelltypen des Nadelholzes (links) und des Laubholzes (rechts) (Göttsching und Katz 1999).

Die unterschiedliche Zellzusammensetzung der untersuchten Baumarten, welche sich auf die Fasereigenschaften (z.B. Faserlänge und Staubanteil) auswirken kann, ist in den Tabelle 2 und Tabelle 3 dargestellt. Bei den in der vorliegenden Arbeit untersuchten Baumarten handelt es sich um die Gemeine Fichte (*Picea abies* Karst.), die Gemeine Kiefer (*Pinus sylvestris* L.), die Europäische Lärche (*Larix decidua* Mill.), die Winterlinde (*Tilia cordata* Mill.), die Schwarzerle (*Alnus glutinosa* Gartn.), die Hängebirke (*Betula pendula* Roth.), die Gemeine Esche (*Fraxinus excelsior* L.) und die Rotbuche (*Fagus sylvatica* L.). Im weiteren Verlauf werden die Baumarten mit ihren Trivialnamen bezeichnet.

Tabelle 2: Zusammensetzung der Zelltypen für die untersuchten Nadelbaumarten (Wagenführ 2007).

Baumart	Tracheiden [%]	Holzstrahlen [%]	Längsparenchym [%]
Gemeine Fichte	95	5	1
Gemeine Kiefer	93	6	
Europäische Lärche	91	9	1

Tabelle 3: Zusammensetzung der Zelltypen für die untersuchten Laubbaumarten (Wagenführ 2007).

Baumart	Fasern [%]	Gefäße [%]	Holzstrahlen [%]	Längsparenchym [%]
Winterlinde	72	17	9	2
Schwarzerle	58	29	12	
Hängebirke	65	25	11	2
Stieleiche engringig	44	39	16	
Stieleiche weitringig	58	8	29	5
Gemeine Esche	62	12	15	11
Rotbuche	40	40	16	5

Neben den unterschiedlichen mikroskopischen Strukturmerkmalen gibt es auch noch Unterschiede bei den chemischen Eigenschaften. Sowohl Nadel- als auch Laubholz sind aus den chemischen Bausteinen Cellulose, Hemicellulosen und Lignin aufgebaut. Dabei macht die Cellulose sowohl beim Nadel- als auch beim Laubholz 40 – 50 % aus. Das Laubholz besteht darüber hinaus aus etwa 15 – 25 % Lignin und 25 – 40 % Hemicellulosen. Das Nadelholz hingegen weist etwa 25 – 30 % Lignin und nur 25 – 30 % Hemicellulosen auf (Wagenführ 2007; Popescu et al. 2009).

Die Rohdichte des gewachsenen Holzes ergibt sich aus dem Verhältnis von Zellwandsubstanz zum Porenraum im Holz. Nadelholz weist dabei in der Regel einen höheren Anteil von Porenraum und dementsprechend eine geringere Rohdichte als Laubholz auf. Darüber hinaus weist Laubholz in der Regel höhere Quell- und Schwindmaße auf als Nadelholz (Tabelle 4). Auch in weiteren mechanischen Eigenschaften, wie beispielsweise der Druckfestigkeit, Zugfestigkeit oder dem E-Modul unterscheiden sich Nadel- und Laubholz (Wagenführ 2007; Wagenführ und Wagenführ 2012).

Tabelle 4: Ausgewählte Baumarten mit wissenschaftlichem Namen und Rohdichte [kg/m³] nach Wagenführ (2007).

Baumart	Rohdichte [kg/m³]	Schwindsatz Volumen (β_v) [%]
Gemeine Fichte	470	11,8
Gemeine Kiefer	510	11,8
Europäische Lärche	590	13,2
Winterlinde	530	14,7
Schwarzerle	550	13,4
Hängebirke	650	14,0
Stieleiche	690	14,1
Gemeine Esche	720	13,2
Rotbuche	720	17,9

Durch die in Kapitel 2.1 beschriebene Verarbeitung zu einem Holzwerkstoff werden die in Tabelle 4 gezeigten Unterschiede jedoch größtenteils vernachlässigbar. Dabei nimmt die Festigkeit zwar ab, Homogenität, Wärmedämmung, Isotropie und Oberflächenqualität steigen jedoch an (Wagenführ und Wagenführ 2012).

2.3 Verwendete Bindemittel

Nach DIN EN 923 sind Klebstoffe nichtmetallische Stoffe, die Fügeteile durch Adhäsion und Kohäsion verbinden. Sie setzen sich aus nichtflüchtigen Bestandteilen (Bindemittel, Pigmente, Füllstoffe, Streckmittel, Hilfsstoffe [Härter, Beschleuniger, Verzögerer]) und flüchtigen Bestandteilen (Lösungsmittel, Dispersionsmittel, Verdünnungsmittel) zusammen (Niemz und Wagenführ 2012).

Wie bereits in Kapitel 2.1 beschrieben, wird für die Herstellung von formstabilen Holzfaserdämmstoffplatten im Trockenverfahren in der Regel pMDI verwendet. Solche Isocyanate sind bereits seit 1848 bekannt und gelten als effizientes Bindemittel. Durch chemische Verbindungen zwischen Klebstoff und Holz erreicht es deutlich festere Bindung als Harnstoff-Formaldehydharze (Zeppenfeld 1991). Weitere Vorteile sind, dass pMDI feuchtebeständig und formaldehydfrei ist. Nachteile von pMDI sind der hohe Preis, der petrochemische Ursprung und dass Trennmittel nötig sind, um ein Ankleben an metallischen Oberflächen wie beispielsweise Pressblechen zu vermeiden. Außerdem ist monomeres MDI toxisch (Deppe und Ernst 1996; Rowell 2012; Niemz und Wagenführ 2012). Auf Grund der hohen Festigkeit werden geringere Klebstoffmengen benötigt. Durch die geringe Polarität und Viskosität dringt pMDI schneller in das Holz ein als Bindemittel auf Harnstoff-Formaldehydbasis (Frazier 2003).

Wasser induziert die Aushärtung von pMDI. Die Verfügbarkeit von Wasser stellt auf Grund der Holzfeuchte kein Problem dar. Die Aushärtung von pMDI ist generell irreversibel (Rowell 2012).

Für die Herstellung flexibler Holzfaserdämmmatten werden in der Regel Kunstfasern verwendet. In den folgenden Veröffentlichungen sind dafür Bikomponentenfasern (Biko-Fasern) genutzt worden. Diese bestehen aus zwei fest, jedoch trennbar miteinander verbunden Polymeren. Dabei hat der Mantel (zum Beispiel Polyethylen) einen niedrigeren Schmelzpunkt als der Kern (zum Beispiel Polypropylen), so dass die Faser zur thermischen Vliesverfestigung genutzt werden kann (Lewin 2006).

3 Veröffentlichung 1: Characterisation of hardwood fibres used for wood fibre insulation boards (WFIB)

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Autoren: Arne A. P. Imken, Burkhard Plinke, Carsten Mai

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A. A. P. Imken	50	75	70	75	66
B. Plinke	25	25	10	0	18
C. Mai	25	0	20	25	16

ORIGINAL ARTICLE

Characterisation of hardwood fibres used for wood fibre insulation boards (WFIB)

Arne A. P. Imken[1]*, Burkhard Plinke[2], Carsten Mai[1]

*corresponding author
Arne A. P. Imken
arne.imken@uni-goettingen.de

[1] Wood Biology and Wood Products, Faculty of Forestry and Forest Ecology, University of Goettingen, Buesgenweg 4, 37077 Goettingen, Germany
[2] Technology for Wood and Natural Fibre-Based Materials, Fraunhofer Institute for Wood Research WKI, Bienroder Weg 54E, 38108 Braunschweig, Germany

Abstract

Wood fibre insulation boards (WFIB) are typically made from softwood fibres. However, due to the rapid decrease in softwood stands in Germany, the industry will be forced to adapt to the wood market. Therefore, alternative approaches for the substitution of softwood with hardwood will be needed in the fibre industry. The objective of this paper is to address the characterisation of hardwood fibres regarding their availability for the WFIB industry. The physico-mechanical properties of WFIB are significantly determined by the length of the fibres. Longer softwood fibres usually generate higher strength properties and a lower thermal conductivity than shorter hardwood fibres. In this paper, the potential application of hardwood fibres (up to 20.500 µm long) produced in a refiner by thermo-mechanical pulping (TMP) to WFIB production was examined. The scanner-based system FibreShape was used for the automatic optical analysis of the geodesic length distribution of fibres. The analysed hardwood fibres contained significantly more dust and were shorter than respectively produced softwood fibres, limiting their applicability to WFIB production. Thus, two analytical approaches were chosen to receive longer fibres and less dust: 1) blending hardwood fibres with supporting softwood fibres (20 %, 50 % and 80 % proportion of softwood), and 2) mathematical fractionation of hardwood fibres based on the fibre length to remove all particles smaller than 500 µm. It was concluded that the practical fractionation seems to be economically and ecologically challenging and that blending hardwood fibres with at least 50 % softwood fibres offers a promising approach, which should be further studied.

Keywords

Fibres, characterisation, FibreShape, image analysis, Wood Fibre Insulation Boards, WFIB, hardwood fibres

3.1 Introduction

The characterisation of fibres used for fibreboards is difficult because their shape is complex, and their size distribution covers several scales from micrometres up to centimetres. There is no generally accepted procedure to perform such a characterisation. In industrial operations, it is mostly done by means of subjective assessment by experienced workers (Benthien et al. 2014). A mechanical analysis by sieving provides a

more objective approach and enhances comparability of obtained data. This is possible, for example, by using a vibrating sieve, a tumbling sieve or an air jet sieve. None of these sieving techniques, however, are suitable for fibres because they agglomerate to balls and, even if the agglomeration can be avoided, sieving indicates only the width of the particles, not their length (Plinke et al. 2012). In addition, characterization based on sieving reflects the mass distribution of the fibres fractionated by sieving. This is due to the probability of fibres passing the sieves' meshes, and this probability depends not only on fibre morphology but also on sieving time and air pressure - if an air jet sieve is used.

On the other hand, fibre size distribution can be characterized via optical measurements of their shape characteristics such as length, width and circumference as defined in ISO 9276-6 (2008). Manual, optical analysis systems such as digital analysis of microscopic images are error-prone, time consuming, and require analysis of a high number of fibres to fulfil statistical requirements (Plinke et al. 2016). Automatic optical analysis systems, however, are the best methods for fibre characterisation. There are various commercial and semi-commercial systems on the European market such as QICPIC (Sympatec GmbH, Clausthal-Zellerfeld, Germany), Valmet FS5 fibre analyser (Valmet, Espoo, Finland), FibreShape (Innovative Sensor Technology IST AG, Vilters, Switzerland) or FibreCube (Johann Heinrich von Thünen-Institut, Hamburg, Germany) based on different measuring technology. All these systems are usable to characterise fibres for production of medium-density fibreboard (MDF), but only FibreShape and FibreCube can analyse fibres for the production of wood fibre insulation board (WFIB) due to the larger size of these fibres. FibreShape is better suited for, e.g., "banana" shapes and especially curled and branched fibres compared with other methods to compute size and shape characteristics. Production of fibres for WFIB is conducted with a wider disc gap during the refining process; this is why this fibre material contains much more fibre bundles and even shives. As previously shown, the systems QICPIC, FibreCube and FibreShape did not provide significantly different results with respect to the characterisation of wood particles to produce wood polymer composites (WPC) (Plinke et al. 2016). On that account, this study focuses on the fibre analyser FibreShape. The representation of particle size distribution by FibreShape is described in the standard ISO 9276-1 (1998), which specifies histograms, density distributions and cumulative distributions. The definition of size parameters of irregular particle geometries is standardized in ISO 9276-6 (2008).

WFIB are usually made of softwood fibres obtained through thermo-mechanical pulping (TMP), where wood chips are treated with superheated steam at high pressure and then defibrillated in a refiner (Lyons 2014). Production proceeds either via a dry or wet process, where today the dry process is applied more frequently. Usually polymeric methylene-diphenyl-isocyanate (PMDI) serves as binder (Vangronsveld et al. 2010). The worldwide production of wood-based panels (WBP) in 2016 amounted to 415.602.000 m³, while 8.956.000 m³ thereof fall upon WFIB (FAO 2018). Accordingly, WFIB account for only a small proportion of the global wood products industry but their production is increasing rapidly. For instance, the use of WFIB in Germany has quintupled from 250.000 m³ in 2008 to 1.250.000 m³ in 2010 (Sprengard et al. 2013). The development will continue to increase because of the public environmental awareness and due to the energy saving ordinance, which stipulates efficient insulation of buildings. The combination of the energy saving ordinance and public environmental awareness will lead to an increased utilisation of insulating materials from renewable resources such as WFIB.

As for the whole wood industry, forest restructuring in many European countries is an important challenge for the producers of WFIB. As an example, the area of coniferous stands in Germany has decreased between 2002 and 2012 by about 267.220 hectares and the area of hardwood stands has increased by about 315.368 hectares (Federal Ministry of Food and Agriculture 2015). Hence, researchers are looking for ways to substitute softwoods in wood-based panels with hardwood, including in WFIB. Previous studies have shown that the refiner disc gap and the wood species are the most influencing parameters for fibre length characteristics (Benthien et al. 2017). This indicates the importance of fibre characterisation, especially of hardwood fibres for WFIB. Hardwood fibres are biologically shorter (average of 1 mm) than softwood fibres (average of 3 to 8 mm) (Miller 1999). So far, using hardwoods to produce WFIB has not widely been reported. Bartholme et al. (2009) produced WFIB from beech fibres in a wet process and investigated the mechanical strength properties. Their findings were in line with the results of Eichhorn (2017), who produced WFIB from a blend of softwood and beech fibres, and showed that the addition of beech fibres decreases the mechanical properties and increases the thermal conductivity compared to WFIB solely of softwood.

This study aimed at characterising and comparing TMP fibres of ash, beech, birch, spruce, and blends of these fibres in order to determine their possible usability in WFIB

production. Industrial fibres to produce WFIB and spruce fibres to produce MDF were used as references. The results are supposed to show whether a blend of softwood and hardwood fibres and/or a fractionation of the hardwood fibres may enable the usability of hardwood fibres for WFIB production.

3.2 Material and Methods

3.2.1 Production of wood fibres

Apart from the industrial reference fibres, all fibres and blends were produced at Fraunhofer Institute for Wood Research - Wilhelm-Klauditz-Institut (WKI) in Braunschweig, Germany. Respective stems (purchased from Lower Saxony State Forests) were debarked with a peeling knife (Wilh. Schmitt & Comp. GmbH & Co. KG, Remscheid, Germany) and split by hand before being chopped in a shredder (120X400H2WT, Klöckner KG, Hirtscheid, Germany) to wood chips. To produce fibre blends, the wood chips were mixed to the targeted composition. The pure chips or their blends were defibrillated in a refiner (Andritz AG, Wien, Austria). The defibration conditions are listed in Table 1.

Table 1: Defibration conditions in the refiner.

Type of fibres	WFIB fibres	MDF fibres
Rotation [rpm]	3000	3000
Pressure [bar]	7.5	7.5
Temperature [°C]	170	170
Retention time [min]	5	6
Disc gap [mm]	0.6	0.15
Fibre moisture content [%]	15 - 20	6.5

3.2.2 Wood fibre materials

Various types of fibres, industrial fibres for WFIB, self-manufactured fibres for MDF as references and self-manufactured fibres for WFIB were used in this study. In total, nine different fibre groups were studied (Table 2). The tested fibres were either made solely from Norway spruce (*Picea abies*), European ash (*Fraxinus excelsior*), European beech (*Fagus sylvatica*) or silver birch (*Betula pendula*) or were blends of Norway spruce with various hardwood fibre blends in proportions of 20, 50 and 80 %. The hardwood fibre blends contained equal proportions of the three named hardwoods and

were produced by blending of the respective wood chips prior to refiner pulping. Industrially produced (mostly) Norway spruce fibres to produce wood fibre insulation boards (WFIB) served as one reference and were purchased from Homatherm, Berga, Germany.

Table 2: Different fibre groups and abbreviations.

Fibre variation	Abbreviation
Industry reference of fibres for WFIB (Homatherm – mostly Norway spruce)	Industry reference
Self-manufactured reference of fibres for MDF (Norway spruce)	100Spruce_MDF
Solely Norway spruce fibres	100_Spruce
Solely European Ash fibres	100_Ash
Solely European beech fibres	100_Bech
Solely silver birch fibres	100_Birch
A blend of 80 % Norway spruce and 20 % of hardwood blends	80SW_20HW
A blend of 50 % Norway spruce and 50 % of hardwood blends	50SW_50HW
A blend of 20 % Norway spruce and 80 % of hardwood blends	20SW_80HW

3.2.3 Fibre characterisation

The various fibre groups were characterized by FibreShape (Innovative Sensor Technology IST AG, Vilters, Switzerland). For every measurement, 0.25 g of fibres were chosen coincidentally from the middle of the fibre mass so that there was the same chance to include dust, fibres and shives for each measurement. The fibres were dispersed manually on a transparent film of A4 size, and a flatbed scanner in transmitted light mode was used to produce images of the fibres. The fibre dimensions were then assessed by static image analysis of the FibreShape software. The “rectangle model” was used to determine geodesic length and geodesic width for the fibres, as wood fibres usually have a shape factor above 1 (i.e. are longer than wide). This model uses the particle’s area (number of pixels belonging to its shape) and circumference (amount of steps needed to circumnavigate the shape) assuming the shape would be a rectangle: length and width derive from the equations for area and circumference applied to rectangles. The theoretical resolution of the used scanner was 21 µm/pixel. Although this is the limit of detectability, the reliable measuring range ranges from approx. 100 µm (corresponding to particles with a shape of at least 5 pixels) up to 5 cm. The

results of particle size analysis were depicted according to DIN ISO 9276-1 (1998), DIN ISO 9276-2 (2014) and DIN ISO 9276-6 (2008). All statistical evaluations rely on the weighting method based on particle area (q_2 distribution) because this size feature was individually measured for each particle and not computed from a volume model. Although this weighting method does not perfectly reflect the mass distribution of particles by length, it is quite close to it and more reliable than size distributions based on the particle number. Therefore, histograms for the particle length distribution are shown as q_2 frequency distributions, and the percentiles of the cumulative frequencies (sum distributions) are Q_2 distributions. Two length scales with the same amplitude were used for the characterisation in this study. The first length scale ranged from 0 µm to 20,000 µm fibre length and included all measured objects in the studied fibre groups. This means that fibres longer than 20,000 µm were not considered. The second length scale ranged from 500 µm to 20,500 µm in order to exclude the dust from statistical evaluation. This limitation to a specific length range can be considered as “optical fractionation”. The full length range of 20,000 µm was subdivided into 50 fractions of 400 µm each: for the first set-up, Fraction 1 included all particles from 0 – 400 µm, and Fraction 2 included all particles from 400 – 800 µm, etc.; for the second set-up, Fraction 1 included all particles from 500 - 900 µm, and Fraction 2 included all particles from 900 – 1,300 µm, etc.

3.3 Results and discussion

3.3.1 Characterisation of single-species fibres

The geodesic length percentiles of the six single-species fibre groups (Table 2) were analysed using FibreShape and presented with respect to the cumulative frequency of the fibre-length-distribution and the percentage distribution within the 50 fractions (400 µm). When the full range of particle length was considered (including dust particles), it became obvious that the hardwood fibre groups contained much higher particle numbers and higher percentages in the small fractions (Figure 1, Figure 2). As an example, 50 % of all ash (“100_Ash”) fibre particles exhibited a length in the range of 0 – 800 µm (Fraction 1 and Fraction 2). In contrast, the lower 50 % of the “Industry reference” particles ranged from 0 – 2,400 µm (Fractions 1 – 6), while Fraction 1 and Fraction 2 (0 – 800 µm) made up only 23 % of the total particle number. Previous studies indicated larger proportions of short fibres in hardwood fibre materials for MDF production compared to softwood fibres. This resulted in a higher bulk density of the

hardwood fibre material (Park et al. 2001). Ohlmeyer et al. (2015) pointed out that the mean fibre length of pine TMP fibres was three times as large as that of beech TMP fibres. The geodesic length percentiles of the single-species fibre groups and the references (Table 3) indicated that the median values (50 % percentiles) for the softwood fibres (“100_Spruce”, “Industry reference” and “100Spruce_MDF”) were higher than those for the hardwoods (“100_Beech”, “100_Birch” and “100_Ash”). “100_Spruce” was even more than three times as large as “100_Ash”. There were also differences between the studied hardwoods. “100_Ash” exhibited the highest proportion of small particles (31 %, 0 – 400 µm), which was higher than for “100_Beech” (26 %, 0 – 400 µm) and “100_Birch” (19 %, 0 – 400 µm). “100_Spruce” (15 %, 0 – 400 µm) was similar to the “Industry reference” (14 % 0 – 400 µm) and to “100Spruce_MDF” (14 %, 0 – 400 µm) (Figure 3).

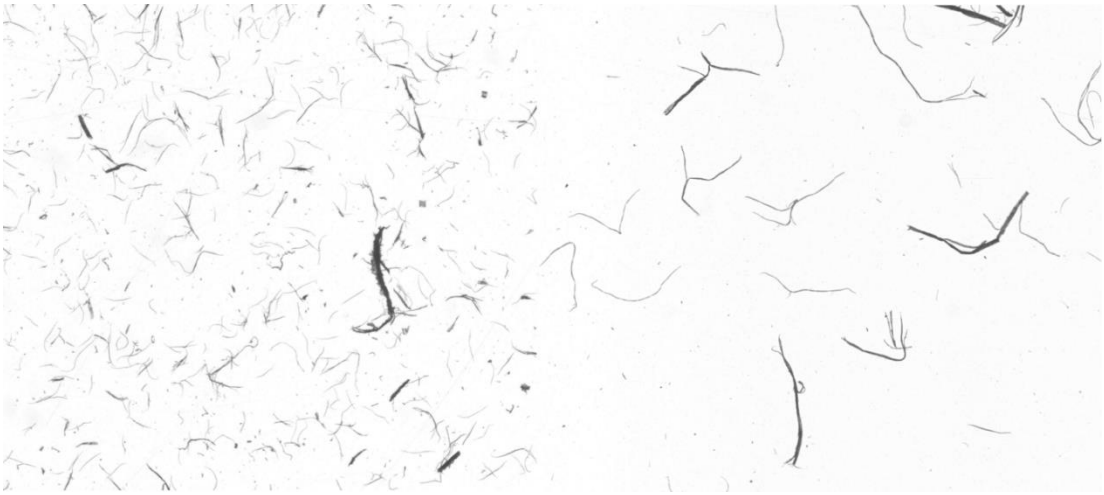

Figure 1: Scanned particles of single-species ash fibres (“100_Ash”) on the left side and the industry reference on the right side.

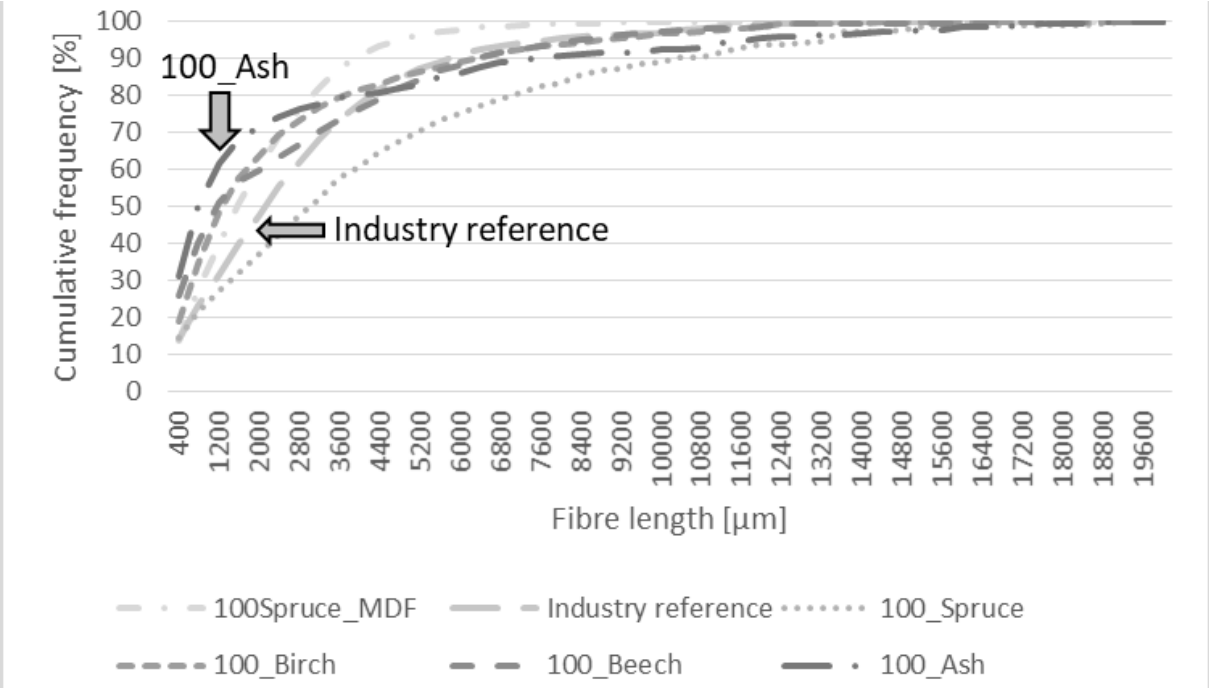

Figure 2: Cumulative frequency of the fibre-length-distribution for the single-species fibre assortments and the references.

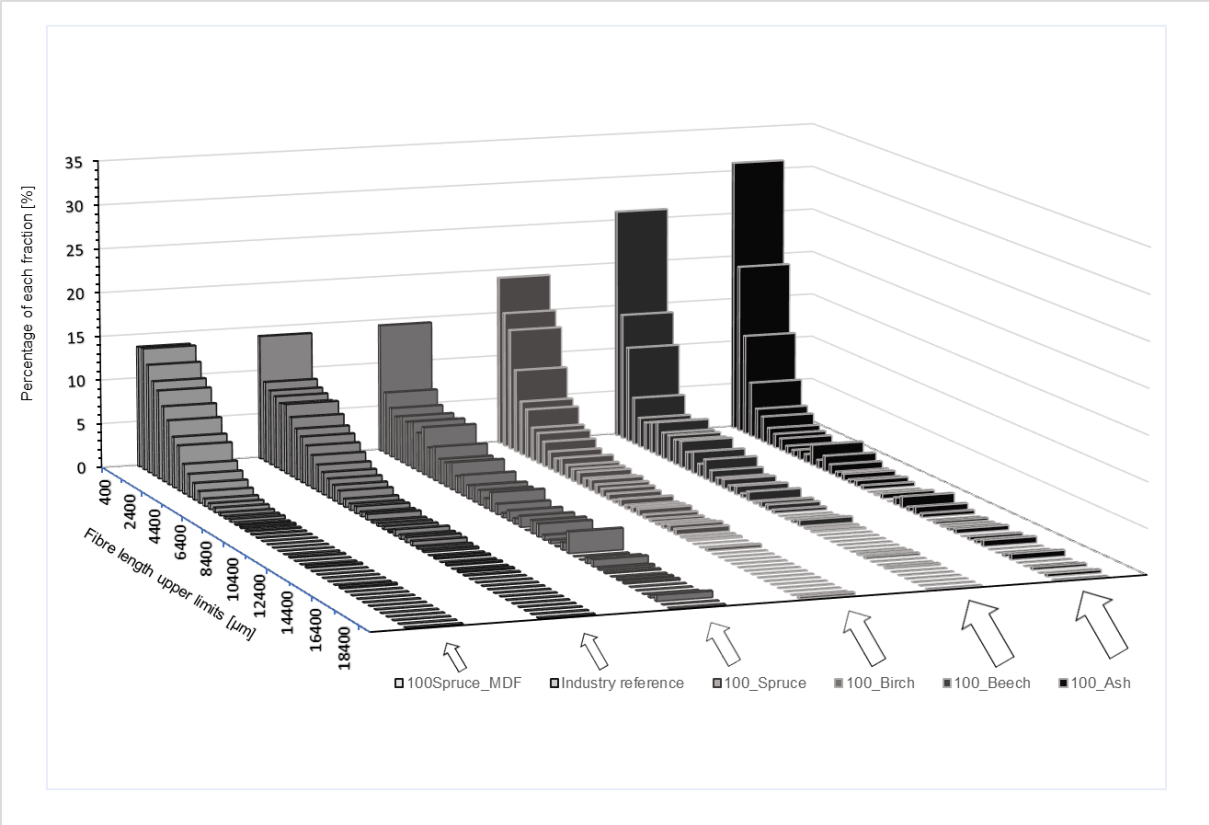

Figure 3: Percentage of the different fractions (400 µm range each) of the fibre-length-distribution for the single-species fibre groups and the references.

Moreover, there were differences in the larger fractions. The geodesic length of the fibres “100Spruce_MDF”, which were produced with the smaller refiner disc gap, reached almost up to Fraction 24 (≤ 9600 µm); only 0.4 % were above this fraction. “100_Spruce”, produced with a larger disc gap for WFIB, exhibited 11.7 % of all fibres above Fraction 24 (≤ 9600 µm). The 90 % percentile (10,178 µm) was 2.6 times longer than that of “100Spruce_MDF” (3,853 µm). The “Industry reference” showed the most uniform length distribution with only 3.2 % of all fibres above Fraction 24 (≤ 9600 µm) and a rather small 90 % percentile of 5,752 µm geodesic length. Even though “100_Ash” had the highest proportion of small particles, it also comprised a relatively high proportion of long particles; 8.3 % of all fibres were above Fraction 24 (3.4 % for “100_Beech” and 4.2 % for “100_Birch”) and the 90 % percentile displayed the second largest value of 7,480 µm (Table 3).

Table 3: Geodesic length percentiles [µm] of various single-species fibre groups and the references.

Variation	10 % Percentile	50 % Percentile	90 % Percentile
100Spruce_MDF	298	1542	3853
Industry reference	259	2110	5752
100_Spruce	256	3012	10178
100_Birch	189	1264	6314
100_Beech	110	1138	6359
100_Ash	117	792	7498

The results generally indicated a higher proportion of particles with length below 400 µm in fibre materials from hardwoods than from softwoods. These low-length fractions can be defined as dust. Depending on the hardwood species, there was significantly more dust (“100_Ash” and “100_Beech”) or slightly more dust (“100_Birch”). WFIBs require high proportions of long fibres and low dust proportions to obtain high strength properties and minimise consumption of adhesive (Benthien et al. 2015). One approach to reach this objective was to use a blend of hardwood and softwood fibres, while another strategy was to fractionate the hardwood fibres and to use only the long-fibre fractions.

3.3.2 Characterisation of the blended fibre groups

Various fibre blends of four wood species - Norway spruce and three hardwoods (ash, beech, birch) were produced by blending the respective wood chips prior to thermo-hydrolytic pulping (TMP) in a pilot-scale refiner. This approach was chosen because blends of softwood and hardwood assortments are likely to be used for future industrial production of fibreboards in Central Europe. The obtained fibre blends were compared with the references (Figure 4 and Figure 5). Three fibre blends were produced (Table 2), in which the hardwood fibre blends contained equal proportions (33%) of ash, beech and birch.

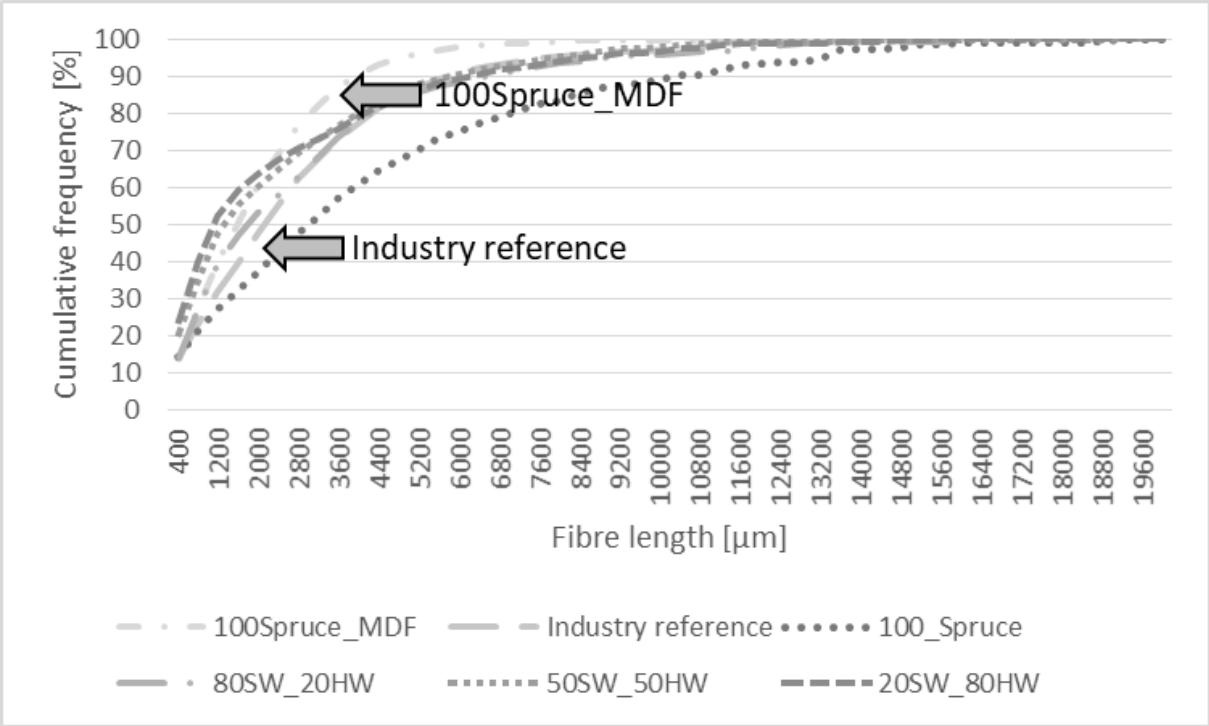

Figure 4: Cumulative frequency of the fibre-length-distribution for the blended groups and the references.

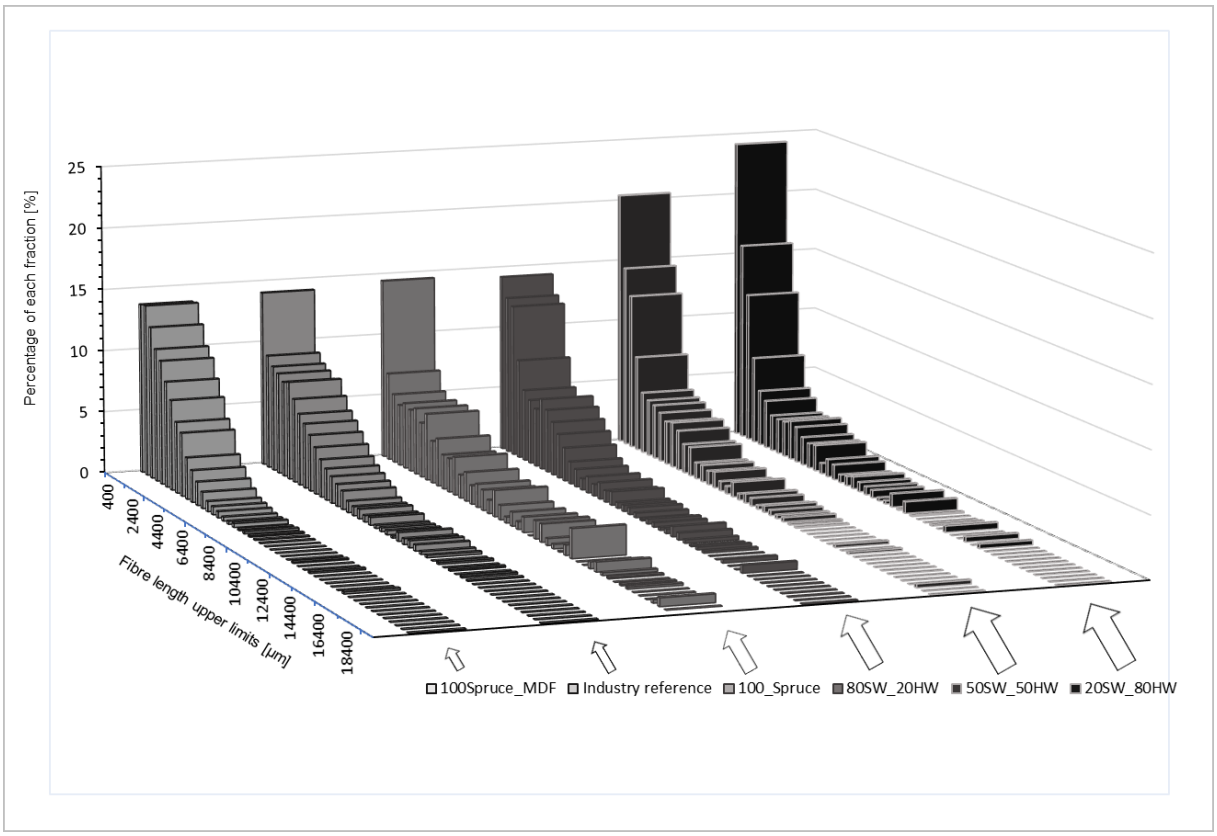

Figure 5: Percentage of the different fractions (400 µm range each) of the fibre-length-distribution for the blended groups and the references.

Previously, a blend of 75 % softwood fibres and 25 % birch fibres was characterised via vibrating sieve by Park et al. (2001). The fibre length distribution was an intermediate between softwood and hardwood fibres. In contrast to this result, in the present study the proportion of Fraction 1 (≤ 400 µm) did not change due to adding 20 % of hardwood fibres. The proportion of Fraction 1 amounted to 14 % for the references ("100Spruce_MDF" and "Industry reference") as well as for the "80SW_20HW" group (Figure 4). Still, the fibre length displayed an intermediate distribution in higher fractions (Fractions > 1). For the "Industry reference", the length of half (50 %) of all fibres ranged up to 2,400 µm; the lower half of the "80SW_20HW" group ranged up to 2,000 µm.

A comparison of the percentile values of the geodesic length distributions revealed a decreasing median of the groups' fibre length with increasing proportion of hardwood fibres (Table 4). A proportion of only 20 % hardwood fibres lowered the median length compared to the "100_Spruce" group almost to half. The group "50SW_50HW" exhibited the lowest 90 % percentile of all fibre blends with 5,794 µm, which was similar to that of the "Industry reference" (5,752 µm). The group "80SW_20HW" reached the

highest value for the 90 % percentile with 6,656 µm, which was slightly higher than the 90 % percentiles of “100_Beech” and “100_Birch”, slightly lower than the 90 % percentile of “100_Ash” and much lower than the 90 % percentile of “100_Spruce” (Table 3, Table 4).

Table 4: Geodesic length percentiles [µm] of various blended fibre groups and references.

Variation	10 % Percentile	50 % Percentile	90 % Percentile
100Spruce_MDF	297.9	1541.7	3852.5
Industry reference	259.2	2110.4	5752
100_Spruce	256.3	3012.2	10177.7
80SW_20HW	265.8	1779.7	6655.5
50SW_50HW	160.1	1313.7	5793.7
20SW_80HW	133.3	1111.6	6250.9

To characterise the long-fibre fractions, Fraction 24 (≤ 9600 µm) was exemplarily chosen as the highest fraction occurring in all groups. None of the three fibre blends exhibited considerable proportions above this fraction (between 2 % and 4 %) (Figure 5). Insulation boards of blends of 25 %, 50 % and 75 % of softwood fibres and 75 %, 50 % and 25 % of beech fibres, respectively, displayed significantly decreasing strength properties for panels containing 75 % beech fibres (Eichhorn 2017). The author, however, did not characterise the fibre length.

3.3.3 Characterisation of fractionated fibre groups

To exclude dust particles from the fibre material, an optical fractionation was conducted via FibreShape (Figure 6, Figure 7). Referring to Blecken (2004), dust is defined as particles smaller than 500 µm and the range for analysis was therefore set from 500 µm to 20,500 µm. After the fractionation, the hardwood materials still contained higher proportions of the small fractions than the material based on softwood. For example, in “100_Ash”, 50 % of all fibres were in Fraction 1, 2 and 3 (500 – 1,700 µm), while the lower 50 % of all fibres in the “Industry reference” ranged up to Fraction 6 (500 – 2,900 µm) (Figure 6).

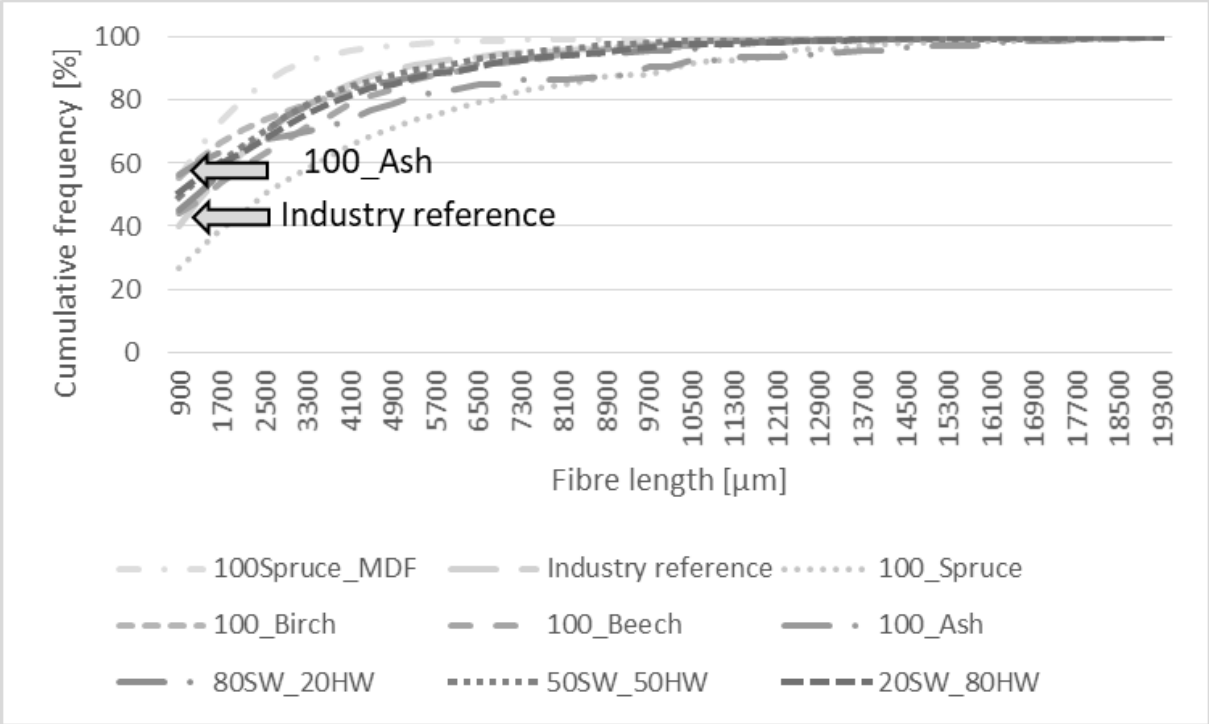

Figure 6: Cumulative frequency of the fibre-length-distribution for all groups after optical fractionation.

As observed for the analysis in Figure 3 and Figure 5, the highest proportion of fibres analysed by fractionation was found in Fraction 1 (≤ 900 µm); for example, in “100_Ash”, Fraction 1 made up 28 %. In other cases, the ratios changed compared to the previous analysis (Figures 3 and 5), for example, Fraction 1“ of 100_Birch” contained as many fibres as “100_Beech” (20 % each) (Figure 7). The median of the fractionated groups without dust (Figure 7) was clearly higher than that of the respective non-fractionated groups (Figures 3 and 5) including dust (Table 5). The medians of “100_Ash” and “100_Beech” were more than twice after the fractionation, while the median of the references only increased by 21 % (“Industry reference”) to 24 % (“100Spruce_MDF”) due to fractionation. For the blended groups, increasing proportions of hardwood fibres resulted in an increasing difference in the median obtained by full-range and by fractionated analysis. The increase in the median due to fractionation for the group “80SW/20HW” amounted only to 37 %, for the group “50SW/50HW” to 63 % and for the group “20SW/80HW” to 84 %. This indicated that increasing proportions of dust were due to increasing proportions of hardwood.

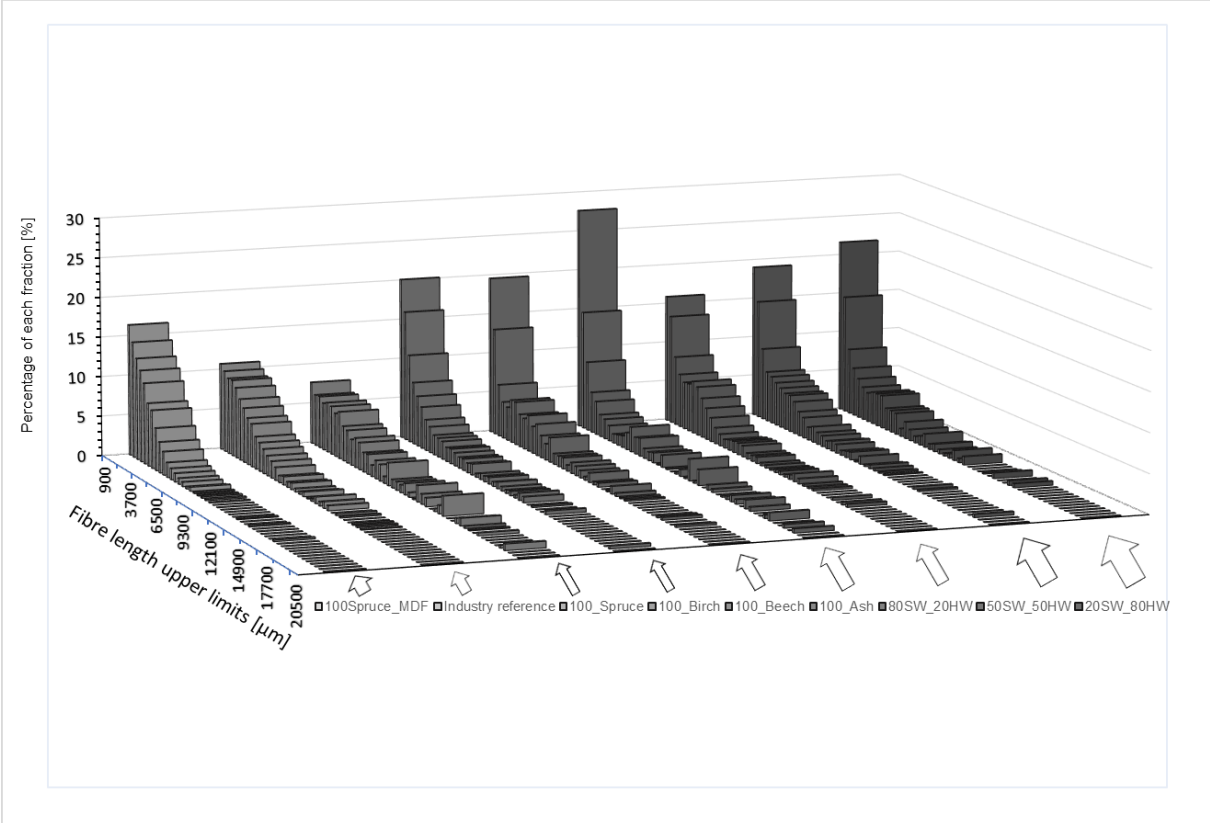

Figure 7: Percentage of the different fractions (400 µm range each) for the fibre-length-distribution for all groups after optical fractionation.

Table 5: Comparison of the geodesic length median [µm] value with and without dust (fractionation).

Variation	Median [µm] with dust	Median [µm] without dust
100Spruce_MDF	1,542	1,912
Industry reference	2,110	2,553
100_Spruce	3,012	3,675
100_Birch	1,264	1,829
100_Beech	1,138	2,614
100_Ash	792	1,620
80SW_20HW	1,780	2,435
50SW_50HW	1,314	2,147
20SW/80HW	1,112	2,044

Another analytical option was to assess the length distribution based on the particle number without weighting by area (q_0 distribution). This approach only compared the relative change of the particle number, because absolute numbers do not reflect the mass distribution as in weighted (q_2-) distributions. However, the results (Table 6) were similar to the ones from Table 5 as fractionation had comparable effects on the percentage reduction in particle number and increase in the median. As an example, in

case of the fractionated groups “100_Ash” and “100_Beech”, the particle numbers exhibited the largest decreases by approximately 84 % and 86 % compared to the numbers for the non-fractionated groups. The smallest decrease of 66 % was observed for “100Spruce_MDF”. For the blended groups, the largest decrease in the particle number was found at the highest hardwood content (“20SW_80HW”). Abubakr et al. (1994) reported that practical fibre fractionation for papermaking resulted in enhanced strength indexes. The authors attributed this to a significant proportion of higher-grade papermaking fibres in the long-fibre fraction detected in a Kajaani fibre analyser (today: Valmet Fibre Image Analyser). For wood-polypropylene composites, fractionated longer fibres showed the highest reinforcing potential due to the larger aspect ratio and higher single fibre character (Horbens et al. 2012). Fractionation, however, is time consuming, expensive and leads to a huge amount of small fibres waste material. For example, approximately one-third of all fibres in “100_Ash” would be sorted out due to fractionation. Discarding this material would be an economic and ecologic aberration. Alternative usage of the dust is necessary; utilisation in wood-plastic composites (WPC) or for pellets production, or as fuel might be a potential option. No in-depth studies on mechanical and insulation properties of WFIB containing hardwood fibres have been reported so far. Subsequent studies on the production of WFIB shall compare the mechanical strength properties and the thermal conductivity of WFIB produced from blends of hardwood and softwood fibres as well as fractionated hardwood fibres.

Table 6: Particle number of the fibre groups without and after fractionation.

Variation	Particle number without fractionation	Particle number after fractionation (> 0,5 mm)	Relative decrease of the particle number
100Spruce_MDF	96,703	33,070	66 %
Industry reference	87,951	23,172	74 %
100_Spruce	37,682	7,635	80 %
100_Birch	96,693	24,067	75 %
100_Beech	137,666	19,553	86 %
100_Ash	105,604	16,812	84 %
80SW_20HW	151,461	29,268	81 %
50SW_50HW	114,856	26,349	77 %
20SW/80HW	95,670	29,543	69 %

3.4 Conclusion

The optical characterisation of single fibre assortments and fibre blends for WFIB reveals that hardwood fibre materials contain distinctly more dust than respective softwood fibre materials. Accordingly, the median length of hardwoods is lower, even lower than the median of the length of softwood MDF-fibres. Furthermore, the softwood fibres for WFIB are twice as long as softwood fibres for MDF. The higher dust content and lower median length of hardwood fibres make their utilisation for WFIB production more difficult, as WFIB requires low dust content and long fibres for successful production. Blends of softwood and hardwood fibres show a fibre length distribution intermediate between softwood and hardwood fibres when adding at least 50 % of softwood fibres to the hardwood fibre blends. This can be an appropriate method for the usage of hardwood fibres for WFIBs. Fractionated hardwood fibres show less dust proportions, as those are mathematically removed from the samples. This suggests that fractionation might be a valid method to introduce hardwood in WFIB production.

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Conflicts of Interest

The authors declare no conflicts of interest.

4 Veröffentlichung 2: Production and characterisation of wood-fibre insulation boards (WFIB) from hardwood fibres and fibre blends

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Autoren: Arne A. P. Imken, Redelf Kraft, Carsten Mai

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A. A. P. Imken	50	70	70	75	64
R. Kraft	25	30	5	0	18
C. Mai	25	0	25	25	18

ORIGINAL ARTICLE

Production and characterisation of wood fibre insulation boards (WFIB) from hardwood fibres and fibre blends

Arne A. P. Imken[1]*, Redelf Kraft[2], Carsten Mai[1]

*corresponding author

Arne A. P. Imken

arne.imken@uni-goettingen.de

[1] Wood Biology and Wood Products, Faculty of Forestry and Forest Ecology, University of Goettingen, Buesgenweg 4, 37077 Goettingen, Germany

[2] Molecular Wood Biotechnology and Technical Mycology, Faculty of Forestry and Forest Ecology, University of Goettingen, Buesgenweg 2, 37077 Goettingen, Germany

Abstract

Due to the rapid decline in coniferous (softwood) stands in Europe, the wood-based panel industry will be forced to adapt its products to the wood market supply. The production of wood fibre insulation boards (WFIB), which are usually made with softwood fibres, must therefore be converted to the use of hardwood fibres. The objective of this study was to investigate the properties of WFIB made from hardwood fibres and blends of softwood and hardwood fibres produced in a refiner by thermo-mechanical pulping (TMP). WFIB with a raw density of 100 kg m^{-3} were produced in a dry process with hot-air and hot-steam. The binder used was polymeric diphenylmethane diisocyanate (pMDI, 5 wt% related to the weight of dry fibre material) for stiff boards or 7 wt% bi-component (Bico) fibres for flexible mats. Mechanical strength results for pure hardwood fibres were significantly lower than for softwood fibres and for fibre blends, while water absorption was significantly higher. However, the thermal conductivity for pure hardwood fibres was higher than for softwood fibres and for fibre blends. The results showed that it is possible to produce WFIB from hardwood fibres with satisfactory properties. WFIB made from hardwood fibre blends with at least 20 % softwood fibre content showed comparable results to those made from pure softwood fibres.

Keywords

Wood fibre insulation board (WFIB), hardwood fibres, fibre blends, thermal conductivity

4.1 Introduction

Buildings accounted for about 40 % of the total final energy consumption in the EU in 2012. Within the residential sector, 67 % of the energy consumed is used for space heating (Bosseboeuf 2015). Improvements to the building envelope can thus play an important role in reducing space heating (Cao et al. 2016). Currently, mineral wool or expanded polystyrene (EPS) are predominantly used to insulate buildings, but the market for renewable insulation materials is growing continuously (Windirsch 2021). In the field of renewable insulation materials, wood fibre insulation boards (WFIB) are one of the most important material for thermal insulation. In 2016, WFIB accounted for 8,956,000 m^3 of the global production of wood-based panels which amounts to

415,602,000 m³ (FAO 2018) and production is increasing rapidly. The use of WFIB in Germany has nearly doubled from 1,250,000 m³ in 2010 (Sprengard et al. 2013) to 2,030,000 m³ in 2020 (Windirsch 2021). This development will most likely continue because of the growing environmental awareness of the public. In addition, EU member states have adopted national programs that include a series of measures such as increasing use of renewable raw materials and energy sources and improving energy efficiency in buildings (Fragkos et al. 2017). Plant-based insulation materials such as WFIB may even sequester carbon dioxide for the life-time of the building (Lawrence et al. 2013). WFIB are usually made from softwood fibres obtained by a thermo-mechanical pulping (TMP) process. In this process, the wood chips are treated with saturated steam under high pressure and afterwards defibrillated in a refiner (Stokke et al. 2014). Insulating panels are manufactured using either a dry or a wet process. The dry process is used more frequently today because less water and energy is needed (Euring et al. 2015). In the dry process, drying and gluing immediately follow pulping, with polymeric methylene-diphenyl-isocyanate (pMDI) usually serving as the binder (Vangronsveld et al. 2010).

Forest restructuring in many European countries is an important challenge for the producers of WFIB, as for the entire wood industry. Artificial spruce monocultures are to be reconstructed to more stable and resilient mixed stands (Klimo et al. 2000). As an example, the area of coniferous stands in Germany has decreased between 2002 and 2012 by about 267.220 hectares, while the area of hardwood stands has increased by about 315.368 hectares (Federal Ministry of Food and Agriculture 2015). As a consequence, researchers and the industry are looking for ways to substitute softwoods in wood-based panels by hardwoods, including in WFIB.

So far, the usage of hardwood fibres for the production of WFIB has not been reported widely. Two studies report on the production of WFIB from beech and birch fibres in a wet process (Bartholme et al. 2009; Sable et al. 2015). The findings of both studies were in line with the results of Eichhorn (2017), who used a blend of softwood and beech fibres in a dry process with polyurethane binder to produce WFIB. The study showed that the addition of beech fibres reduces the mechanical strength properties and increases the thermal conductivity compared to WFIB made solely from softwood. In another study, however, no differences were found in the thermal conductivity of industrially produced WFIB from pine, spruce and beech (Brombacher 2015).

The aim of this study was to investigate the possibility of using hardwood fibres and fibre blends of softwood and hardwood to produce WFIB with adequate properties as WFIB from pure softwood fibres. Therefore, WFIB were produced solely from hardwood fibres, from fibre blends and solely from softwood fibres and their mechanical properties and thermal conductivity were analysed.

4.2 Material and Methods

4.2.1 Production of wood fibres

All fibres and blends were produced at the Fraunhofer Institute for Wood Research - Wilhelm-Klauditz-Institute (WKI) in Braunschweig, Germany. Respective logs (purchased from Lower Saxony State Forests) were debarked with a peeling knife (Wilh. Schmitt & Comp. GmbH & Co. KG, Remscheid, Germany) and split by hand before being chopped to wood chips in a chipper (120X400H2WT, Klöckner KG, Hirtscheid, Germany).

To produce fibre blends, the wood chips were mixed to the targeted composition before the refining process. The pure chips or their blends were defibrated by a refiner (Andritz AG, Wien, Austria). The defibration conditions used for refining can be found in Table 1.

Table 1: Defibration conditions in the refiner.

Type of fibres	WFIB fibres
Rotation [rpm]	3000
Pressure [Pa]	750,000
Temperature [°C]	170
Retention time [min]	5
Disc gap [mm]	0.6
Fibre moisture content [%]	15 - 20

4.2.2 Wood fibre materials

In total, five types of fibres were examined (Table 2). These were either made solely from Norway spruce (*Picea abies*) or silver birch (*Betula pendula*) or were blends of Norway spruce with a hardwood fibre mixture in proportions of 20 %, 50 % and 80 %. The hardwood fibre mixture contained equal proportions of European ash (*Fraxinus*

excelsior), European beech (*Fagus sylvatica*) and silver birch and were made by blending respective wood chips (finally including respective proportions of spruce chips) prior to refiner pulping (see 2.1).

Table 2: Different fibre types and abbreviations.

Fibre types	Abbreviation
Solely Norway spruce fibres	100_Spruce
Solely silver birch fibres	100_Birch
A blend of 80 % Norway spruce and 20 % of hardwood blends	80SW_20HW
A blend of 50 % Norway spruce and 50 % of hardwood blends	50SW_50HW
A blend of 20 % Norway spruce and 80 % of hardwood blends	20SW_80HW

4.2.3 Production of wood fibre insulation boards (WFIB)

The boards were produced in a dry process. Two types of binders - low temperature curing polymeric methylene diphenyl diisocyanate (pMDI) resin (I-Bond WFI 4370, Huntsman, Everberg, Belgium) and bicomponent fibres (Bico-Fibres) (AL-Adhesion C, FiberVisions, Varde, Denmark) - were used to produce either stiff boards or flexible mats. The adhesive amounts used were 5 wt% pMDI and 7 wt% bicomponent (Bico) fibres related to the dry mass of the fibres. The fibres were spread into a frame and compacted with a hydraulic pre-press. A hot-steam/hot-air aggregate was used to cure pMDI or melt the Bico fibres. The stiff boards (pMDI) were hardened by injecting 120 s of hot-steam, while the flexible mats were made using 120 s of hot-air to melt the Bico fibres. The manufactured boards and mats had dimensions of 650 mm × 650 mm × 40 mm and a target raw density of 100 kg m^{-3}. Boards for each fibre type and type of binder were produced in duplicates.

4.2.4 Physico-mechanical properties of fibres and WFIB

Before testing the physico-mechanical properties, the boards were sanded and cut into specimens of a size according to the following standards. The specimens were conditioned at 65 % RH and 20 °C. Bulk density (n = 3 per fibre type) of the fibres was determined according to EN ISO 17828 (2016), compression strength (5 specimens per board, n = 10) according to EN 826 (2013), internal bond strength (5 specimens

per board, n = 10) according to EN 1607 (2013), water absorption (4 specimens per board, n = 8) according to EN 1609 (2013), thermal conductivity (n = 1 for raw fibres; 2 specimens per board, n = 4 for boards and mats) according to EN 12667 (2001) and flaming behavior (2 specimens per board, n = 4) according to EN ISO 11925-2 (2010).

4.2.5 Statistical analysis

The obtained data were statistically analysed using Excel 2016 (Microsoft, Redmond, WA, USA). The Levene-test was used to determine if the data showed variance homogeneity. A two-sample unequal variance (heteroscedastic) t-test with Bonferroni correction was used to determine if there were significant differences between the different fibre types. These determinations could only be done with an appropriate number of test specimens; these were only available for testing the compression strength, the internal bond strength and the water absorption.

4.3 Results and discussion

4.3.1 Bulk density of the fibres

A statistical evaluation of the bulk density was not possible because the number of specimens was too small (n = 3). Still, the absolute values were compared. The fibres 100_birch had the highest bulk density (17.4 kg m^{-3}), 80SW_20HW (15.5 kg m^{-3}) the lowest (Figure 1). With the exception of the fibres 100_spruce, which showed a higher value than 80SW_20HW, the bulk density increased as the proportion of hardwood fibres increased. This can be explained by a higher proportion of small particles in the hardwood fibres used (Imken et al. 2021).

Another study found higher bulk densities for hardwood fibres than for softwood fibres (Park et al. 2001). Deviating from the results in this study, it revealed that bulk densities of fibre blends were even higher than those of hardwood fibres. The bulk density of the fibres has a major influence on the strength properties of fibreboards, which generally increase with decreasing bulk density of the fibres, especially if the degree of compaction of the boards is low (Suchsland and Woodson 1991). In addition, the bulk density has a major influence on the thermal conductivity, which is discussed in chapter 3.5.

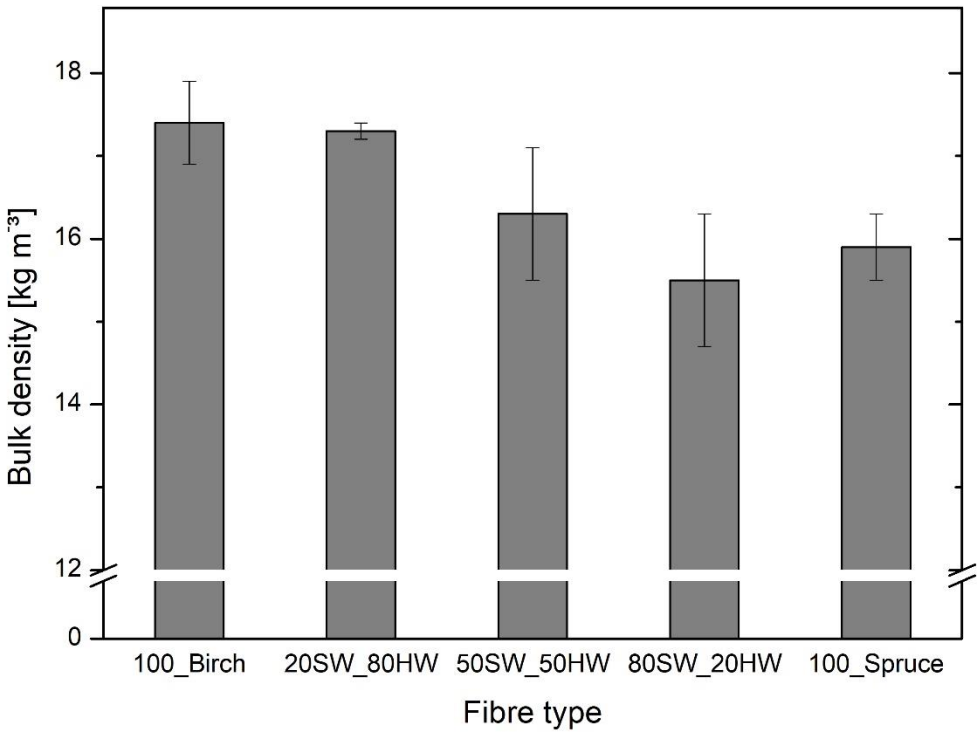

Figure 1: Arithmetic average and standard deviation of the bulk density of WFIB from different fibre types.

4.3.2 Compression strength of the WFIB

Regarding the WFIB bonded with 5 wt% pMDI, the four fibre types (Table 2) with at least 20 % softwood fibres (20SW_80HW) showed similar compression strengths (between 46.4 kPa and 49.8 kPa); the strength of boards from 100_birch (11.0 kPa) was significantly lower and amounted to only about 25 % of the boards containing softwood fibres (Figure 2). In contrast, the compression strength of the WFIB bonded with Bico fibres was less than half of the pMDI-bonded boards, while the values were proportional to the respective pMDI-bonded boards. The fibre type 100_birch displayed the significantly lowest compression strength (6.8 kPa), while the four other fibre types were at the same level between 15.6 kPa and 19.8 kPa and showed no significant differences (Figure 2).

It has previously been shown that 40 mm thick WFIB with a density of 200 kg m^{-3} produced from softwood fibres in a dry process with 4 % pMDI reach an average compression strength of more than 200 kPa (Euring et al. 2015). This is more than four times the value of the results for the same fibre types, including blends with softwood fibres, investigated in this study (Figure 2) and can be explained by the much higher density of the boards. Accordingly, another study even reported compression strengths

of 250 – 330 kPa for WFIB made from softwood fibres with a density of 180 kg m^{-3}, which were produced in a dry process with 4 % pMDI (Kirsch et al. 2018).

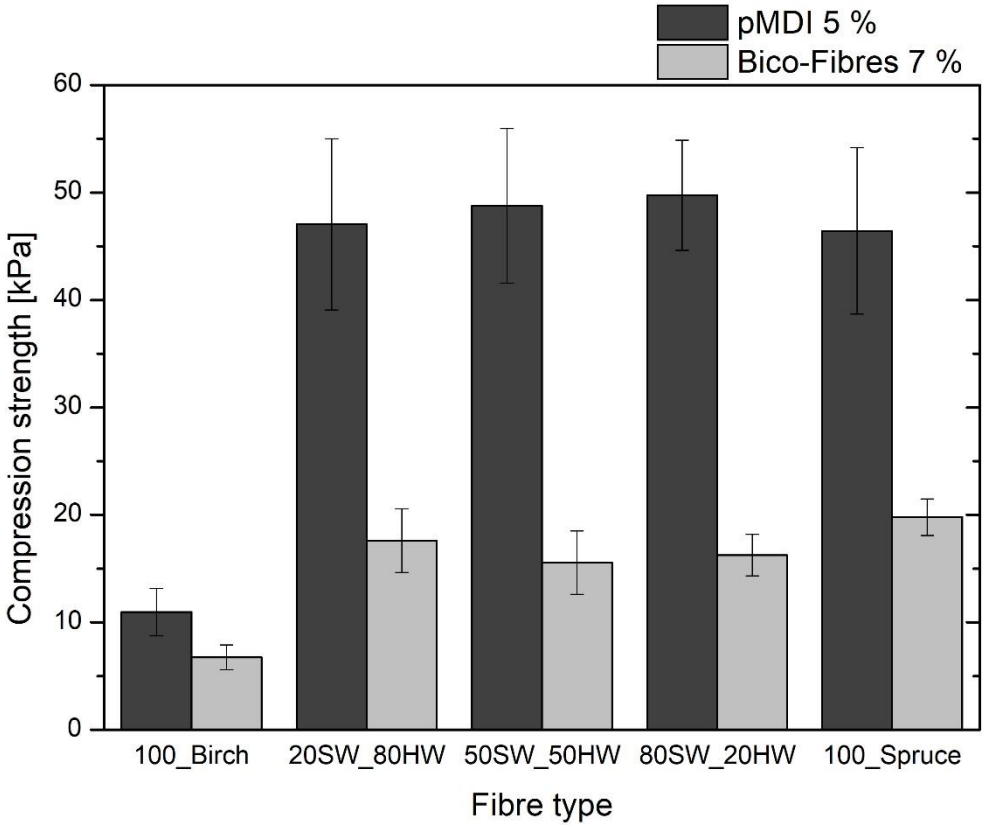

Figure 2: Arithmetic average and standard deviation of the compression strength of WFIB from the different fibre types produced with 5 wt% pMDI and 7 wt% Bico fibres.

Another study determined the influence of beech fibres, also in blends with softwood fibres, on the properties of WFIB (Eichhorn 2017). WFIB of lower density (100 kg m^{-3}) from softwood fibres bonded with pMDI resulted in 45.5 kPa compression strength, which is similar to the results of this study. Boards made of beech fibres and softwood-beech fibre blends consistently revealed decreasing strengths with increasing proportion of beech fibres in the boards (Eichhorn 2017), but not such a big difference between WFIB made of pure hardwood fibres and all other boards containing at least 20 % softwood fibres as in this study.

As in another study (Sable et al. 2015), only fibres of silver birch were used as hardwood fibres in pure form in this study; other hardwood fibres were used as a blend. These (100_birch) were chosen because in a previous study the fibre length distribution of birch fibres was more similar to the softwood fibres studied than that of ash and beech fibres and the birch fibres showed the lowest content of small particles of the

three hardwoods (Imken et al. 2021). The large difference between the strength values of the panels from 20SW_80HW and 100_birch could be due to problems with the bondability of the birch fibres caused by polar chemical constituents such as fats and waxes (Sjöström and Alén 1999). In addition, it could be due to the high bulk density of 100_Birch fibres (Figure 1), which results in a lower number of fibres in a board at a given density compared to spruce fibres and accordingly a low compaction ratio, meaning that the compressive resistance might not be high.

4.3.3 Internal bond strength (IB) of WFIB

Internal bond strength (IB) was assessed for WFIB made of the five fibre types (Table 2) bonded with 5 wt% pMDI (Figure 3), but not for the mats bonded with Bico fibres, as this strength property is of particular interest for WFIB in external wall insulation systems where only stiff boards and not flexible mats are used. Analogous to the compression strength (Figure 2), the same proportionalities can be seen with respect to IB (Figure 3). WFIB made of 100_Birch exhibited an IB of 1.1 kPa, while boards of the four other fibre types with at least 20 % softwood fibres showed significantly higher IB values between 4.1 kPa and 6.0 kPa (Figure 3). Other studies on WFIB produced in a dry process with 4 wt% pMDI reported IB values in the range of 40 to 50 kPa for WFIB made of softwood fibres at a density of 200 kg m^{-3} (Euring et al. 2015) or provided comparable results (Kirsch et al. 2018; Kawasaki et al. 1998). As already observed with regard to compression strength, the significantly (about 10 times) higher IB compared to this study is attributed to the higher board densities. Comparison of the IB values of this study with the results of WFIBs examined by Eichhorn 2017, which also contained proportions of hardwood fibres, reveal the same proportional sequence as for the compression strengths. The values for the fibre blends are nearly the same, e. g. 4.7 kPa for 20SW_80HW (Figure 3) and 4.3 kPa for 25SW_75HW (Eichhorn 2017). In contrast to this study, Eichhorn reported consistent decrease in IB with increasing proportion of hardwood fibres and not such a clear difference between WFIB from pure hardwood fibres and those made of fibre blends (Eichhorn 2017).

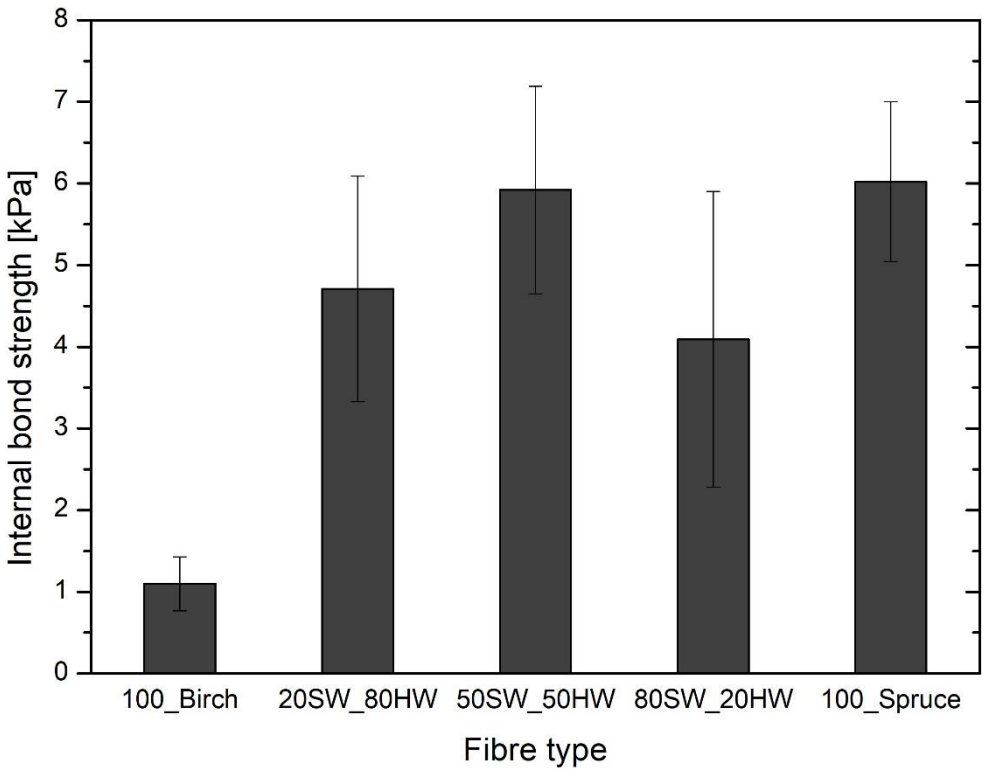

Figure 3: Arithmetic average and standard deviation of the internal bond strength of WFIB from different fibre types produced with 5 wt% pMDI.

4.3.4 Water absorption of WFIB after 24 h

Water absorption was assessed for WFIB made of the five fibre types (Table 2) bonded with 5 wt% pMDI (Figure 4), but not for the mats bonded with Bico fibres, which are mainly used for insulation between rafters where hardly any capillary water absorption occurs. WFIB of 100_birch absorbed the significantly highest amount of water within 24 h (6.0 kg m^{-2}). This result is in line with Eichhorn (2017) who also found the clearly highest water uptake within 24 h for WFIB made of pure hardwood fibres. This could be due to problems with the bondability (see 3.2) if the pMDI adhesive does not enclose all of the fibres. In addition, the number and volume of birch fibres per board volume should be lower resulting in reduced bonding areas and a greater pore volume between the fibres. The latter might additionally enhance the water penetration.

Boards made of 100_spruce showed water absorption of 0.9 kg m^{-2}. In general, the water absorption of boards made of the four fibre types containing softwood was below 2 kg m^{-2}. Among these boards, water absorption increased with increasing amount of hardwood fibres (Figure 4). Accordingly, Zabihzadeh reported that water absorption is

lower in composites containing softwood than in those containing hardwood and attributed this to the higher proportion of hydrophobic lignin and lower proportion of hemicelluloses in softwood, which may enhance water absorption (Zabihzadeh 2010). A hydrophobic agent could possibly compensate for this. Moreover, the higher water absorption can also be attributed to the lower number of fibres per given volume in the boards containing a higher proportion of high-density hardwood (see above). Other studies reported water absorption for WFIB made of softwood fibres and 4 wt% pMDI of 1 kg m^{-2} (Euring et al. 2015), 0.5 – 0.8 kg m^{-2} (Kirsch et al. 2018) and 0.7 kg m^{-2} (Eichhorn 2017).

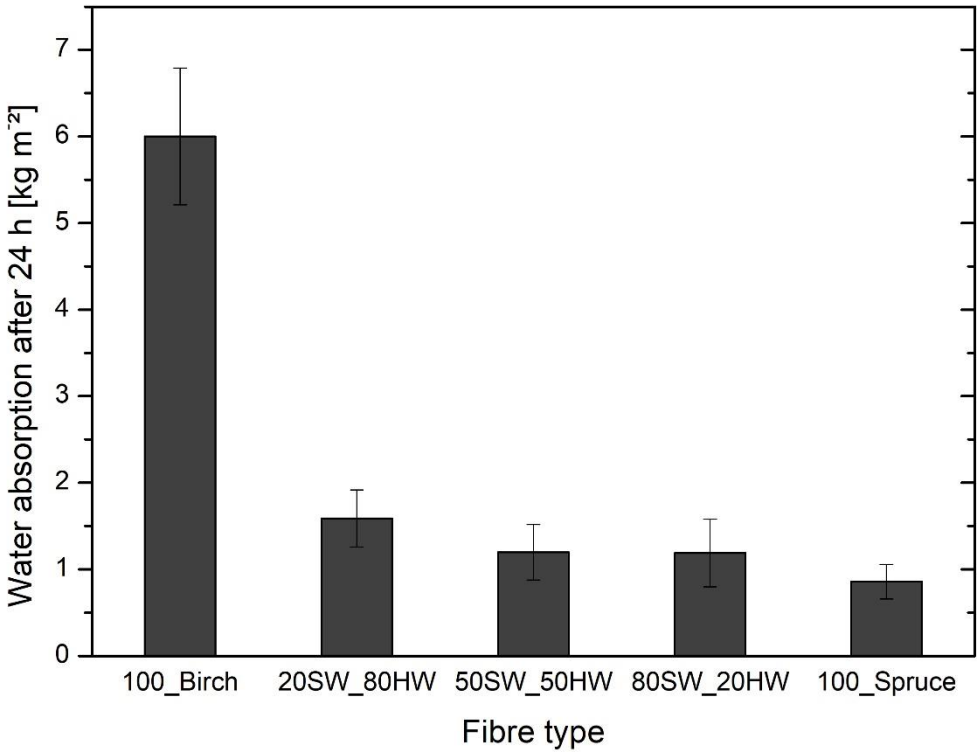

Figure 4: Arithmetic average and standard deviation of the water absorption after 24 h of WFIB from different fibre types produced with 5 wt% pMDI.

4.3.5 Thermal conductivity

The thermal conductivity was determined for three types of material: the raw (unbonded) fibres, the pMDI-bonded boards and the mats bonded with Bico fibres (Figure 5). As for the bulk density a statistical evaluation was not possible because the number of specimens was too small. Nevertheless, a comparison of the absolute values was made.

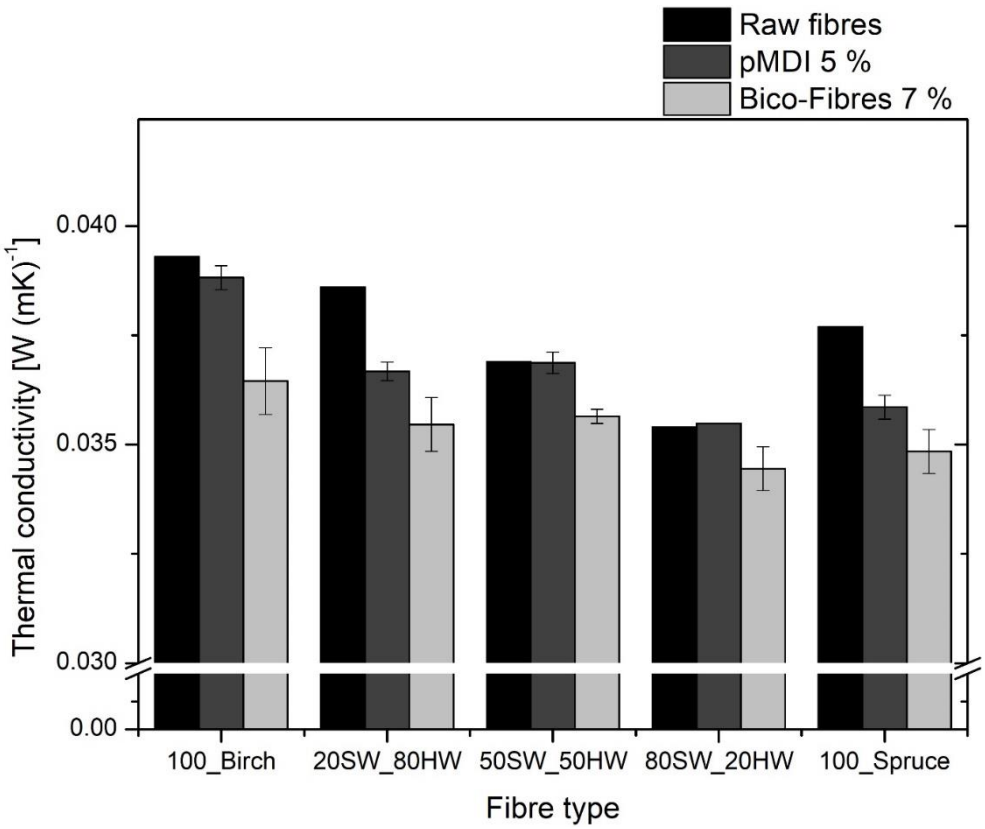

Figure 5: Arithmetic average and standard deviation of the thermal conductivity of the raw fibres, WFIB produced with 5 wt% pMDI and mats produced with 7 wt% Bico fibres for the different fibre types.

The fibre type 100_birch showed the highest thermal conductivity for raw fibres, boards and mats. The lowest thermal conductivity was found for the fibres 80SW_20HW for all three material types. These findings are attributable to the bulk density of the fibre types; a higher bulk density of the fibres (see 3.1) results in a higher thermal conductivity. In addition, the mats bonded with Bico fibres consistently had a thermal conductivity at least 0.001 W $(mK)^{-1}$ lower than their equivalent panels bonded with pMDI. The boards bonded with pMDI showed a similar proportional sequence as the mats bonded with Bico fibres (Figure 5). Other studies found no dependence of thermal conductivity on the binder type. The thermal conductivity for WFIB with a density of 200 kg m^{-3} made of softwood fibres in a dry process with 4 % pMDI as binder was determined to be 0.041 ± 0.001 W $(mK)^{-1}$ (Euring et al. 2015). It is confirmed that the thermal conductivity of fibreboards depends more on the board density than on the type of resin or on the fibre dimension (Kawasaki et al. 1998). The thermal conductivity of WFIB produced in a dry process with four different binders was comparable but no major differences were found (Lee et al. 2019). The study reported values around 0.035 W $(mK)^{-}$

[1] for boards with a density of 150 kg m^{-3} and reportedly 35 % pMDI, which is similar to the results of 100_spruce and 80SW_20HW bonded with pMDI in this study (Figure 5). WFIB made using a wet process from pure birch fibres exhibited thermal conductivities in the range of 0.040 – 0.043 W $(mK)^{-1}$ (Sable et al. 2015), which is slightly higher than the value of 0.039 W $(mK)^{-1}$ obtained for the birch fibre panels bonded with pMDI in this study. Thermal conductivity of loose-fill material from wood waste material amounted to 0.050 W $(mK)^{-1}$ (Cetiner and Shea 2018). The raw fibres in this study resulted in much lower results from 0.0354 W $(mK)^{-1}$ for 80SW_20HW to 0.0393 W $(mK)^{-1}$ for 100_birch. According to Domínguez-Muñoz et al., the key factor influencing thermal conductivity is density, once temperature and humidity content are fixed at reference conditions (Domínguez-Muñoz et al. 2010). This study confirms the great influence of the density because the lowest thermal conductivity was measured in the three material types of 80SW_20HW, which had the lowest bulk density of all five fibre types (chapter 3.1). The results indicate that the bulk density has a stronger influence on thermal conductivity than the wood species or the fibre length.

Assuming that the individual fibres of the different fibre types have approximately the same volume, the number of fibres in a given volume of the WFIB should be smaller for the birch fibres. Thus, the void volume between the fibres would be greater and the number of crossing points between the fibres at which heat transfer takes place would also be smaller for fibre type 100_birch. However, this assumption does not result in lower thermal conductivity for the WFIB made of pure birch fibres. This could be due to the thicker cell walls of the hardwood fibres, which lead to a higher heat transfer through these cell walls. Moreover, the lowest thermal conductivities were found between 30 and 60 kg m^{-3} (Domínguez-Muñoz et al. 2010), which explains why the thermal conductivities observed in this study are lower than those for WFIB, which have a higher raw density.

4.3.6 Fire retardancy

A statistical evaluation of the fire test results was not possible because the number of specimens was too small. Nevertheless, a comparison of the absolute values was made. The flammability increased with an increasing amount of hardwood fibres (Figure 6 and Figure 7). Still, none of the specimens met the requirements of DIN EN ISO

11925-2 (2010), because the flame did not go out within three seconds after the Bunsen burner was retracted. The addition of fire retardants might increase fire resistance, but a previous study reported that WFIB made of birch fibres did not meet the standard, regardless of whether flame retardants were added or not (Sable et al. 2015). In addition, recent studies found out that nano-wollastonite can act as a fire retardant in MDF panels but leads to an increased thermal conductivity which could be a problem in the application for WFIB (Esmailpour et al. 2021).

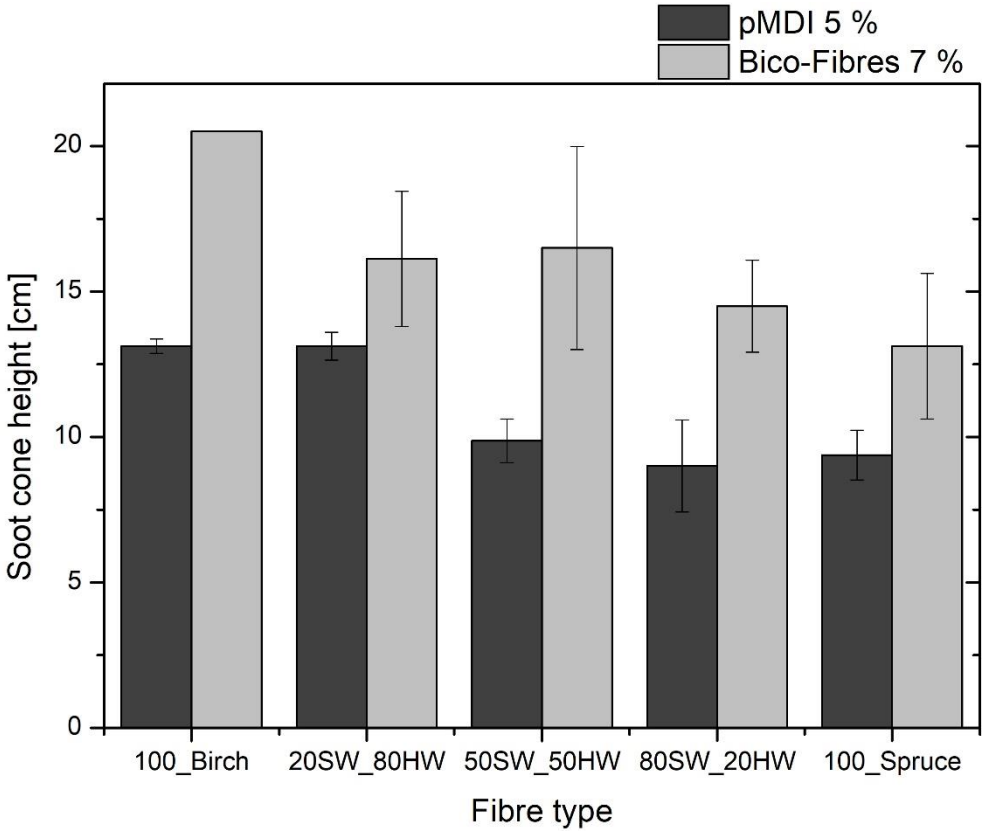

Figure 6: Arithmetic average and standard deviation of the soot cone height of WFIB from the different fibre types produced with 5 wt% pMDI and 7 wt% Bico fibres.

Figure 7: Fire performance according to EN ISO 11925-2 (2010) of WFIB made of 100_birch (left) and of 100_spruce (right) with 5 wt% pMDI.

4.4 Conclusions

This study showed that the production of WFIB from hardwood fibres and fibre blends of hardwood and softwood fibres with a density of 100 kg m^{-3} is possible in a dry process. As the mechanical strength properties decreased greatly and the thermal conductivity increased when only hardwood fibres are used, a blend is recommended in which at least 20 % softwood fibres are mixed with the hardwood fibres.

Moreover, further studies should investigate the bondability, i. e. the compatibility of different hardwood species with the adhesive in order to assess which hardwoods are suitable for WFIB production. In addition, different defibration conditions (especially different disc gaps) should be investigated.

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Conflicts of Interest

The authors declare no conflicts of interest.

5 Veröffentlichung 3: Examination of various hardwood and softwood fibres for the usage in wood fibre insulation boards (WFIB)

Titel: Examination of various hardwood and softwood fibres for the usage in wood fibre insulation boards (WFIB)

Autoren: Arne A. P. Imken, Lea Bächle, Sascha Brinker, Redelf Kraft, Burkhard Plinke, Jochen Aderhold, Carsten Mai

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L. Bächle	0	20	20	0	12
S. Brinker	20	0	5	0	7,5
R. Kraft	0	25	0	0	7,5
B. Plinke	0	0	25	0	7,5
J. Aderhold	0	25	0	0	7,5
C. Mai	30	0	20	80	23

ORIGINAL ARTICLE

Examination of various hardwood and softwood fibres for the usage in wood fibre insulation boards (WFIB)

Arne A. P. Imken[1], Lea Bächle[1], Sascha Brinker[1], Redelf Kraft[2], Burkhard Plinke[3], Jochen Aderhold[3], Carsten Mai[1]*

*corresponding author

Carsten Mai

carsten.mai@uni-goettingen.de

[1] Wood Biology and Wood Products, Faculty of Forestry and Forest Ecology, University of Goettingen, Buesgenweg 4, 37077 Goettingen, Germany

[2] Molecular Wood Biotechnology and Technical Mycology, Faculty of Forestry and Forest Ecology, University of Goettingen, Buesgenweg 2, 37077 Goettingen, Germany

[3] Technology for Wood and Natural Fibre-Based Materials, Fraunhofer Institute for Wood Research WKI, Bienroder Weg 54E, 38108 Braunschweig, Germany

Abstract

The wood-based panel industry in Europe will be forced to adapt its products to the wood market supply due to the rapid decline in softwood stands. Consequently, the wood fibre insulation board (WFIB) industry, which usually processes softwood fibres, has to adapt their raw material to the use of hardwood fibres. The objective of this study was to investigate the mechanical, physical and chemical properties of WFIB made from fibres of different hardwood and softwood species produced in a refiner by thermo-mechanical pulping (TMP). WFIBs with a raw density of 100 kg m^{-3} for rigid boards and 50 kg m^{-3} for flexible mats were produced in a dry process with hot-steam (rigid boards) and hot-air (flexible mats). The rigid boards were bonded by polymeric diphenylmethane diisocyanate (pMDI, 5 wt% related to the weight of the dry fibre material) and the flexible mats were bonded with 7 wt% bi-component (Bico) fibres. The results show that hardwood fibres can be used to produce WFIB for both rigid boards and flexible mats. The fibre structure and porosity of the WFIBs were also investigated using computed tomography on smaller samples. No correlation was found between porosity and bulk density of the fibres, nor between porosity and thermal conductivity nor between porosity and mechanical properties. The physico-mechanical properties, thermal conductivity and flammability differ between the different wood species. Overall, of the WFIBs made from hardwood fibres, those made from beech fibres showed the best properties. They are comparable to those made from softwood fibres.

Keywords

Wood fibre insulation board (WFIB), hardwood fibres, physico-mechanical properties, computer tomography, thermal conductivity

5.1 Introduction

Climate change is an important issue nowadays. To combat the climate change, the Paris Agreement was adopted by 196 countries in 2015. The goal of the Paris Agreement is to limit global warming to well below 2°, preferably to 1.5° C, compared to pre-industrial levels. To achieve this goal greenhouse gas emissions need to be reduced intensely (United Nations 2015).

One factor to reduce greenhouse gas emissions is to reduce energy consumption accounted to buildings, especially for space heating. Against this background, insulation materials play a major role. Currently, mineral wool or expanded polystyrene (EPS) are the predominant insulation materials for buildings but they are based on fossil resources. Burning and chemical transformation of fossil resources such as natural gas, mineral oil and coal significantly contribute to global warming due to CO_2 emissions. Plants used for renewable insulation materials such as wood fibre insulation boards (WFIB) even sequester atmospheric carbon dioxide through photosynthesis. If this sequestered carbon dioxide is greater than the embodied carbon dioxide for their manufacture, this can result in a “negative” carbon footprint (Lawrence et al. 2013). Moreover, WFIBs are diffusion-open and can absorb and desorb water, which is another functional advantage over mineral wool or EPS. Due to these ecological advantages, the market for renewable insulation materials is growing continuously (Windirsch 2021).

Forest restructuring in many European countries is an important challenge for the producers of WFIB, as for the entire wood industry. Non-natural spruce monocultures are to be reconstructed to more stable and resilient mixed stands (Klimo et al. 2000). WFIB are usually made from softwood fibres obtained by a thermo-mechanical pulping (TMP) process. In this process, wood chips are treated with saturated steam under high pressure and afterwards defibrillated in a refiner (Stokke et al. 2014). Insulating panels are manufactured using either a dry or a wet process. The dry process is used more frequently nowadays because less water and energy is needed (Lempfer 2004). In the dry process, pulping is immediately followed by drying and gluing. Generally, polymeric methylene-diphenyl-isocyanate (pMDI) serves as the binder for rigid insulation boards (Vangronsveld et al. 2010).

Softwoods and hardwoods differ immensely regarding chemical composition and cell types. The cellulose content of hardwoods ranges from 40 to 50 wt% and the lignin content comprises between 20 and 25 wt%, while the hemicelluloses content varies from 15 to 30 wt%. Softwoods contain the same amount of cellulose but 5 – 8 wt% more lignin and accordingly less hemicelluloses. Additionally, there can be 1 – 10 % extractives in hardwoods as well as in softwoods (Sjöström and Alén 1999). Wood extractives may influence wood bonding (Roffael 2016). The composition of the extractive is not only different between sapwood and heartwood, but also may even differ in

one species from that of another group that may belong to the same genus (Hillis 1971). The aim of this study was to investigate the mechanical properties and thermal conductivity of insulation boards from eight different hardwood and softwood fibres and to determine if they are suitable for the production of wood fibre insulation boards.

5.2 Material and Methods

5.2.1 Production of wood fibres

All fibres were produced at the Fraunhofer Institute for Wood Research - Wilhelm-Klauditz-Institute (WKI) in Braunschweig, Germany. Respective logs (purchased from Lower Saxony State Forests) were debarked with a peeling knife (Wilh. Schmitt & Comp. GmbH & Co. KG, Remscheid, Germany) and split by hand before being chopped to wood chips in a chipper (120X400H2WT, Klöckner KG, Hirtscheid, Germany).

To produce fibres, the wood chips were defibrated by a pilot plant refiner (Andritz AG, Wien, Austria). The defibration conditions used for refining can be found in Table 1. The different disc gaps for softwoods and hardwoods were chosen based on preliminary tests.

A total of eight types of fibres were examined. These were made from Norway spruce (*Picea abies* (L.) H. Karst.), European larch (*Larix decidua* Mill.), Scots pine (*Pinus silvestris* L.), European beech (*Fagus sylvatica* L.), silver birch (*Betula pendula* Roth), common oak (*Quercus robur* L.), small leaved lime (*Tilia cordata* Mill.) and European black alder (*Alnus glutinosa* (L.) Gaertn).

Table 1: Defibration conditions in the refiner.

Type of fibres	WFIB fibres
Rotation [rpm]	3000
Pressure [Pa]	550,000
Temperature [°C]	155
Retention time [min]	5
Disc gap [mm]	0.4 (Softwood) 0.6 (Hardwood)
Fibre moisture content [%]	15 - 20

5.2.2 Production of wood fibre insulation boards (WFIB)

The boards were produced in a dry process. Two types of binders - low temperature curing polymeric methylene diphenyl diisocyanate (pMDI) resin (I-Bond WFI 4370, Huntsman, Everberg, Belgium) and bicomponent fibres (Bico-Fibres) (Grilon EP855 (KA115) à 3,3 DTEX / 3mm, EMS-CHEMIE, Domat/Ems, Switzerland) - were used to produce either rigid boards or flexible mats. The adhesive amounts used were 5 wt% pMDI and 7 wt% bicomponent (Bico) fibres related to the dry mass of the fibres. The mixture of fibres and adhesives were spread into a frame and compacted with a hydraulic pre-press. A hot-steam/hot-air aggregate (self-build (Euring et al. 2015)) was used to cure pMDI or melt the Bico-Fibres. The rigid boards (pMDI) were hardened by injecting 120 s of hot-steam, while the flexible mats were made using 120 s of hot air to melt the Bico-Fibres. The manufactured boards and mats had dimensions of 650 mm × 650 mm × 40 mm and a target raw density of 100 kg m^{-3} for rigid boards and 50 kg m^3 for flexible mats. The boards of each fibre type and type of binder were produced in three replicates.

5.2.3 Physico-mechanical properties of fibres and WFIB

Bulk density (n = 1 per fibre type) of the fibre material was determined according to the standard EN ISO 17828 (2016). Before testing the physico-mechanical properties of

the boards, these were cut into specimens of a size according to the following standards and these were conditioned at 65 % RH and 20 °C. Compression strength (5 specimens per board, n = 15) was determined according to EN 826 (2013), internal bond strength (5 specimens per board, n = 15) according to EN 1607 (2013), water absorption (4 specimens per board, n = 12) according to EN 1609 (2013), thermal conductivity (n = 1 for boards and mats) according to EN 12667 (2001) and flaming behaviour (2 specimens per board, n = 6) according to EN ISO 11925-2 (2010).

5.2.4 Computed tomography (CT) data acquisition and analysis

One specimen (approx. 50 mm x 50 mm x board thickness) of each wood species and binder type was cut from the boards and scanned using the CT device (Type CT Duo Alpha, Manufacturer ProCon X-Ray, Sarstedt, Germany) at Fraunhofer WKI, Braunschweig. The specimens were placed on a rotating scan table and fixed with an adhesive tape as shown in Figure 1.

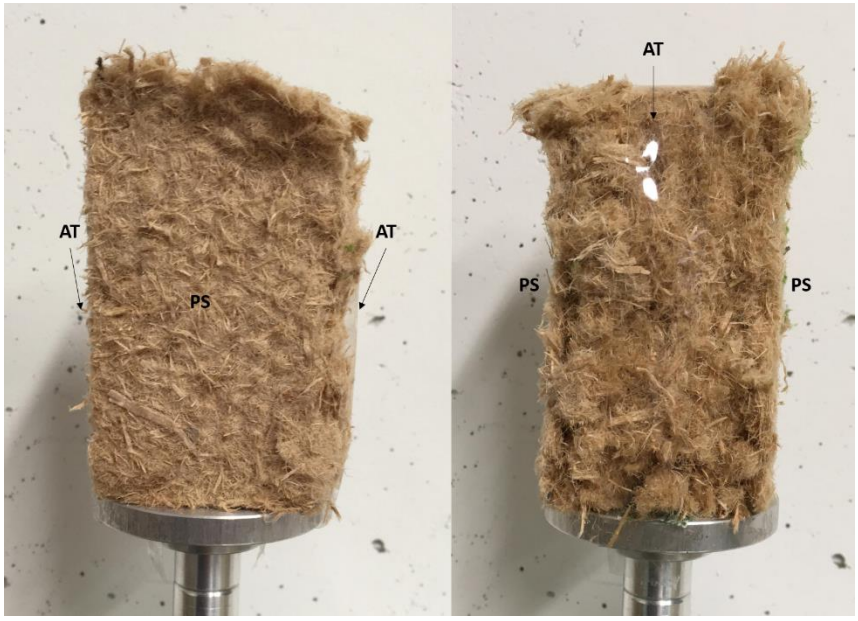

Figure 1: Sample preparation and placement on the rotation table for CT-data acquisition; PS= pressing surface, AT= adhesive tape for fixation.

The scans were performed either as axial or as helix scans at two different X-ray energy levels (tube parameters set to a voltage of 125 kV, current of 120 µA or 70 kV and

300 µA, respectively). The resulting spatial resolution was approx. 38 µm / voxel edge. Raw projection data were reconstructed using the Software Xray Office (Fraunhofer, EZRT, Fürth, Germany), then imported into VG Studio Max (Volume Graphics, Heidelberg, Germany) for a first visual data screening, exported again as a DICOM formatted image series. Image processing and analysis was conducted using Avizo® 2021.2 (FEI, Thermo Fisher Scientific, Hillsboro, Oregon, USA).

The sample subvolumes were extracted as shown in Figure 2 and aimed for an examination dimension of 38 mm (1000 voxels) x 38 mm (1000 voxels) x board thickness. However, these dimensions had to be adjusted for several samples to exclude structural defects or deformations. The board thickness was defined between the pressing surfaces, though excluding border regions with pressing patterns or fringy edges.

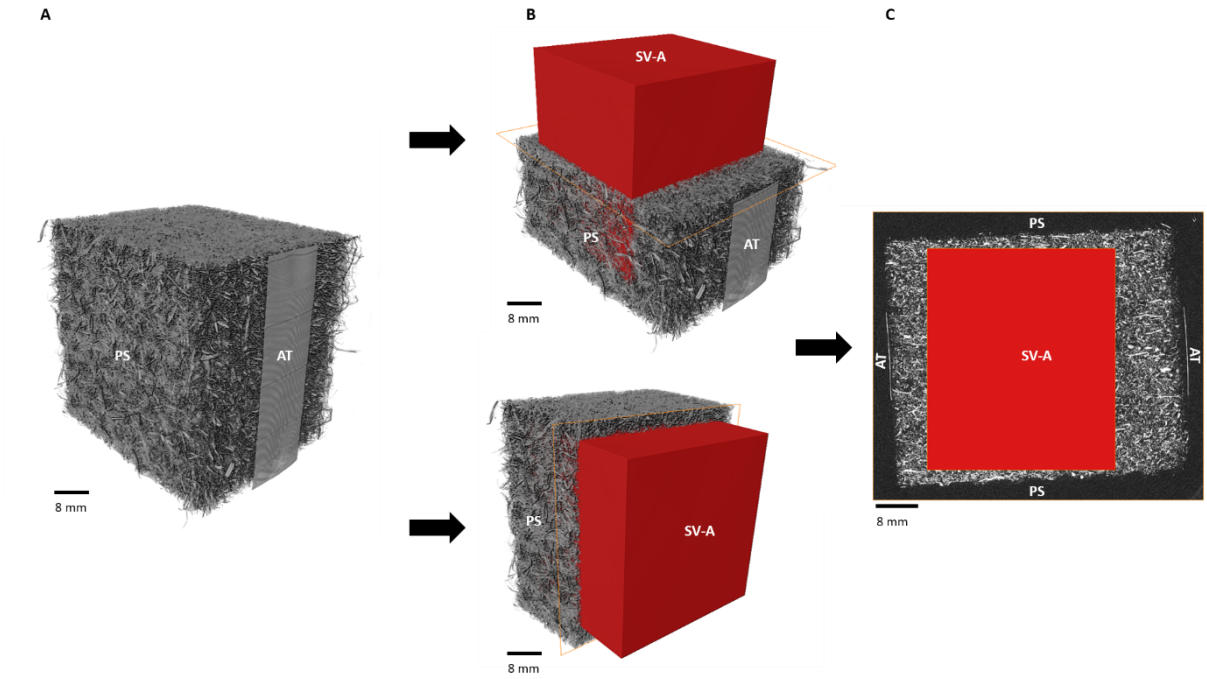

Figure 2: Visualisation of spruce pMDI 5% boards; A: Reconstructed CT-data with spatial markers; B: Exemplary definition of subvolumes within the 3D-dataset; C: Exemplary 2D visualisation of the definition of sample subvolumes; PS= pressing surface, AT= adhesive tape for fixation, SV-A (red)= subvolume for analysis.

The extracted sample subvolumes were processed using the Median filter in order to achieve a smoothening effect and reduce background noise. Median filtering was conducted via 2D-slice-by-slice processing using the pressing surface orientation as base

of the calculations. The segmentation of the filtered data was carried out with Avizo's AutoThresholding algorithm using the factorization method based on the Otsu criterion (Otsu 1979). The resulting binary images contained labelled voxels representing wood fibre material and unlabelled void voxels, determined based on the respected grey value (GV) properties (Figure 3).

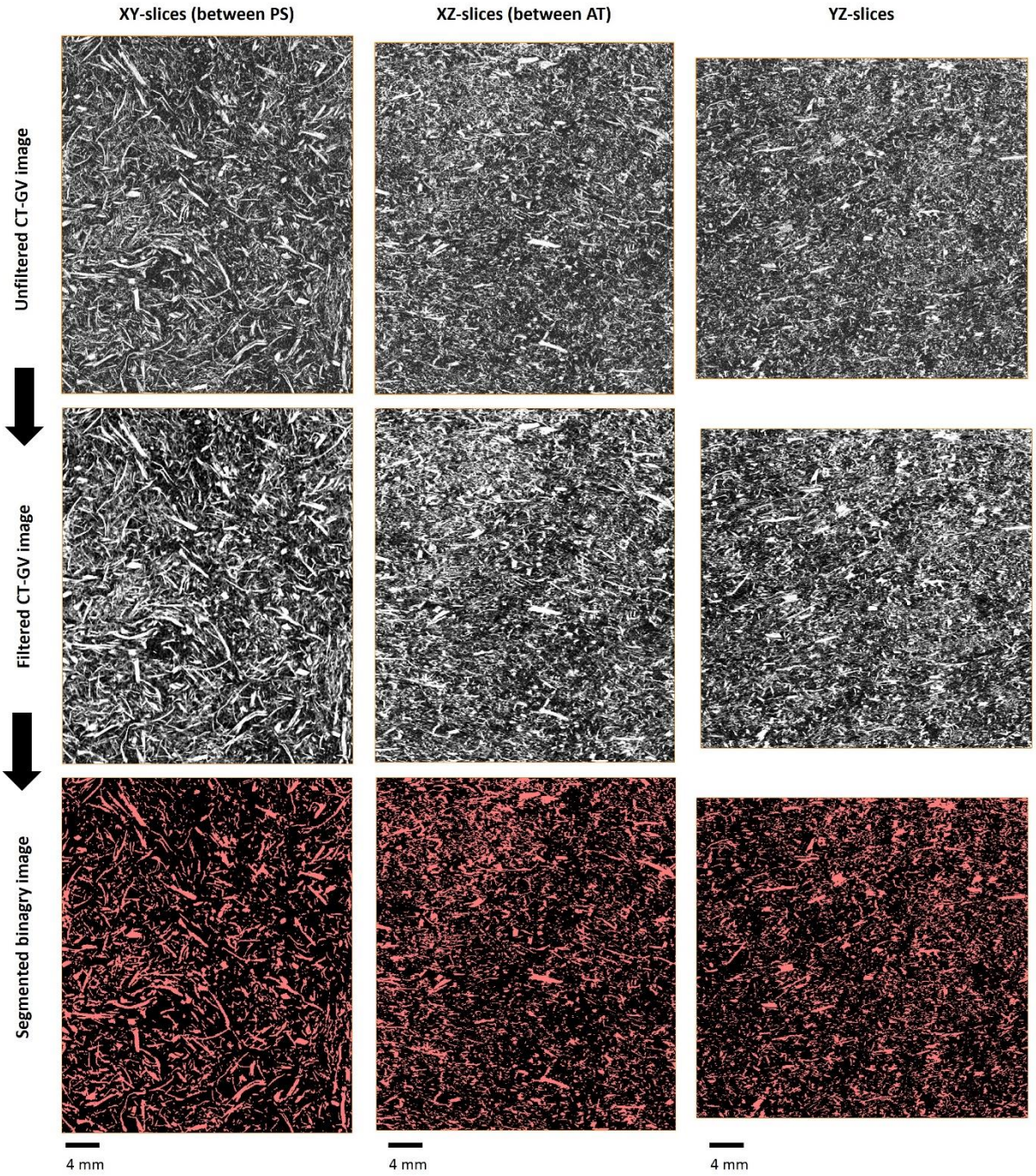

Figure 3: Exemplary visualisation of segmentation process for spruce pMDI 5% boards; PS= pressing surface, AT= adhesive.

Quantitative analysis of the binary images aimed to determine the porosity of the WFIBs. The porosity (Φ) was defined as the fractional void volume of the fibre board. A pixel count for the segmented wood fibre material and unlabelled void was performed on a 2D-slice-by-slice base. This was performed through the cross-section of the WFIB, from one pressing surface to the other. According to Equation 1 the porosity of each slice was calculated as the percentage ratio of all pixels (∑pixall) of the considered slice (void and wood fibres) to the pixels of the void (∑pixv).

An analysis of the GV distribution was performed to examine the variation of spatial orientation within the sample subvolumes. Therefore, the GV Intensity Integral (Aviso tool) was calculated on a 2D-slice-by-slice base for each dimension (XY-slices, ZY-slices, ZX-slices). The resulting values represent the sum of GVs for each slice image and offer a GV profile throughout each dimension of the sample subvolume. As CT-data provides no density calibration for GV, the median of the summed-up GVs of all slices per dimension was used to standardize the GVs. The resulting graphs show the variation of the GVs of each slice percentile to the median GV of all slices of the respective dimension, which is defined as 100 %. As the number of slices per dimension varied depending on the board thickness and sample integrity, the middle slice of the examined dimension was set as neutral point (slice number 0).

5.2.5 Statistical analysis

The obtained data were statistically analysed using Excel 2016 (Microsoft, Redmond, WA, USA). The Kolmogorov-Smirnov-Test was used to determine if the data showed normal distribution. The Levene-test was used to determine if the data showed variance homogeneity. A two-sample unequal variance (heteroscedastic) t-test with Holm-Bonferroni method was used to determine if there were significant differences between the different fibre type variants. These determinations could only be done with an appropriate number of test specimens; these were only available for testing the compression strength, the internal bond strength, the water absorption and the data from the computer tomography.

5.3 Results and discussion

5.3.1 Physico-mechanical properties of fibres and WFIB

The influence of different refiner disc gaps on the fibre material was tested in preliminary trials. Even with a larger disc gap, the median geodesic length was still smaller for the hardwoods than for the softwoods. To achieve a similar mean geodesic length in this study, a larger disc gap was adopted for the hardwoods (0.6 mm) than for the softwoods (0.4 mm).

The bulk densities of the five hardwood fibre materials were all higher than those of the three softwoods. The highest bulk densities were determined for oak (29.9 kg m^{-3}) and beech (29.2 kg m^{-3}). The other three hardwood fibres exhibited lower bulk densities, but they were still higher than those of the softwoods. Larch fibres showed the lowest value (18.1 kg m^{-3}) (Figure 4). This can be due to the higher proportion of small particles in the hardwood fibres, which fill the voids between longer fibers (Suchsland and Woodson 1991, Imken et al. 2021a). The bulk density of the fibres has a major influence on the strength properties of WFIB, which generally increase with decreasing bulk density of the fibres, especially if the degree of compaction of the board is low (Suchsland and Woodson 1991).

The highest compression strength values of the eight different fibre types bonded with 5 wt% pMDI (Figure 5) were determined for spruce (34.3 kPa), lime (33.2 kPa) and beech (32.1 kPa), followed by pine (28.0 kPa) and alder (27.5 kPa). The results were significantly lower for oak (21.5 kPa), birch (21.1 kPa) and larch (20.7 kPa). The highest compression strength for fibre types bonded with 7 wt% Bico-Fibres was determined for alder (2.9 kPa) and lowest for birch (2.2 kPa). The five hardwood species and the three softwood species showed very different values among themselves. Due to this strong variation, no general differences between hardwoods and softwoods could be determined. While boards from larch and oak only showed low strength among the pMDI-bonded boards, birch boards showed the second lowest value among pMDI-bonded boards and the lowest value among the mats bonded by Bico-Fibres (Figure 5). This is in agreement with the study of Imken et al. (2021b), which also reported low compression strength for birch WFIB. This finding was attributed to the higher bulk density of the birch fibres compared to the other fibres tested. However, this assumption can be refuted by this study, as WFIB made of beech fibres showed very high compression strength, even though beech fibres had the second highest bulk density.

In contrast to this study, Eichhorn (2017) found no significant differences between WFIB from beech and oak. The compression strength of rigid WFIB made of beech and oak with a density of 100 kg m^{-3} was 26.3 kPa, which is exactly in the middle of the value for boards made of beech and oak in this study. The same study showed the large impact of the board density. Boards produced from beech fibres with a density of 115 kg m^{-3} showed a compression strength of 37.3 kPa (Eichhorn 2017). According to a manufacturer, rigid boards of 110 kg m^{-3} density made of spruce and fir fibres from industrial production show a significantly higher compression strength of 50 kPa (GU-TEX 2020) than reported here. This can be due to better conditions in an industrial production.

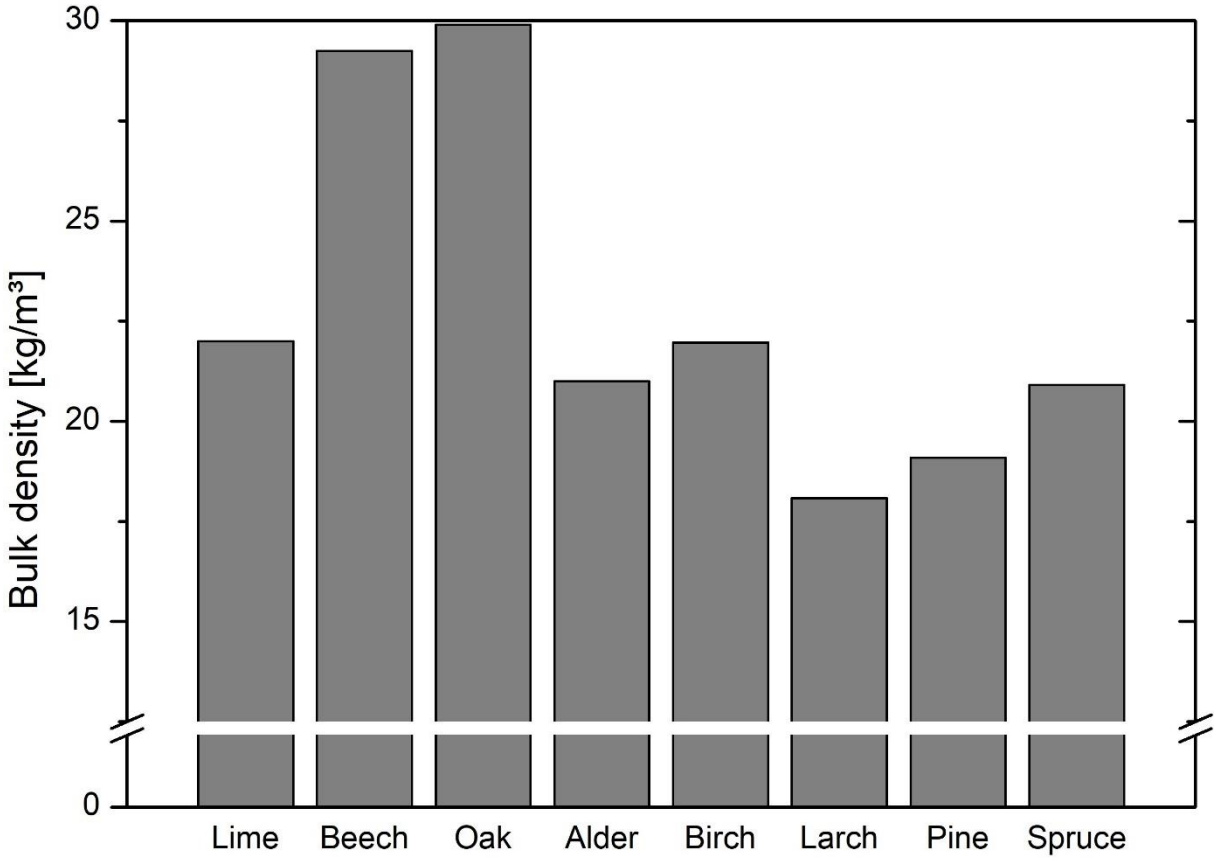

Figure 4: Bulk density of the eight fibre types produced in a refiner with a disc gap of 0.4 mm (softwood) and 0.6 mm (hardwood).

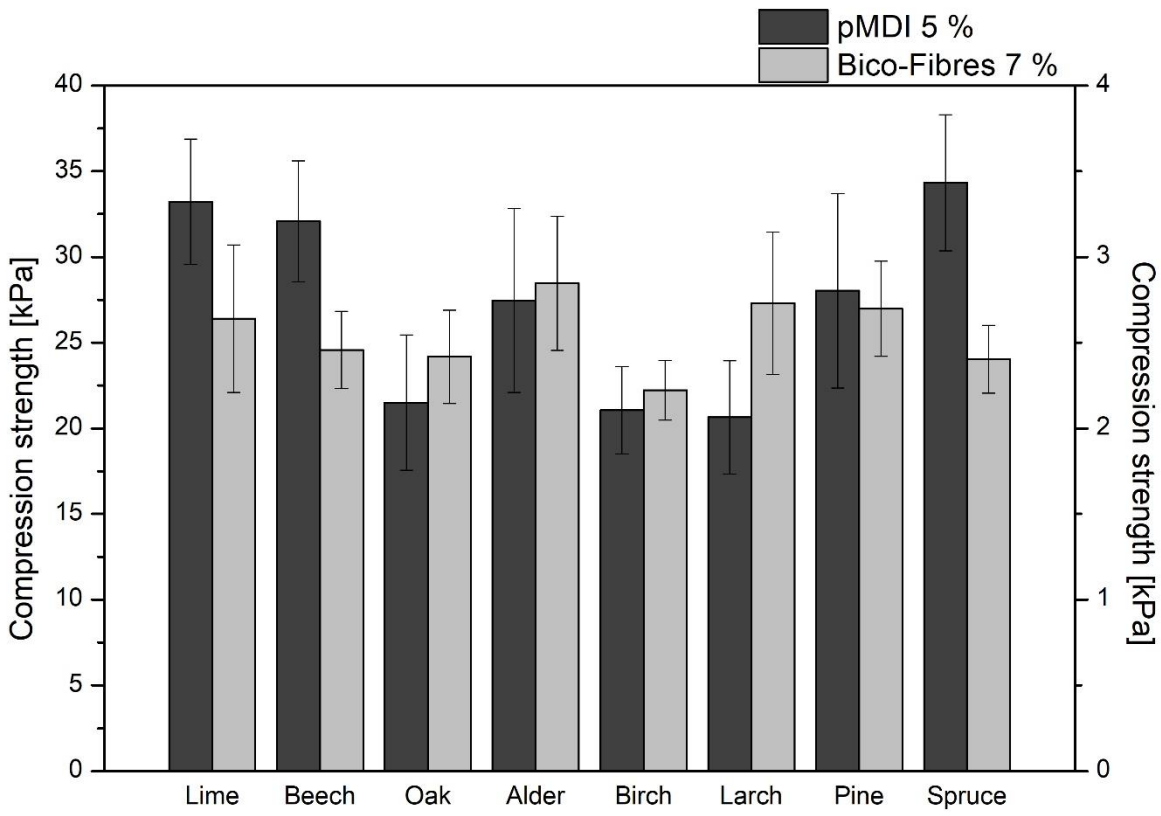

Figure 5: Arithmetic mean and standard deviation (n=15) of the compression strength of WFIB from the different fibre types produced with 5 wt% pMDI and 7 wt% Bico-fibres. The scale on the left side relates to the pMDI bonded rigid boards, the scale on the right side relates to the flexible boards bonded with Bico-fibres.

Regarding internal bond strength, the highest value for the rigid boards was 9.6 kPa for beech and the lowest value was 1.4 kPa for larch (Figure 6). The internal bond strength was not examined for the flexible mats because this property is not of interest for these products, which are mainly used indoors for between-rafter insulation.

In a previous study, the internal bond strength for rigid boards with a density of 100 kg m^{-3} made of beech fibres was 3.7 kPa, for those made of spruce fibres it was 10.5 kPa and 5.5 kPa for boards made of oak fibres (Eichhorn 2017). While the value for beech boards is only one-third of that reported in this study, the value for spruce boards is one and a half times as high and that for oak is almost the same in both studies. The reason for the different results may be attributed to differences in the process conditions, particularly the disc gap, for fibre production, which influences the length and geometry of the fibres (Imken et al. 2021a).

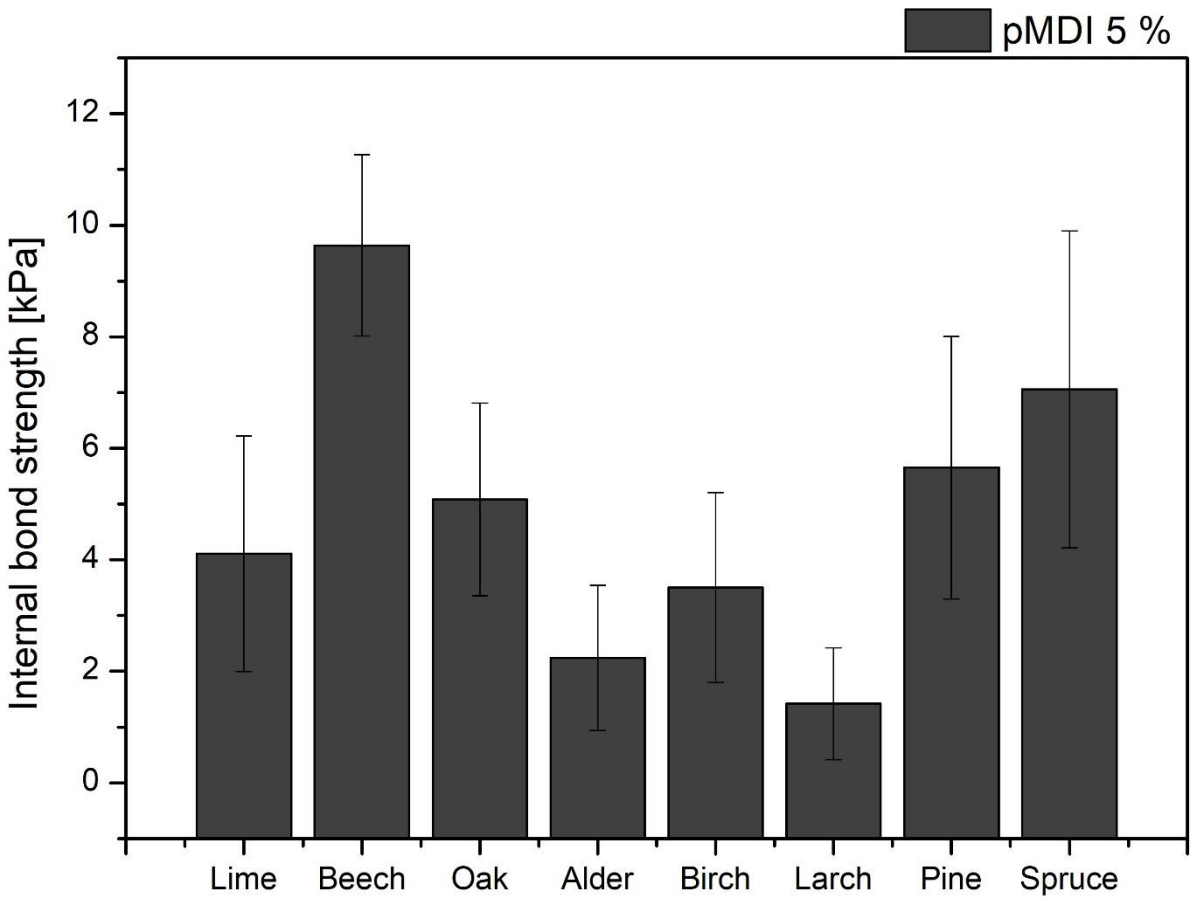

Figure 6: Arithmetic mean and standard deviation (n=15) of the internal bond strength of WFIB from the different fibre types produced with 5 wt% pMDI.

The defibration conditions from Table 1 are based on findings from a previous study (Imken et al. 2021a), while Eichhorn (2017) did not indicate it. A previous study using a disc gap of 0.6 mm revealed internal bond strengths of 1.1 kPa for birch and 6.0 kPa for spruce (Imken et al. 2021b). Both values are slightly lower but comparable to those in this study. According to a manufacturer, rigid boards from industrial production show an internal bond strength of 5.0 kPa (GUTEX 2020). Of the eight different fibre types in this study, the boards of beech, spruce, pine and oak show higher values than the industrial boards, while those of lime, birch, alder and larch show lower values.

The water absorption of the rigid boards after 24 h differs between 0.7 kg m^{-2} (larch) and 16.2 kg m^{-2} for alder (Figure 7). As with the internal bond strength, only the rigid boards were tested, because the flexible mats are mainly used for between-rafter insulation, where there is hardly any capillary water absorption. In contrast to other stud-

ies that found significantly higher water absorption - in addition to higher strength properties - for comparable hardwood boards (Zabihzadeh 2010, Imken et al. 2021b, Eichhorn 2017), this study revealed significant differences both among the five hardwood species and among the softwood fibres. Due to this strong variation, no general differences between hardwoods and softwoods could be determined. On the one hand, the three significantly lowest values are given for the boards made of the softwoods larch and spruce and the hardwood beech. On the other hand, pine boards showed the second highest value (7.4 kg m^{-2}) (Figure 7). Other studies reported similar water absorption for spruce boards (Eichhorn 2017) and for birch boards (Imken et al. 2021b) as in this study.

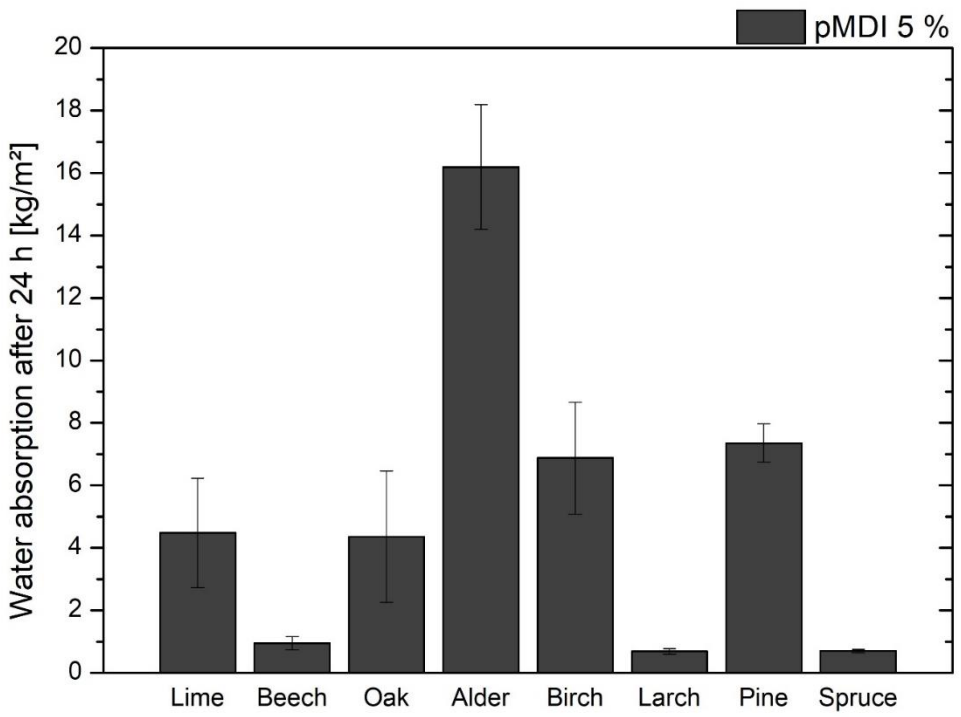

Figure 7: Arithmetic mean and standard deviation (n=12) of the water absorption after 24 h of WFIB from the different fibre types produced with 5 wt% pMDI.

5.3.2 Thermal conductivity

The highest thermal conductivity value for the rigid boards (0.037 W $(mK)^{-1}$) and the flexible mats (0.040 W $(mK)^{-1}$) was obtained for those of oak, followed by those of larch (Figure 8). The lowest value was determined for spruce both for the rigid boards (0.030 W $(mK)^{-1}$) and the flexible mats (0.034 W $(mK)^{-1}$) followed by beech and birch.

In contrast to the results of Imken et al. (2021b)), no correlation with bulk density of the fibres (Figure 4) is discernible. Previous studies reported a decreasing thermal conductivity of insulation boards with decreasing density (Kawasaki et al. 1998, Sonderegger and Niemz 2009). However, in this study the thermal conductivity of the flexible mats was at least 0.001 W $(mK)^{-1}$ higher than that of the respective rigid boards, although their raw density was only half as high as that of the rigid boards. This can be explained by the effect of long-wave radiant exchange inside the pores, which particularly occurs at very low densities between 30 – 60 kg m^{-3} (Domínguez-Muñoz et al. 2010), the range in which the flexible mats are located with a targeted raw density of 50 kg m^{-3}. Another study reported thermal conductivities in the range of 0.040-0.043 W $(mK)^{-1}$ for WFIB with raw densities of 102-120 kg m^{-3} made solely from birch fibres using a wet process (Sable et al. 2015). These values are much higher than those in this study for rigid boards made of birch fibres of 0.032 W $(mK)^{-1}$. According to a manufacturer, industrially produced rigid boards with a raw density of 110 kg m^{-3} made of spruce and fir fibres have a thermal conductivity of 0.038 W $(mK)^{-1}$ (GUTEX 2020); this is higher than the values in this study for rigid boards made of spruce fibres, which showed a thermal conductivity of 0.030 W $(mK)^{-1}$. The lower values of this study can be attributed to the lower raw density compared to the previous study and the industrial boards.

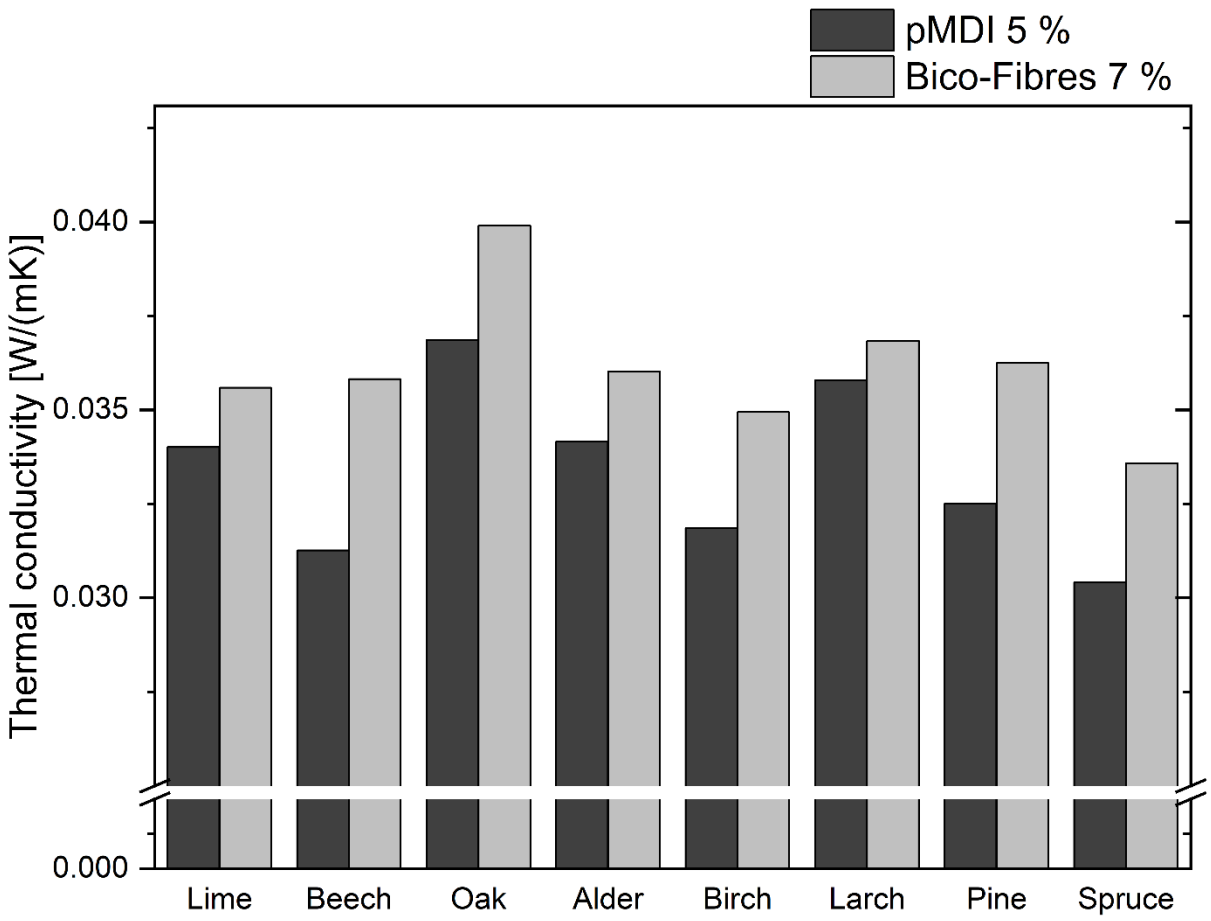

Figure 8: Thermal conductivity of the WFIB from the different fibre types produced with 5 wt% pMDI and 7 wt% Bico fibres.

5.3.3 Flammability

The flammability of the WFIB was determined on the basis of the soot cone height (Figure 9). All flexible mats reached the maximum of 20 cm soot cone height; there were no differences between the eight fibre types used. The soot cone height of the rigid boards ranged from 9.3 cm (larch) to 12.1 cm (birch). In contrast to previous study, which reported lower flammability of softwood boards (Zabihzadeh 2010, Imken et al. 2021b, Eichhorn 2017), this study revealed differences both among the five hardwood species and among the softwood fibres. Due to this strong variation, no general differences between hardwoods and softwoods could be found. Still, none of the specimens met the requirements of DIN EN ISO 11925-2 (2010). The addition of fire retardants might reduce flammability, but a previous study found that WFIB made of birch

fibres did not meet the standard, regardless of whether flame retardants were added or not (Sable et al. 2015).

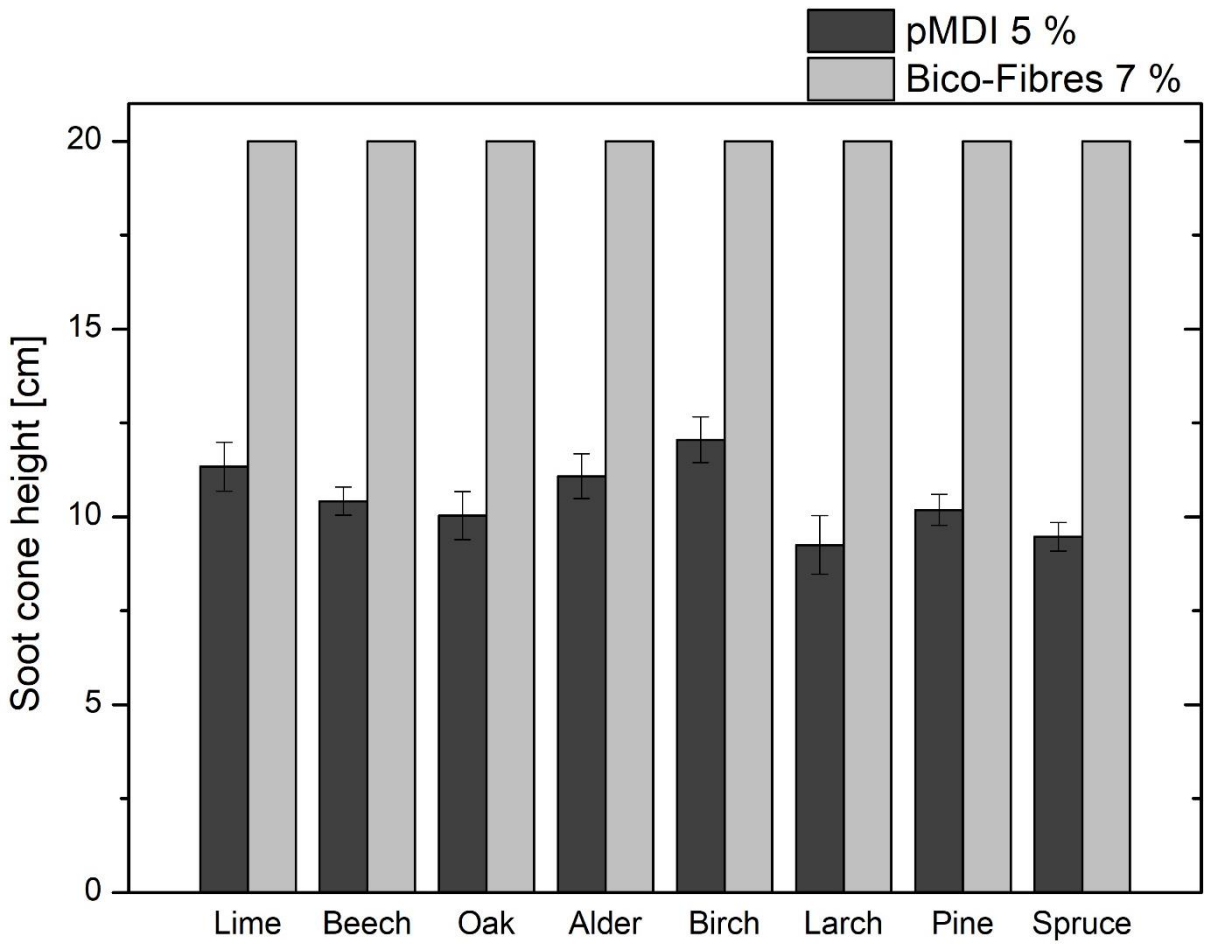

Figure 9: Arithmetic mean and standard deviation (n=6) of the soot cone height of WFIB from the different fibre types produced with 5 wt% pMDI and 7 wt% Bico-Fibres.

5.3.4 Porosity and computer tomographic analysis

The mean porosity values over all wood species varied from 71% (spruce) to 91 % (oak) for pMDI-bonded WFIBs and from 90 % (alder) to 96 % (beech) for Bico-Fibre-bonded WFIBs (Figure 10). Porosity values above 90 % appeared relatively high. A previous study presented porosity values between 46 % and 54 %, though for fibre boards with a density of 332 – 338 kg m^{-3} (Segovia et al. 2020). In relation to these findings, the values determined seem plausible. Moreover, that fact that the pMDI-bonded WFIBs with a target density of 100 kg m^{-3} for each wood species showed lower porosity than the Bico-Fibre-bonded WFIBs with a target density of 50 kg m^{-3} is also in

line with the expectations. Visual assessment of the segmented sample subvolumes also revealed that the fibre structure presented can account for the structural integrity of the WFIBs despite higher porosity values than expected and contributes to the reliability of the results. Exemplary visualisation of spruce and beech WFIBs with both binders are presented in Figure 11. The CT examination method used, with a resolution of 38 µm / voxel edge, allowed for a continuous and conclusive examination of the entire WFIB cross-section, rather than only examining small portions of specific regions in the board centre or at the board edges. However, based on experience with wood particle-based materials (Plinke et al. 2018), this resolution does not allow to identify individual fibres, but fibre bundles and pores are clearly visible. Nevertheless, as individual fibres and small particles (≤ 38 µm) could not be detected, the porosity might be overestimated. The proposed bias affected all examination subjects equally and allows the results to be related to each other and to porosity data acquired at similar resolution to be considered reliable. However, as dust particles smaller than 500 µm are more common in hardwood fibres (Imken et al. 2021a), the underestimation of porosity might have had a stronger effect on hardwood specimens than on softwood specimens. While the data indicate a tendency of lower porosity of softwood WFIBs bonded with pMDI compared to hardwood boards produced with the same binder, this pattern did not occur with WFIBs produced with Bico-Fibres. The statistical analysis showed significant differences between all tested collectives. However, reason for this might be the high number of values per collective, as the 2D-slice-by-slice calculation generated a porosity profile with over 1000 porosity values per sample subvolume. It is known that the statistical testing methods used show a higher tendency to alpha error with a sample size of this extent (Dormann 2013). Additionally, all porosity data values for each collective were acquired from one sample subvolume.

Overall, the expected correlations of porosity and bulk density of the initial fibres, as well as porosity and mechanical properties could not be confirmed. Kain et al. demonstrated a positive correlation between bulk density of the fibres and porosity (Kain et al. 2020), which could not be confirmed with the results presented in this study; only the results of the rigid oak boards indicate such a correlation (Figure 10). In contrast to a study by Segovia et al., a correlation between porosity and thermal conductivity could not be found either (Segovia et al. 2020).

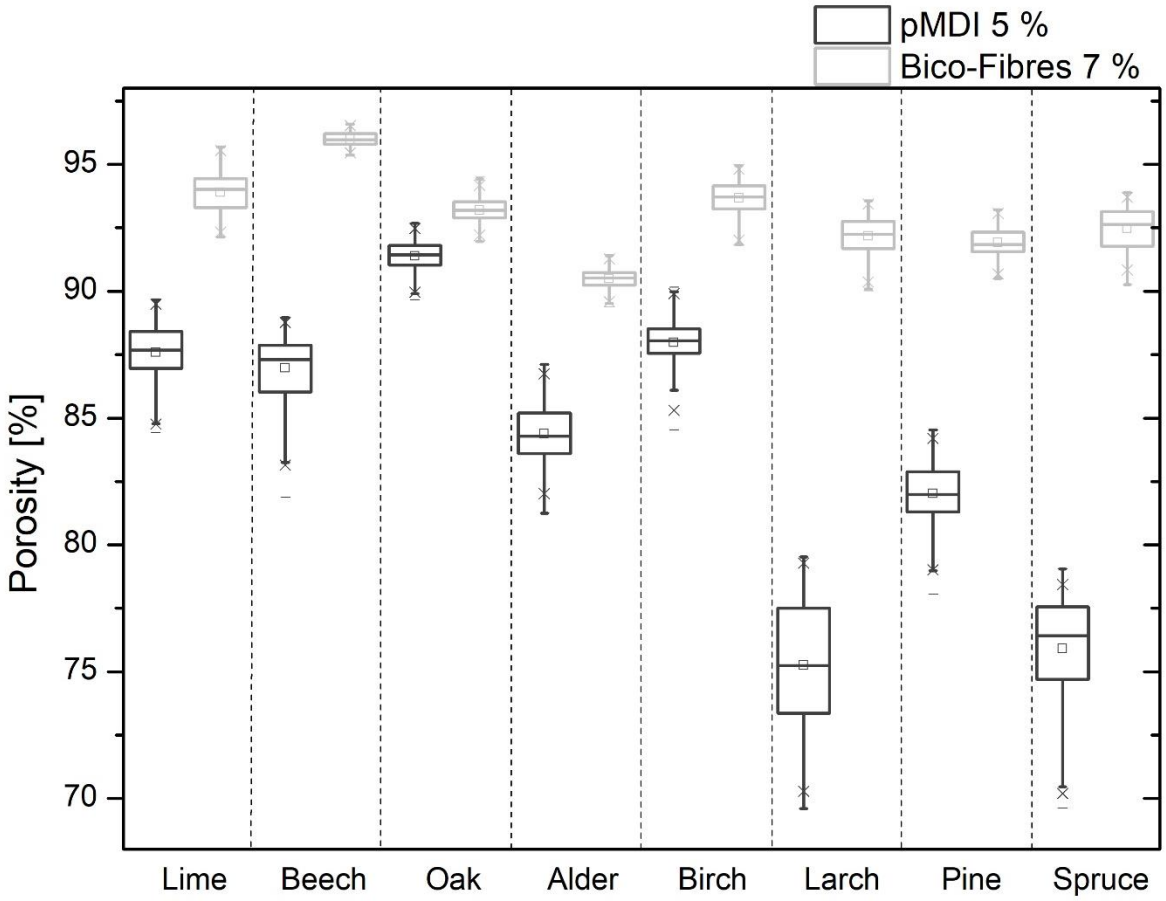

Figure 10: Porosity of WFIB from the different fibre types produced with 5 wt% pMDI and 7 wt% Bico-Fibres; data sets contain 2D-slice-by-slice porosity values of one scan/ sample sub-volume.

The fact that no correlation could be found between bulk density of the fibres and porosity might be related to the masking of small particles due to the CT resolution settings and to the small sample subvolumes (approx. 40 x 40 x 40 mm³) available for the CT measurements. For a conclusive statement on the correlation of CT data and thermal conductivity, further investigations are necessary regarding spatial orientation and fibre tensor.

As the CT data covered the entire cross-section of the WIFBs it was possible to investigate the GV profile using Intensity Integral calculation. Figure 12 shows exemplary GV profiles for spruce and beech WIFBs throughout all dimensions. Normalisation to the median GV was used, as CT data do not provide calibration for GVs. Generally, WFIBs show a homogeneous raw density profile due to their manufacturing method by

means of steam injection (Boehme 1992); the U-shaped density profile, which is common for many wood-based panels, therefore does not occur. The observed variations of ± 15 % of the median GV throughout the sample subvolumes and the absence of U-shaped graph progression are in line with studies that show a homogeneous raw density profile and suggest that typical WIFB characteristics were met overall, despite the fact, that the WIFBs were produced on a pilot-plant scale.

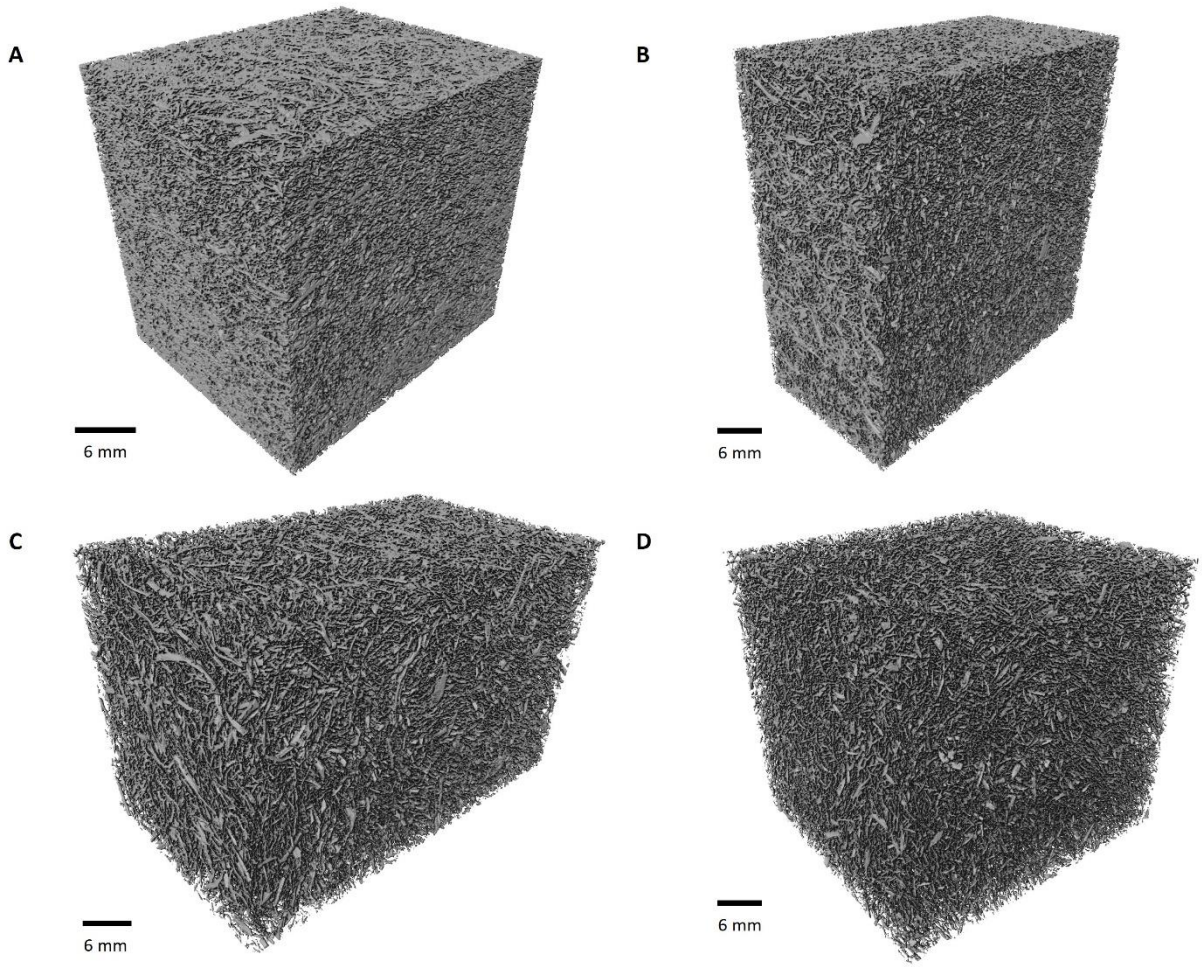

Figure 11: Exemplary visualisation of structural integrity of segmented sample subvolumes. A: Spruce WIBF produced with 5 wt% pMDI; B: Beech WIBF produced with 5 wt% pMDI; C: Spruce WIBF produced with 7 wt% Bico-Fibres; D: Beech WIBF produced with 7 wt% Bico-Fibres.

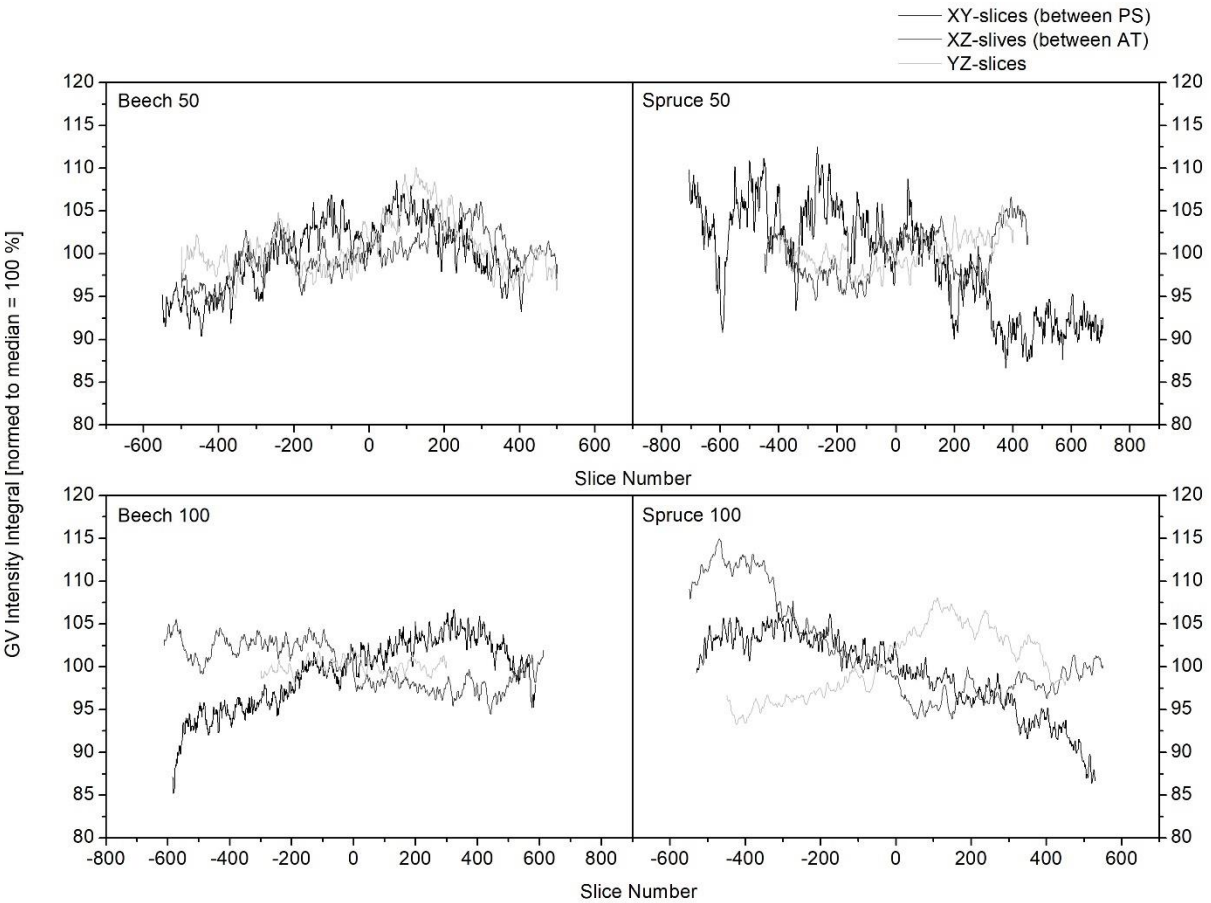

Figure 12: Exemplary grey value (GV) profiles for spruce and beech WIFBs throughout all dimensions calculated as Intensity Integral standardized to the median GV of the respected dimension; PS= pressing surface, AT= adhesive tape for fixation.

Nevertheless, some sample subvolumes showed tendencies of a gradient for the GV profile between the pressing surfaces, as can be seen in rigid boards of beech and spruce (Figure 12). One possible reason for these findings can be attributed to the discontinuous pilot-plant pressing unit. This production approach might have allowed small particles to ripple through the fibre fleece during manual dispersion of the fibre material. Thus, the impact of the pilot-plant pressing and production techniques may have influenced the WIFB properties to an unidentified extent. Therefore, follow-up studies should be conducted with WIFB specimens produced on an industrial scale.

5.4 Conclusions

This study shows that it is possible to produce rigid boards with a density of 100 kg m^3 and flexible mats with a density of 50 kg m^3 from different hardwood species. The physico-mechanical properties, thermal conductivity and flammability differs between the different species. The CT analysis shows no correlation between the porosity and board properties such as strength, water uptake and thermal conductivity. Under the manufacturing conditions, oak WFIBs exhibit the highest thermal conductivity, alder boards the highest water absorption. Use of birch causes low strength properties. Nevertheless, WFIBs from all examined wood species show satisfactory properties in terms of practical application. WFIBs from beech fibres provided the overall best properties. They are comparable to those made from softwood fibres. WFIBs could be a useful application for low-value beech wood, which is usually only used as fuel. In addition, low-value beech wood may be an adequate substitute for softwoods such as spruce or pine conventionally used for WFIBs. Further studies should investigate the reasons for the varying properties of the different hardwood species.

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Conflicts of Interest

The authors declare no conflicts of interest.

6 Veröffentlichung 4: Resistance of different wood-based materials against mould fungi: a comparison of methods

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Autoren: Arne A. P. Imken, Christian Brischke, Sebastian Kögel, Kim C. Krause, Carsten Mai

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C. Mai	10	0	15	20	10

Resistance of different wood-based materials against mould fungi – a comparison of methods

Arne A.P. Imken[1], Christian Brischke[1], Sebastian Kögel[1], Kim C. Krause[1], Carsten Mai[1]

*corresponding author

Arne A. P. Imken

arne.imken@uni-goettingen.de

[1] Wood Biology and Wood Products, Faculty of Forestry and Forest Ecology, University of Goettingen, Büsgenweg 4, 37077 Göttingen, Germany

Abstract

Wood-based materials are generally prone to colonization by mould fungi and other discoloring microorganisms, but their resistance to fungal discoloration varies. Different standardized test methods for determining the susceptibility to mould fungi have been used to evaluate various wood-based materials, but the obtained results suggest that mould resistance depends on the method applied. Therefore, this study aimed at a comparative evaluation of two commonly used methods for determining the mould resistance of wood-based materials, i.e. the chamber method according to BS 3900 – Part G6 and the malt agar plate method according to ISO 16869. Solid wood, wood fiber insulation boards (WFIB) and wood polymer composites (WPC) were inoculated, incubated for different time intervals, and assessed with regard to superficial mould growth. Mould growth ratings obtained with the two methods did not correlate well, neither within one type of material nor across different materials, which can be attributed to higher moisture contents and additional nutrients available for the specimens in the agar plate test compared to those in the chamber test. It was concluded, that the experimental set up could have an overriding effect on the results of mould resistance tests.

Keywords

Mould fungi, comparison of methods, BS 3900 – Part G6 (1989), ISO 16869 (2008), wood polymer composites, wood fiber insulation boards

6.1 Introduction

Numerous fungi have potential to negatively affect the performance of wood-based materials through cell wall degradation or superficially deteriorate its optical appearance. Besides various decay fungi, which can cause brown, white, or soft rot, different blue stain and mould fungi can lead to discoloration of wood. Mould fungi mostly belong to the group of fungi imperfecti and are therefore micro-fungi. Even though mould fungi do not influence the strength properties of wood-based materials (Schmidt 1994), they affect their appearance and can cause allergic responses (Sutter 2002; Robbins and Morrell 2002).

Growth of mould fungi requires a wood moisture content between 30 % and 150 %, temperature between 0 °C and 40 °C and easily accessible nutrients (Sutter 2002). Typically, mould fungi are forming surface mycelium, which can release spores through conidia.

Mould fungi can infect nearly all materials, i. a. wood polymer composites or wood fiber insulation boards. Wood polymer composites (WPC) are composite materials made from wood, polymers such as polyethylene (PE), polypropylene (PP) and polyvinyl chloride (PVC), and different additives. The latter may be coupling agents, lubricants, fungicides or dyes. Usually, the wood percentage in WPC is 50-70 % (Karus et al. 2006). Production of WPC proceeds in a continuous extrusion process or in a discontinuous injection moulding process. Typical applications of WPC are deckings, claddings, and fence elements.

Wood fiber insulation boards (WFIB) are usually made of softwood fibers obtained through thermomechanical pulping (TMP): wood chips are thermally treated with steam at high pressure and afterwards defibrillated in a refiner (Krug 2010). The boards are produced in a wet or in a dry process, where the latter is more common today. Usually polymeric methylendiphenylisocyanate (PMDI) serves as binder. Optionally, hydrophobic additives or fungicides can be added (Holzmann et al. 2012).

Different standardized test methods are available for evaluating the susceptibility of wood-based materials to mould fungi (e.g. ISO 16000-21, 2014; ASTM D 3273 – 00, 2000; EN 15457, 2014; EN 60068-2-10, 2006; ISO 846, 2018; EN 15101-1, 2013 and EN 15534-1, 2018). Only EN 15534-1 is related to WPC and only EN 15101-1 is related to WFIB, all others were developed for testing of building materials, plastics and coatings. Nevertheless, the purpose of this study was to compare the two mainly used standards for evaluating mould growth on wood in Europe, the British standard BS 3900 – Part G6 (1989) and the ISO standard 16869 (2008), and to evaluate whether the ratings obtained correlate with each other.

BS 3900 – Part G6 (1989) is usually applied to testing the performance of paints on various substrates such as wood, metal, and plaster. To test panels of different wood species, Scots pine sapwood (*Pinus sylvestris*) is used as a reference. Painted flat panels are inoculated with a spore suspension (*Aspergillus versicolor, Aureobasidium pullulans, Cladosporium cladosporioides, Penicillium purpurogenum, Phoma violacea,*

Rhodotorula rubra, Sporobolomyces roseus, Stachybotrys atra and *Ulocladium atrum*). The test takes place in an incubation chamber with optimum temperature and humidity for fungal growth. Evaluation of fungal growth proceeds via optical assessment after 28 days and rating in one of five classes. The test is extendable for up to twelve weeks. The specimens are levitating and have no direct contact with water.

ISO 16869 (2008) serves to evaluate the effectiveness of fungistatic compounds in plastic formulations. Disc-shaped specimens are embedded in nutrient-salt agar in an agar plate and a fungal spore suspension (*Aspergillus niger, Chaetomium globosum, Paecilomyces variotii, Penicillium funiculosum* and *Trichoderma longibrachiatum*) is added. As a reference, malt-extract agar is embedded instead of a specimen in the agar plate. The plates are inoculated for 21 days. The specimens are laying on agar and have direct contact to water.

Previous studies showed that mould fungi were the first colonizers on WPC material after three months of outdoor exposure (Plaschkies and Scheiding 2014). Ibach et al. (2013) compared decay of WPC from outdoor exposure and in the laboratory. They found mould and algae as the first colonizers. Ibach (2010) also mentioned that the effects of mould fungi are difficult to stop without periodic washing with dilute bleach solution. Lie et al. (2019) compared laboratory screening tests and outdoor performance of exterior wooden claddings. They used agar plate tests and water uptake tests as laboratory methods. The authors investigated various inoculation methods and incubation temperatures. They did not find any significant correlation between the agar test and the outdoor test, but they established significant correlations between the water uptake test and the outdoor test, namely between the water uptake of the specimens and the mould rating of the same specimens after 126 days of outdoor exposure. Scheiding (2007) pointed out that there is a lack of an explicit standard for testing the resistance to mould fungi for wood-based materials including WFIB. Kumar et al. (2016) used octadecyltrichlorosilane for hydrophobic surface treatment of wood fibers to reduce the susceptibility for microorganisms. According to EN ISO 846 (2018), it improved the effectiveness towards mould significantly. Hundhausen et al. (2013) identified the accuracy of the visual assessment as strongly dependent on the evaluator, the type of rating scale and the standard used. They developed a procedure that enabled objective determination of mould growth by using the public domain software ImageJ.

The aim of this study was to compare two standard methods most commonly used for testing the mould resistance of wood-based materials in Europe and to figure out whether the corresponding results correlate. Therefore, two very different types of wood-based materials were compared, i.e. wood polymer composites (WPC) and wood fiber insulation boards (WFIB). Solid wood and pure polymers were tested as references. Mould resistance tests were performed according to BS 3900 – Part G6 (1989) and ISO 16869 (2008). It was hypothesized that hardwood containing materials are more susceptible to mould growth compared to softwood containing products due to a higher hemicellulose content and that the mould resistance of WPC decreases with rising wood content.

6.2 Material and Methods

6.2.1 Materials

Different types of materials, wood (Scots pine sapwood, beech, black locust purchased from Lower Saxony State Forests) and polymer references (polypropylene from Sabic (Saudi Basic Industries Corporation, Riyadh, Saudi Arabia) and polyethylene from Braskem (Sao Paulo, Brazil)), wood-polymer-composites (WPC) and wood fiber insulation boards (WFIB) were used in this study. For both tests, specimens of the references and WPC had a thickness of 4 mm while the specimens of the WFIB had a thickness of 36 mm. For the tests according to BS 3900-G6 (1989), the specimens were 30 mm x 20 mm with a 2 mm bore-hole drilled 4 mm from the mid-point of the 20 mm side of the references and the WPC specimens. The WFIB specimens did not exhibit a hole. Specimens used for tests according to ISO 16869 (2008) were 20 mm x 20 mm. All test specimens were conditioned at 20 ± 2 °C and 65 ± 10 % relative humidity (RH) until constant mass. The number of replicates for each test and material was five references, five WPC specimens, and six WFIB specimens. For WFIB specimens the higher number of replicates was chosen because two boards per variation were produced and three specimens per board were analyzed.

6.2.1.1 Production of Wood-polymer composites (WPC)

WPC produced in an extrusion (EX), injection molding (IM) and compression molding (CM) process had different shapes; some were solid boards, and some were hollow-

chamber profiles. They were partly produced industrially by different industrial partners, partly in laboratory processes conducted by “Süddeutsches Kunststoff-Zentrum (SKZ)” in Würzburg, Germany (WPC 1 - 3) and partly in cooperation with the Institute of Polymer Materials and Polymer Technology (PuK) at the TU Clausthal, Germany (WPC 4 - 9). Specimens of industrially produced WPC decking were cut from the inner layer of the material and had accordingly a non-sealed surface with exposed wood particles. Specimens of WPC 1 and 2 were cut from the lateral surface area of the extruded rectangular hollow-chamber profiles. The resulting specimens had a smooth top side and a rough bottom side. The compression molded WPC 3 as well as the injection molded WPC formulations 4-9 had smooth surfaces on both sides of the specimens. Details about the wood species, polymer matrix, and pre-weathering are summarized in Table 1.

Table 1: Wood-polymer composites (WPC), wood and polymer references, wood species and wood percentages.

Material	Polymer matrix	Wood species	Wood percentage [%]	Manufacturing method	Density [kg/m³]
Scots pine sapwood	---	*Pinus sylvestris*	100		513
Beech	---	*Fagus sylvatica*	100		667
Black locust	---	*Robinia pseudoacacia*	100		689
Polypropylene	---	---	0	IM[1]	883
Polyethylene	---	---	0	IM	951
WPC 1	Polypropylene	*Softwood*[5]	60	EX[2]	937
WPC 2	Polypropylene	*Softwood*	70	EX	1112
WPC 3 (plus biocide[4])	Polypropylene	*Softwood*	60	CM[3]	1076
WPC – Industrial 1	Polypropylene	n.a.	60		1120
WPC – Industrial 2	Polyvinyl chloride	n.a.	50		1314
WPC – Industrial 3	Polyethylene	n.a.	75		1235
WPC – Industrial 4	Polypropylene	Pulp	50		1143
WPC – Industrial 5	Polyvinyl chloride	n.a.	50	EX	1337
WPC-4-poplar	Polypropylene	*Populus spp.*	60	IM	1096
WPC-5-willow	Polypropylene	*Salix spp.*	60	IM	1084

WPC-6-spruce	Polypropylene	*Picea abies*	60	IM	1074
WPC 7-spruce industrial	Polypropylene	*Softwood*	60	IM	1139
WPC 8-young beech	Polypropylene	*Fagus sylvatica*	60	IM	1079
WPC 9-old beech	Polypropylene	*Fagus sylvatica*	60	IM	1091
WPC – Industrial 1 (4 years o.e.[6]	Polypropylene	n.a.	60		1137
WPC – Industrial 2 (6 years o.e.)	Polyvinyl chloride	n.a.	50		1310
WPC – Industrial 3 (1 year o.e.)	Polyethylene	n.a.	75	EX	1130

[1] = Injection moulding

[2] = Extrusion

[3] = Compression moulding

[4] = Biocide = preservative against mould growth (industrial product)

[5] = Softwood source: raw cellulose (industrial product)

[6] = outdoor exposure

6.2.1.2 Production of wood fiber insulation boards (WFIB)

Specimens were cut from sanded boards produced in a dry process in the Section of Molecular Wood Biotechnology and Technical Mycology, Faculty of Forest Science and Forest Ecology, University of Goettingen. The tested WFIB were made either solely from Norway spruce fibers (Picea abies) or from mixtures of Norway spruce with various hardwood fiber blends in proportions of 20, 50 and 80 %. The hardwood fiber blends contained equal proportions of European ash (Fraxinus excelsior), European beech (Fagus sylvatica) and silver birch (Betula pendula). Two types of binders - low temperature curing poly-methylendiphenylisocyanate (PMDI) resin (I-Bond WFI 4370) and bicomponent fibers (Bico-Fibers) - were used to produce either stiff or flexible boards. Further additives used were paraffin wax as hydrophobic agent and ammonium polyphosphate (APP) as flame retardant (Table 2). The percentages of the additives always refer to the dry mass of the fibers.

Table 2: Wood fiber insulation boards (WFIB) and respective binders and additives.

Material	Binders/Additives	Density [kg/m³]
20SW[1]/80HW[2]	pMDI[3] (5 %)	116,5
50SW/50HW	pMDI (5 %)	114,4
80SW /20HW	pMDI (5 %)	108,9
100 Spruce	pMDI (5 %)	106,5
20SW/80HW	pMDI (5 %) & APP[4] (10 %)	112,2
50SW/50HW	pMDI (5 %) & APP (10 %)	113,5
80SW/20HW	pMDI (5 %) & APP (10 %)	106,4
100 Spruce	pMDI (5 %) & APP (10 %)	104,2
20SW/80HW	Bico (7 %)	110,2
50SW/50HW	Bico (7 %)	103,8
80SW/20HW	Bico (7 %)	98,7
100 Spruce	Bico (7 %)	99,3
20SW/80HW	pMDI (5 %) & paraffin (1 %)	111
50SW/50HW	pMDI (5 %) & paraffin (1 %)	107,7
80SW/20HW	pMDI (5 %) & paraffin (1 %)	107,2
100 Spruce	pMDI (5 %) & paraffin (1 %)	111,7

[1] = Softwood

[2] = Hardwood

[3] = Polymeric methylendiphenylisocyanate

[4] = Ammonium polyphosphate

6.2.2 Mould fungi

To prepare the spore suspension, 5 ml of a wetting agent (0.05 % polysorbate dissolution) was added to the cultured (for six to eight weeks) mould fungi (cultivated in agar plates on potato dextrose agar or on malt agar. The different media were selected to provide ideal growth conditions for each fungal species.). Afterwards, the spores were harvested with a sterile inoculating loop and all mixed in a beaker. The number of cultures per fungi differed between one and five. To make the standards comparable, a unique spore suspension was used. Differing from the suggested fungi in the standards for all mould resistance tests, the following fungi were used: *Aspergillus niger* (ATCC 6275), *Aspergillus versicolor* (IMI 45554), *Chaetomium globosum* (ATCC 6205), Cladosporium cladosporioides (IMI 178517), Penicillium purpurogenum (IMI178519), *Paecilomyces variotii* (CBS 628.66), *Rhodotorula rubra* (main name of strain ID: *Rhodotorula mucilaginosa*) (NCYC 1659), *Stachybotrys atra* (IMI 082021),

Sydowia polyspora (IMI 269217), *Trichurus spiralis* (MG 31) and *Ulocladium atrum* (IMI 79805).

6.2.2.1 Assessment of mould resistance according to BS 3900 - Part G6 (1989)

An incubation chamber (40 x 25 x 25 cm³) was used for the mould resistance tests according to BS 3900-G6 (1989). The conditioned specimens were inoculated via an atomizer with 1 ml of mixed spore suspension. Potential contamination after inoculation was accepted, because the contamination would be with mould fungi again. After inoculation, the specimens were placed in the incubation chamber over a water reservoir with a heating coil. Hooks were plugged through the WPC holes or directly through the WFIB and were hung up on metal ledges (Figure 1). The temperature of the room, where the incubation chamber was stored, was 23 °C ± 2 ° C. Heating of the water reservoir in the incubation chamber proceeded every 10 h for 2 h throughout the incubation. Temperature and relative humidity were checked every day.

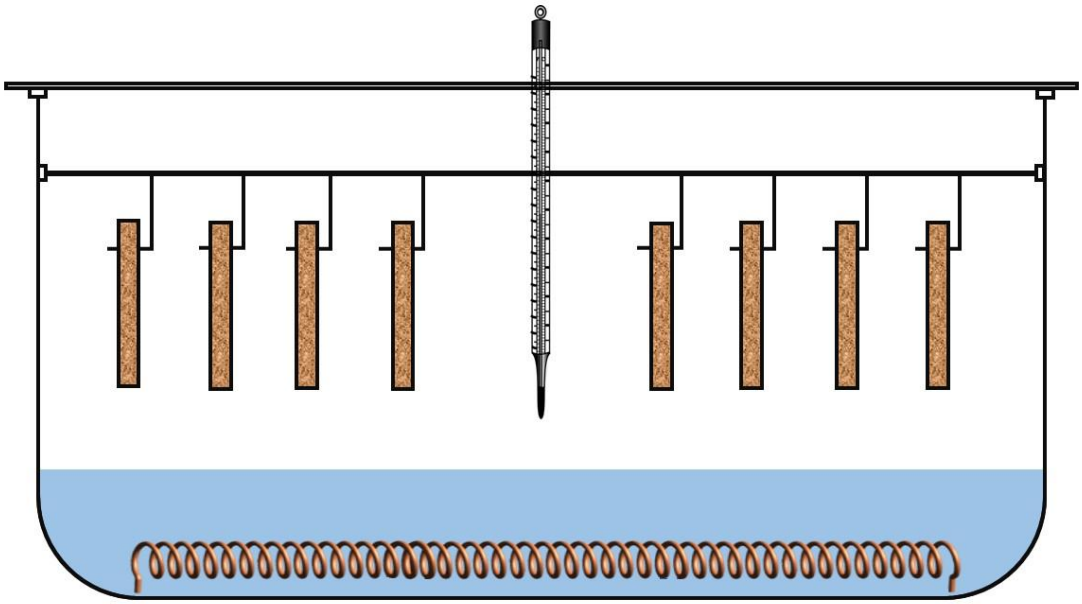

Figure 1: Incubation chamber used for mould resistance tests according to BS 3900 (1989).

Specimens were assessed visually - in the beginning every 2 days, subsequently at larger intervals up to 12 days. Images were taken using a digital microscope VHX 5000 (Keyence, Osaka, Japan) at 50x magnification. The incubation period was 60 days.

6.2.2.2 Assessment of mould resistance according to ISO 16869 (2008)

The WPC specimens were placed in the center of screw jars (diameter: 115 mm, height: 70 mm), which were previously filled with 20 ml of nutrient-salt-agar (2.62 g KH_2PO_4, 0.2 g $Na_2HPO_4 \cdot 2H_2O$, 0.7 g $MgSO_4 \cdot 7H_2O$, 1.0 g NH_4NO_3, 15.0 g agar-agar, and 10 ml stock solution of micro-nutrients per 1000 ml aqueous solution). The solution of micro-nutrients contained 0.5 g NaCl, 0.2 g $FeSO_4 \cdot 7H_2O$, 0.2 g $ZnSO_4 \cdot 7H_2O$, 0.06 g $MnSO_4 \cdot H_2O$ per 1000 ml aqueous solution. The jars were autoclaved at 121 °C for 20 min. All specimens were inoculated via an atomizer with 1 ml of the mixed inoculum. All but the WFIB specimens were put on the nutrient-salt-agar, while the WFIB specimens were stamped in the nutrient-salt-agar due to the large thickness. Subsequently, all specimens were covered with 15 ml of nutrient-salt-agar again (Figure 2). As a reference, malt-agar (30.0 g malt extract, 3.0 g soya peptone, 15.0 g agar-agar, water) was placed in the screw jar replacing the test specimen. All jars were incubated at 22 °C ± 1 °C and 70 % RH during 28 days. The deviations in temperature and RH from the standard were defined through the conditions of the culture room. Other deviations from the standard were made to make it comparable to BS 3900.

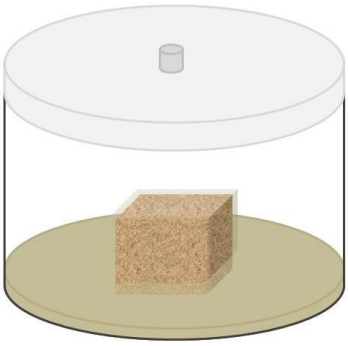

Figure 2: Screw jar with an inoculated WFIB-specimen in a mould resistance test according to ISO 16869 (2008).

Specimens were assessed visually every 2 - 4 days and images were taken using a digital microscope VHX 5000 (Keyence, Osaka, Japan) at 50x magnification.

6.2.3 Evaluation of the mould resistance

According to both standards, surface colonization by mould is rated visually. In the chamber test according to BS 3900-G6 (1989), five mould growth classes are defined, while only three classes are distinguished using the agar plate test method ISO 16869 (2008). To allow for a uniform evaluation of both tests, the following five-class assessment scheme was applied in this experiment:

Class 0 = no infestation of the surface

Class 1 = 1 – 25 % infestation of the surface

Class 2 = 26 – 50 % infestation of the surface

Class 3 = 51 – 75 % infestation of the surface

Class 4 = 76 – 100 % infestation of the surface

Deviations from the rating scale of the BS 3900-G6 (1989) were made because it includes very small differences between the classes which are not possible to distinguish by a subjective viability control.

6.2.4 Moisture content measurements

The moisture content (MC) of the specimens was determined after incubation. Therefore, the specimens were cleaned with a soft brush from adhering mould, weighed to the nearest 0.001 g, oven-dried at 103 °C and after cooling down in a desiccator weighed again.

Equation 1: Moisture content (MC).

$$MC = \frac{w - d}{d} * 100$$

MC = moisture content, in %
w = wet mass of the test specimen, in grams
d = oven dry mass of the test specimen, in grams

6.3 Results and discussion

6.3.1 Mould resistance of wood-polymer composites (WPC)

After seven days, the specimens in the agar plate test were already infected; however, in the chamber test, the first infection was observed after 21 days (Figure 3). Specimens with higher hardwood content showed a higher degree of colonization by the mould fungi in both tests, which might be attributed to the higher amount of hemicellulose in the hardwoods (Findlay and Savory 1954).

At the end of the test, none of the PP and PE specimens were infested neither in the chamber test nor in the agar plate test. Solid beech wood specimens were rated in class 2 in the agar plate test and in class 3 in the chamber test: black locust specimens were rated in class 2 and in class 0, respectively. The pine sapwood specimens were rated in class 0 (not infected at all) in the agar plate test, but were rated in class 4 in the chamber test. Lie et al. (2019) also found that pine sapwood was nearly not infected in the agar plate test, but this was not the case in an outdoor test. In the relatively small petri dishes, the emissions of volatile organic compounds (VOCs) might act as an antifungal component.

Mould growth on industrially produced WPC started always earlier in the agar plate test compared to the chamber test. Only on three of the WPC produced in laboratory processes (WPC 1 – 3), the mould growth started at the same time in both tests.

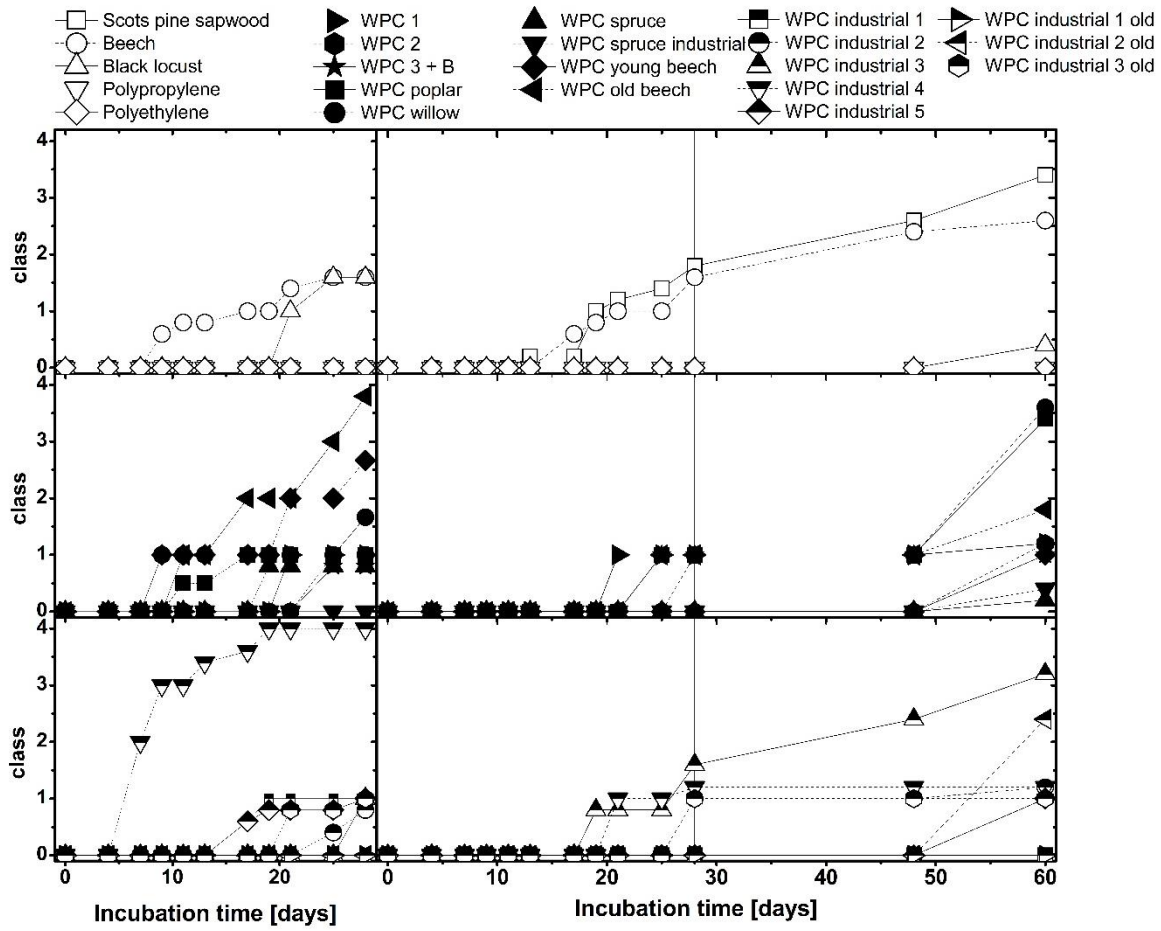

Figure 3: Classification of mould growth on WPC specimens during the agar plate test (left) and the chamber test (right).

6.3.2 Mould resistance of Wood fiber insulation boards (WFIB)

In the agar plate test, the mould growth started always earlier and proceeded faster than in the chamber test. After 28 days, none of the WFIB specimens in the chamber test was infected by mould. Therefore, the test was extended to 60 days. The materials with higher hardwood proportions showed more severe mould growth (Figure 4).

Unlike Kumar et al. (2016), no positive effect of a hydrophobation additive became visible. Furthermore, there was no effect of the fire retardant additive APP and no significant effect of the binder type (PMDI and bicomponent fibers). The specimens with and without APP and with both types of binder were equally colonized.

Moreover, some of the WFIB specimens were shattered during their placement in the test chamber, because the high porosity of WFIB resulted in brittleness of the specimens.

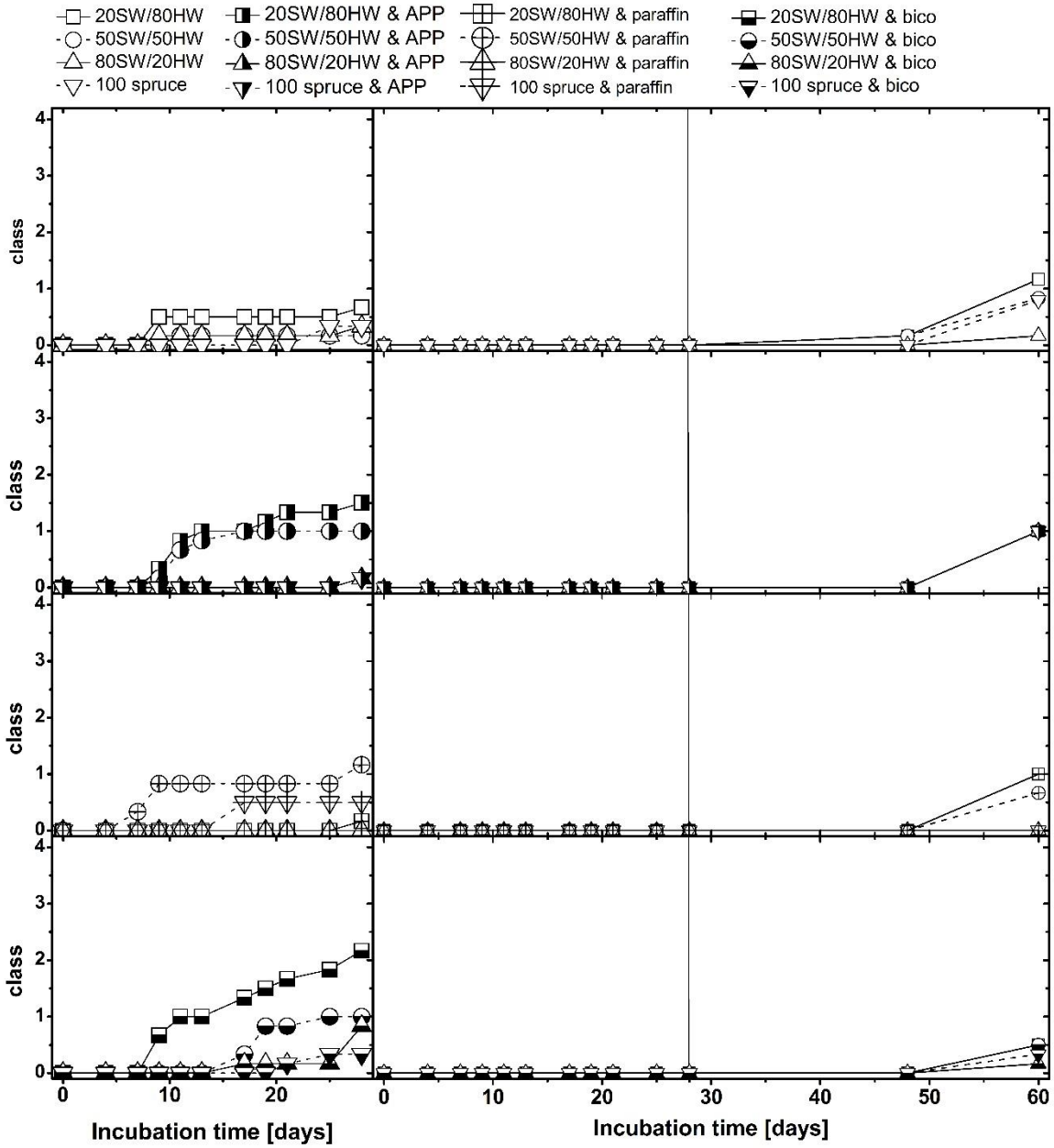

Figure 4: Mould growth for WFIB during the agar plate test (left side) and the chamber test (right side).

6.3.3 Moisture content after incubation

During the agar plate test, the wood references absorbed clearly the highest amount of water. Scots pine sapwood exhibited an average moisture content of 148.3 %, beech of 106.7 % and black locust of ca. 84.2 %. In terms of WPC, higher wood content resulted in higher water absorption (Table 3). ‘WPC - Industrial 4’ (50 % wood percentage) and ‘WPC - Industrial 3 old’ (75 % wood percentage) absorbed 13.6 % and 23.9 % of water, respectively. This is due to the higher wood particle content of ‘WPC - Industrial 3 old’.

Table 3: Moisture content of the WPC specimens.

Material	Mean moisture content (%)	
	Agar plate test	Chamber test
Scots pine sapwood	148.3	15.9
Beech	106.7	21.1
Black locust	84.2	13.5
Polypropylene	0.4	0.0
Polyethylene	0.2	0.0
WPC 1	21.1	11.2
WPC 2	19.0	14.6
WPC 3 (plus biocide)	15.4	12.6
WPC – Industrial 1	21.0	13.2
WPC – Industrial 2	14.0	10.3
WPC – Industrial 3	21.5	14.9
WPC – Industrial 4	13.6	7.9
WPC – Industrial 5	14.9	9.8
WPC-4-poplar	19.0	14.2
WPC-5-willow	23.0	12.8
WPC-6-spruce	15.7	13.6
WPC 7-spruce industrial	18.8	13.4
WPC 8-young beech	18.3	13.2
WPC 9-old beech	17.0	14.1
WPC – industrial 1 (4 years o.e.[1])	19.9	13.4
WPC – industrial 2 (6 years o.e.)	14.2	11.0
WPC – industrial 3 (1 year o.e.)	23.9	14.6

[1] = outdoor exposure

The moisture content of all specimens in the chamber test was much lower than that of the specimens in the agar plate test. For the wood references, the values were 15.9 % for Scots pine sapwood, 21.1 % for beech and 13.5 % for black locust. As for the agar plate test, WPCs containing more wood had higher moisture content around 14.6 % (WPC industrial 3 old) compared to the ones containing less wood with 7.9 % moisture content (WPC industrial 4) (Table 3). Clemons (2002) mentioned that the

wood flour content, wood particle size, processing methods, and additives influence the moisture absorption of WPC.

High temperatures (over 10 °C are required for growth; 30 °C are favored) and high moisture contents (over 75 %) are favorable for mould growth (Schirp and Wolcott 2005; Krause and Schmid 2012; Ibach et al. 2017). Even though many mould species, which are known to grow on wood, have also been isolated from polymers (Schirp et al. 2008), there was no infection of polyethylene and polypropylene specimens in these tests (Figure 3 and Figure 5). This might be explained by insufficient water uptake of the pure polymers (Caulfield et al. 2005) and a lack of additional nutrients.

As for WPC, the agar plate test led to much higher moisture content of WFIB specimens (up to 908.9%) compared to the chamber test (up to 212.6 %) (Table 4). This is attributed to the direct contact between the specimens and the agar medium in the agar plate test. In contrast, chamber test specimens took up water only from ambient air in the chamber based on diffusion and condensation only.

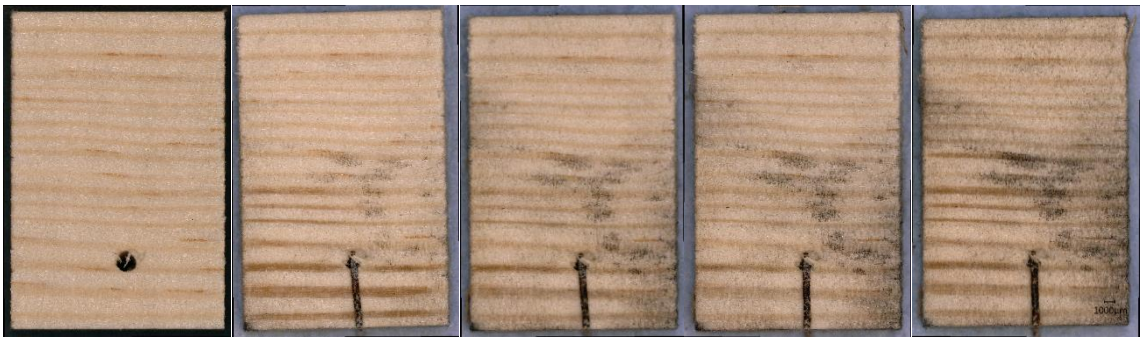

Figure 5: Mould growth classes from 0 (left) to 4 (right).

Table 4: Moisture content of the WFIB specimen.

Material	Additives	Mean moisture content (%)	
		Agar plate test	Chamber test
20SW/80HW	PMDI (5 %)	242.3	100.8
50SW/50HW	PMDI (5 %)	161.0	86.5
80SW /20HW	PMDI (5 %)	140.7	86.2
100 Spruce	PMDI (5 %)	438.1	132.0
20SW/80HW	PMDI (5 %) & APP (10 %)	840.3	212.6
50SW/50HW	PMDI (5 %) & APP (10 %)	881.5	205.9
80SW/20HW	PMDI (5 %) & APP (10 %)	765.8	161.7
100 Spruce	PMDI (5 %) & APP (10 %)	532.9	189.6
20SW/80HW	Bico (7 %)	722.8	111.2
50SW/50HW	Bico (7 %)	908.9	133.3
80SW/20HW	Bico (7 %)	436.9	88.4
100 Spruce	Bico (7 %)	446.5	108.5
20SW/80HW	PMDI (5 %) & paraffin (1 %)	130.6	177.5
50SW/50HW	PMDI (5 %) & paraffin (1 %)	151.4	135.2
80SW/20HW	PMDI (5 %) & paraffin (1 %)	112.5	178.7
100 Spruce	PMDI (5 %) & paraffin (1 %)	439.9	138.6

6.3.4 Comparison of methods

As most of the chamber test specimens were not infected even after 28 days of incubation, ratings were done after 60 days. However, mould growth ratings did not correlate between the two test methods, neither after 28 days nor after 60 days, and neither for WPC nor for WFIB (Figure 6). The mould fungi grew much faster in the agar plate test than in the chamber test due to the presence of malt extract agar and higher moisture content (Bardage 2004, Schirp et al. 2008).

There are many implications that can affect mould growth; for instance, the surface structure of the specimens. Gobakken et al. (2010) tested mould growth on paints with different surface structures. They examined six different model paints and found that the mould growth varied with exposure time and type of paint. They suggested that differences in surface structure affect spore attachment and germination, but this did not become evident from their results. They explained that the chemical effect in the coating could be as important as, or more important than, the physical characteristic of the surface.

Moreover, in this study, chemical and/or physical characteristics of the surface could have had an influence on the mould growth, because there were very different surface structures (2.1.1 and 2.1.2) and the chemical ingredients changed a lot between the different variations. The two different additives (APP and Paraffin) and binders (PMDI and bicomponent fibers) used for WFIB production influence chemical surface properties.

In addition, the duration of a mould growth experiment plays an important role, since the risk of mould infestation increases with incubation time (Johansson et al. 2012). Hence, future studies shall include long-term outdoor experiments with matched samples to allow for a direct comparison with results from laboratory tests as presented in this study.

Apart from this, different mould growth classification systems are used according to the two standards. In some publications, ‘classes’ are also referred to as ‘index’. Further, Ojanen et al. (2010) report that the defined intervals for the classification vary in different studies. These different assessment systems lead to very poor comparability of the different standards.

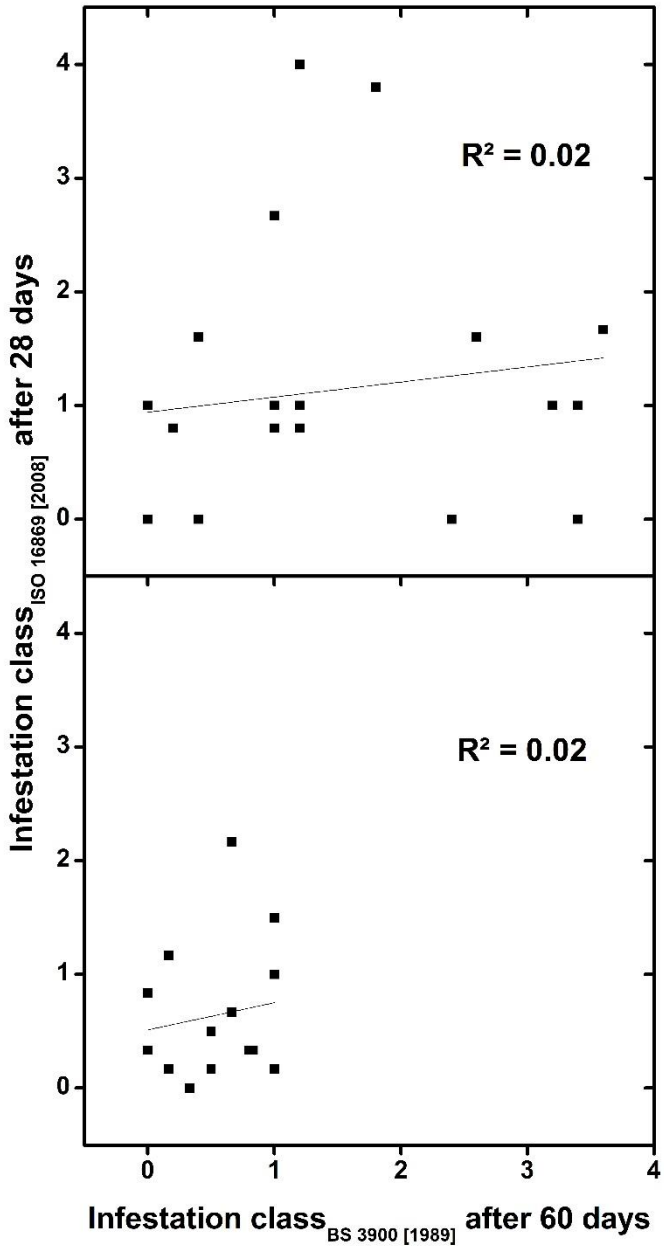

Figure 6: Correlation between mould infestation classes according to ISO 16869 (2008) and BS 3900 (1989) for the WPC (above) and WFIB (below) specimens at the end of the tests. Each point represents the arithmetic mean of one material.

6.3.5 Microscopic evaluation of the mould fungi growth

The microscopic evaluation of the mould growth at 50x magnification turned out unfeasible, because the specimens' surfaces were very heterogeneous, and thus prone to create shadows and irregularities, which made it impossible to evaluate the infected surfaces.

6.4 Conclusion

Mould growth ratings obtained with the chamber method and the agar plate method were not well correlated, neither within the group of materials nor across different materials. This was attributed to the much higher moisture content and additional nutrients available for the specimens in the agar plate test compared to those in the chamber test. Thus, for the interpretation of the results, it is very important to know and clearly indicate which standard was used.

Some of the WFIB specimens disintegrated during installation in the test chamber because they were too brittle. For future experiments, it is therefore recommended to use a wire basket or a similar support, when handling WFIB specimens.

Finally, the chamber test appeared preferable over the agar plate method because it represents more realistic exposure conditions for wood-based materials compared to the agar plate test. One more reason that makes the chamber test more comparable to materials used in construction than the agar plate test is that there are no artificially added nutrients. For further validation of the method, field test experiments under different exposure regimes are under preparation.

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Conflicts of Interest

The authors declare no conflicts of interest.

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7 Synopsis

Welche Baumarten aktuell für die industrielle Produktion von HFDS eingesetzt werden ist schwer zu bestimmen. Jedoch gehen die Annahmen zur Verwendung von Laubholz von maximal 10 Prozent als Obergrenze aus (Mantau 2013). Im Zuge der in Kapitel 1 bereits erwähnten Veränderungen durch den ökologischen Waldumbau wird die HFDS-Industrie die Verwendung der eingesetzten Baumarten zunehmend in Richtung Laubholz verschieben müssen. Aktuell werden auftretende Lieferengpässe beim Nadelholz noch durch Rohholzimporte aus Russland oder Skandinavien kompensiert (Schlotzhauer 2018). Diese Importe sind in Anbetracht des fortschreitenden Klimawandels und der weltpolitischen Lage jedoch nicht mehr zeitgemäß.

In der Veröffentlichung in Kapitel 3 sind Fasern verschiedener Nadel- und Laubbaumarten, sowie Fasermischungen und zuvor fraktionierte Fasern mittels scannerbasierten FibreShape System analysiert und charakterisiert worden. In Tabelle 5 sind alle in dieser Arbeit verwendeten Baumarten zusammenfassend aufgelistet. Solche, die in der Veröffentlichung aus Kapitel 3 noch nicht erschienen waren, wurden im Rahmen einer Bachelorarbeit zusätzlich ermittelt (Heckel 2022). Die Bezeichnung der Fasermischungen umfasst, wie in Kapitel 3 beschrieben dargestellt, den prozentualen Anteil der Fichtenfasern, Nadelholzfasern (NH), gefolgt vom prozentualen Anteil der Laubholzfasern (LH). Die Laubholzfasern bestanden immer zu gleichen Teilen aus Esche, Buche und Birke. Die in Tabelle 5 dargestellten Werte zeigen dabei nicht die Länge von Einzelfasern, sondern von Faserbündeln an. Dies liegt am Aufschlussverfahren mit einem großen Mahlscheibenabstand (0,6 mm), wodurch Faserbündel und keine Einzelfasern aufgeschlossen wurden.

Tabelle 5: Median der geodätischen Länge verschiedener Faservarianten.

Faservariante	Median [µm]
Gemeine Esche	792
Winterlinde	1100
20NH_80LH	1111
Rotbuche	1138
Hängebirke	1264
50NH_50LH	1313
Stieleiche	1617
80NH_20LH	1779
Schwarzerle	2392
Gemeine Fichte	3012
Gemeine Kiefer	3419
Europäische Lärche	3811

Forschungsfrage 2 aus Kapitel 1.1 lässt sich anhand von Tabelle 5, welche bereits absteigend nach mittlerer Faserlänge sortiert ist, eindeutig beantworten. Es sind klare Unterschiede in der mittleren Länge der verschiedenen Faservarianten erkennbar. Die Fasern der drei untersuchten Nadelbaumarten sind deutlich länger als jene der untersuchten Laubbaumarten sowie der Fasermischungen. Die in Kapitel 2.2 gezeigten Verhältnisse werden somit bestätigt (Göttsching und Katz 1999; Wagenführ 2007). Aber auch zwischen den verschiedenen Laubbaumarten lassen sich deutliche Unterschiede der mittleren Faserlängen erkennen. Während die Esche mit 792 µm den niedrigsten Wert aufweist, erreicht die Erle eine annähernd dreifach höhere mittlere Faserlänge (2392 µm). Diese fast dreifach längere mittlere Faserlänge der Erle gegenüber der Esche lässt sich nicht durch die unterschiedlichen Zelltypen (Tabelle 3) erklären. Auch

die Unterschiede in der Porigkeit der Laubhölzer können hier nicht als Grund aufgeführt werden. Auch wenn die Erle zerstreutporig und die Esche ringporig ist, liegt die Eiche als ebenfalls ringporige Baumart mit 1617 µm zwischen den beiden zuvor erwähnten Baumarten (Ilvessalo-Pfäffli 1995).

Die Beimischung von Laubholzfasern zu Fichtenfasern zeigt erkennbare Auswirkungen. Bereits die Zugabe von 20 % Laubholzfasern verkürzt die mittlere Faserlänge der Fichtenfasern um ca. 41 %. Eine Zugabe von 50 % Laubholzfasern bewirkt eine Verkürzung der mittleren Faserlänge der Fichtenfasern um 56 % bzw. um 63 % bei der Zugabe von 80 % Laubholzfasern.

Forschungsfrage 3 wird in Kapitel 3 im dazugehörigen Kapitel 3.3 beantwortet. Die mathematische Fraktionierung der verschiedenen Faservarianten, bei welcher Partikel kleiner 500 µm ausgeschlossen worden sind, zeigt, dass sich die größten Staubanteile bei Faservarianten aus Laubbaumarten zeigen. Dies lässt sich möglicherweise durch den geringeren Anteil von Libriformfasern im Laubholz (50 – 60 %) gegenüber dem höheren Anteil von Tracheiden im Nadelholz (90 – 95 %) erklären, da, wie bereits in Kapitel 2.1 beschrieben, der Sklerenchymanteil für die Faserstoffausbeute entscheidend ist. Dies lässt sich besonders gut bei den Mischsortimenten aus Laubholz- und Nadelholzfasern erkennen, bei denen der Staubanteil mit steigendem Laubholzanteil ebenfalls zunimmt. Da eine Fraktionierung allerdings zeitaufwändig und kostenintensiv ist und darüber hinaus zu einer großen Menge an Abfall aus kleinen Fasern führt, wurde dieser Ansatz verworfen und nicht weiterverfolgt.

In Kapitel 4 wird auf Forschungsfrage 4 eingegangen. Solange ein Mindestanteil von 20 % Nadelholzfasern in der Fasermischung vorhanden ist, gibt es keine signifikanten Auswirkungen auf die mechanischen und technologischen Eigenschaften, sowie auf die Brennbarkeit der HFDS. Diese Erkenntnisse stehen im Widerspruch zu Ergebnissen einer Studie von Eichhorn, bei der Nadelholzfasern teilweise durch Buchenfasern substituiert wurden. Dabei wurde eine geringfügige Abnahme der Festigkeiten bei steigendem Buchenholzfaseranteil festgestellt. Nichtsdestotrotz wird auch in dieser Studie die teilweise Substitution von Nadelholzfasern durch Buchenfasern empfohlen (Eichhorn 2017).

Forschungsfrage 1 und 5 werden in den Kapiteln 4 und 5 beantwortet. Laubholzfasern können zur Produktion von Holzfaserdämmstoffen eingesetzt werden, die mechanischen und technologischen Eigenschaften, sowie die Brennbarkeit der HFDS unterscheiden sich allerdings zwischen Laub- und Nadelholzfasern. Zudem gibt es ebenfalls zwischen den verschiedenen Laub- und Nadelholzvarianten Unterschiede. Im Vergleich zwischen den drei Nadelbaumarten zeigt die Lärche die geringsten Festigkeiten und die höchste Wärmeleitfähigkeit. Das für HFDS hauptsächlich genutzte Industrieholz wird in Deutschland nicht nach Baumarten, sondern nach Güteklasse sortiert (DFWR, DHWR 2020). Da das Nadelholzaufkommen in Deutschland überwiegend aus Fichte und Kiefer besteht, ist der Anteil der Lärche im gesamten Industrieholz gering (Bundesministerium für Ernährung und Landwirtschaft 2012). Daher machen sich die niedrigeren Festigkeitseigenschaften und die höhere Wärmeleitfähigkeit der Lärche in der Industrie nicht bemerkbar.

Auch zwischen den Eigenschaften der aus verschiedenen Laubbaumarten produzierten HFDS gibt es große Unterschiede. Die Buche erreicht über mechanische, technologische und chemische Eigenschaften hinweg sehr gute Werte. Andere Laubbaumarten offenbaren in verschiedenen Bereichen nachteilige Eigenschaften. Die Erle zeigt ein sehr hohes Wasseraufnahmepotential. Die Birke erreicht nur sehr geringe Festigkeiten und die Eiche zeigt eine höhere Wärmeleitfähigkeit als die anderen Baumarten. Mit Ausnahme der Buche schneiden die Laubbaumarten gegenüber den Nadelbaumarten in Bezug auf die mechanischen Eigenschaften mit etwas niedrigeren Werten ab. Auch das Wasseraufnahmepotential von Linde, Eiche, Erle und Birke ist gegenüber Lärche und Fichte erhöht. Bei der Wärmeleitfähigkeit und der Feuerfestigkeit zeigt erneut lediglich die Buche vergleichbare Werte zu den Nadelbaumarten.

In der DIN EN 13171 sind Anforderungen für bestimmte Produkteigenschaften festgelegt. Dazu zählen Druckfestigkeit, Querzugfestigkeit und Wasseraufnahme. Die in den Kapiteln 4 und 5 untersuchten druckfesten HFDS-Platten der verschiedenen Faservarianten sind in Tabelle 6 entsprechend der in der Norm hinterlegten Stufen eingeordnet worden. Die den jeweiligen Stufen zugrundeliegenden, ermittelten Werte stammen dabei aus zwei verschiedenen Untersuchungen und werden in der nachfolgenden Tabelle zusammengefasst. Dies erklärt beispielsweise die höheren Druckfestigkeiten der Mischsortimente aus Laub- und Nadelholz. Zudem zeigt sich, dass viele Faservarianten ohne Zugabe von Hydrophobierungsmitteln, die laut Norm geforderten Werte für

die Wasseraufnahme nicht erfüllen können. In DIN 4108-10 werden die Stufen aus DIN EN 13071 Anwendungsgebieten und -typen zugeordnet. Da in vielen Innenanwendungen keine maximale Wasseraufnahme vorgegeben ist, lassen sich selbst die Faservarianten mit einer Wasseraufnahme von über 2 kg/m² beispielsweise für die Innendämmung der Wand einsetzen.

Tabelle 6: Einstufung der druckfesten Holzfaserdämmplatten mit einer Rohdichte von 100 kg/m³ aus verschiedenen Baumarten gemäß DIN EN 13171. CS(10\Y) = Symbol für die angegebene Stufe der Druckfestigkeit. WS = Symbol für die angegebene Stufe der Wasseraufnahme.

Faservariante	**Druckfestigkeit [kPa]**		**Querzugfestigkeit [kPa]**		**Wasseraufnahme [kg/m²]**	
	Stufe	Wert	Stufe	Wert	Stufe	Wert
Fichte	CS(10\Y)30	34,33	TR5	7,06	WS1,0	0,70
Kiefer	CS(10\Y)20	28,03	TR5	5,65	-	7,35
Lärche	CS(10\Y)20	20,65	TR1	1,42	WS1,0	0,69
Buche	CS(10\Y)30	32,08	TR7,5	9,64	WS1,0	0,95
Eiche	CS(10\Y)20	21,50	TR5	5,08	-	4,36
Linde	CS(10\Y)30	33,2	TR2,5	4,11	-	4,48
Erle	CS(10\Y)20	27,46	TR1	2,24	-	16,19
Birke	CS(10\Y)20	21,06	TR2,5	3,50	-	6,88
80NH_20LH	CS(10\Y)40	49,75	TR2,5	4,09	WS2,0	1,10
50NH_50LH	CS(10\Y)40	48,75	TR5	5,92	WS2,0	1,20
20NH/80LH	CS(10\Y)40	47,04	TR2,5	4,71	WS2,0	1,59

Unterschiede im Wasseraufnahmepotential und der Feuerfestigkeit lassen sich mit Zusatzstoffen wie Hydrophobierungsmitteln und Brandschutzmitteln ausgleichen. Allerdings ergaben eigene Untersuchungen an den Fasersortimenten aus Kapitel 4, die

über die Ergebnisse in diesem Kapitel hinausgehen, dass die Festigkeiten durch Zugabe dieser Zusatzstoffe herabgesetzt werden und die Wärmeleitfähigkeit steigt. Die geringeren Festigkeiten sind beispielhaft anhand der Druckfestigkeit in Abbildung 4 dargestellt. Speziell bei Brandschutzmitteln steigt auch das Wasseraufnahmepotential. Als Brandschutzmittel wurde in dieser Studie 10 % [atro Faser] Ammoniumpolyphosphat genutzt, was in der HFDS-Industrie überwiegend Anwendung findet (Paulitsch und Barbu 2015). Als Hydrophobierungsmittel wurde Paraffin mit 1 % [atro Faser] genutzt (Niemz und Wagenführ 2012).

Die erhöhte Wasseraufnahme durch Ammoniumpolyphosphat wurde bereits in vorherigen Studien ermittelt (Sonderegger et al. 2012; Eichhorn 2017). Die durch die Zugabe von Paraffin herabgesetzten Festigkeiten können durch eine inaktive Faseroberfläche erklärt werden, wodurch während der Bindemittelzugabe die Faserbenetzung reduziert wird (Antonović et al. 2010). Dies führt zu einer geringeren Adhäsion der Fasern und dementsprechend zu geringeren mechanischen Festigkeiten (Nazerian et al. 2015).

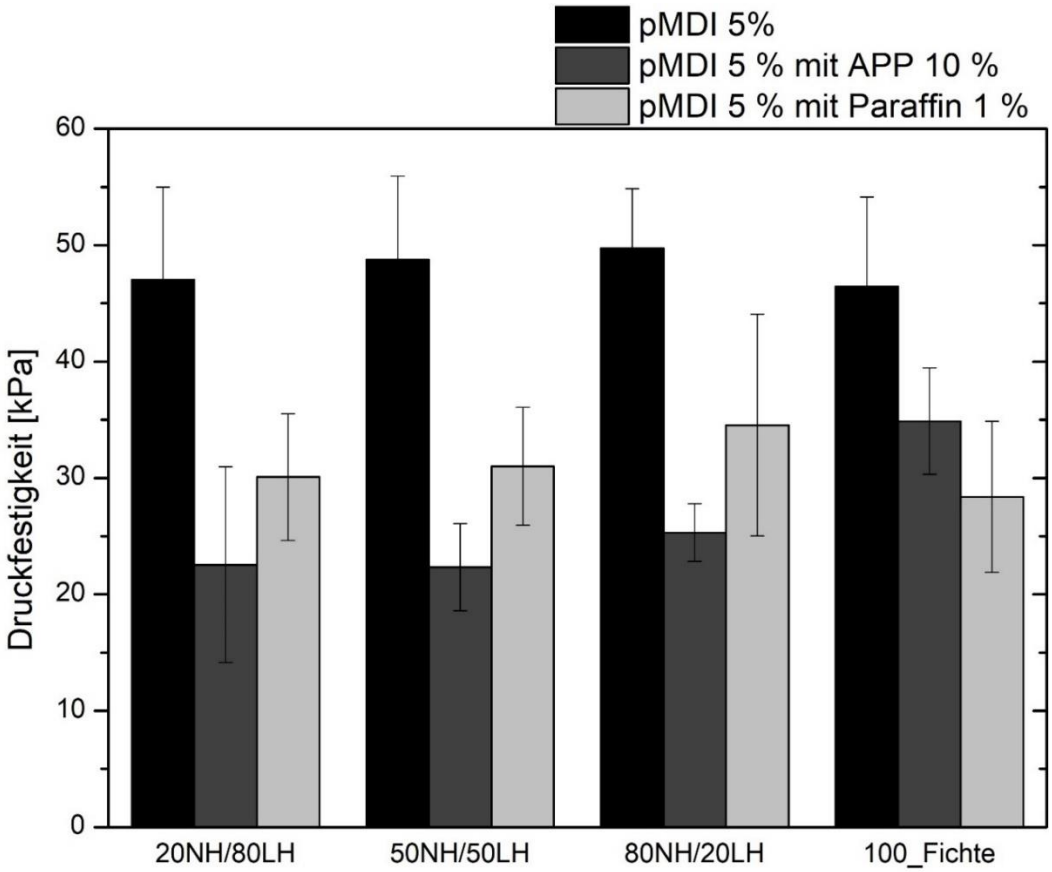

Abbildung 4: Druckfestigkeit verschiedener Holzfaserdämmstoffe ohne Zusatzstoffe (schwarz) und mit Zusatzstoffen (dunkelgrau für APP und hellgrau für Paraffin).

In den Kapiteln 4 und 5 wird die Forschungsfrage 6 beantwortet. Mit Hilfe von Biko-Fasern hergestellte HFDS weisen eine hohe Flexibilität auf und werden für andere Verwendungsbereiche (vor allem Zwischensparrendämmung) genutzt, als die mit pMDI hergestellten druckfesten Holzfaserdämmstoffe (Lempfer 2010). Dementsprechend unterschiedlich wirken sich die Bindemittel auf verschiedene Eigenschaften der HFDS aus. Über die in Kapitel 4 erfolgten Untersuchungen hinaus wurde die Querzugfestigkeit auch für die mit Biko-Fasern gebundenen flexiblen Matten geprüft (Abbildung 5). Die mit Biko-Fasern gebundenen flexiblen HFDS weisen bei gleicher Rohdichte eine höhere Querzugfestigkeit als die druckfesten Platten auf, bieten aber eine geringere Druckfestigkeit (siehe Kapitel 4). Darüber hinaus ist auch in anderen Studien ein gesteigertes Brandverhalten von mit Biko-Fasern gebundenen HFDS nachgewiesen worden (Eichhorn 2017). Das gesteigerte Brandverhalten kann durch die leichte Entflammbarkeit von Polyolefinen (bspw. Polyethylen und Polypropylen) begründet werden (Kruse 2009). Diese Unterschiede zeigen sich allerdings über alle Fasersortimente und sind nicht davon beeinflusst, ob Laubholzfasern oder Nadelholzfasern eingesetzt worden sind.

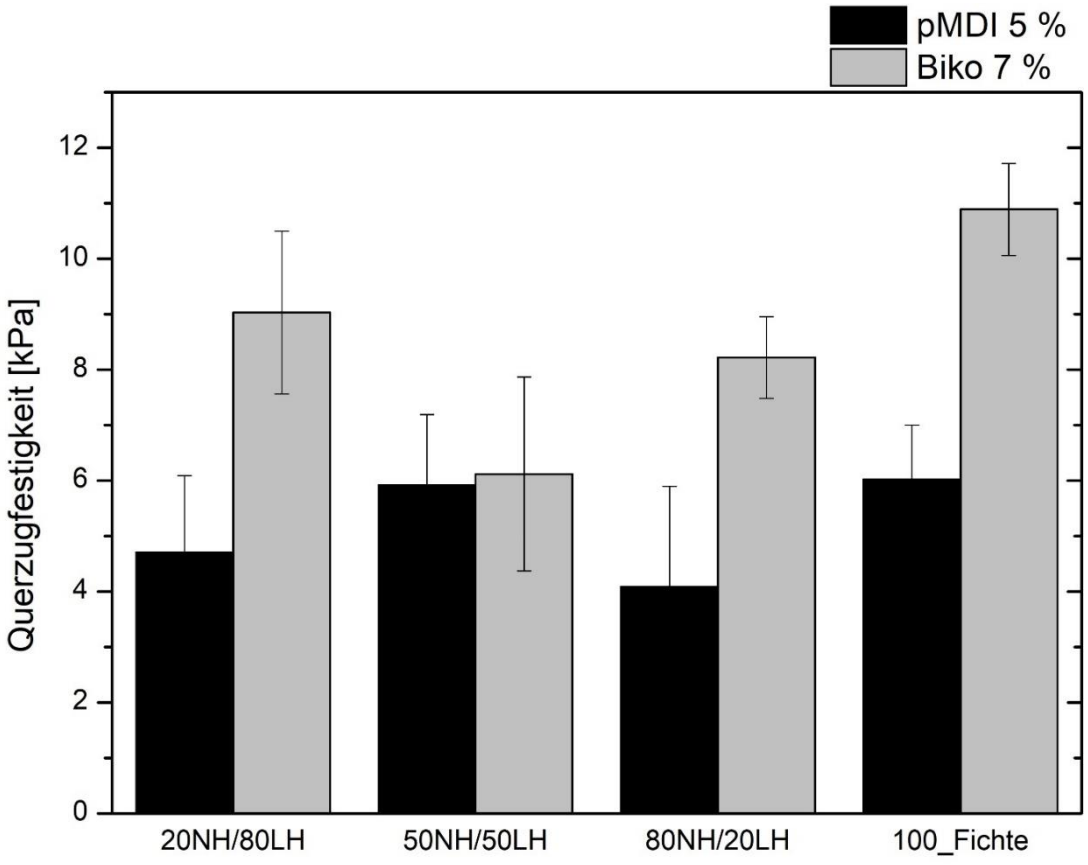

Abbildung 5: Querzugfestigkeit verschiedener Holzfaserdämmstoffe (Rohdichte = 100 kg/m³) mit pMDI und Biko-Fasern gebunden.

Die Forschungsfrage 7 wird in den Kapiteln 3 und 5 beantwortet. Sowohl zwischen der Faserlänge, die mittels scannerbasierten FibreShape System in Kapitel 3 ermittelt worden ist, als auch zwischen der Porosität, die mittels Computertomographie in Kapitel 5 ermittelt worden ist, und den physikalischen und mechanischen Eigenschaften sind keine Korrelation festzustellen.

Forschungsfrage 8 ist in Kapitel 6 beantwortet worden. In dieser Untersuchung wurden nur Mischsortimente aus Laubholzfasern untersucht. Hierbei wurde mit steigendem Laubholzanteil ein stärkerer Schimmelpilzbefall gegenüber reiner Fichte festgestellt. Dies wurde mit dem höheren Anteil von Hemicellulosen begründet, wie es auch schon in anderen Studien festgestellt worden ist (Hosseinaei et al. 2011; Cheng et al. 2013). Des Weiteren konnte auch eine Korrelation zwischen Wasseraufnahme und Schimmelpilzbefall festgestellt werden. Sowohl die Wasseraufnahme als auch der Schimmelpilzbefall steigen mit zunehmendem Laubholzanteil an. Dieser Zusammenhang ist auch schon in früheren Studien erkannt worden (Lie et al. 2019). Er kann mit dem hohen Holzfeuchtebedarf zwischen 30 – 150 % von Schimmelpilzen erklärt werden (Sutter 2002). Mit Hilfe von Fungiziden kann die Anfälligkeit gegenüber Schimmelpilzen herabgesetzt werden.

8 Fazit und Ausblick

Im Rahmen dieser Arbeit erfolgte die Untersuchung des Einsatzes von Laubholzfasern für die Produktion von HFDS mit dem Ergebnis, dass die Herstellung generell möglich ist. Dabei hängt es wesentlich davon ab, welche Laubbaumart genutzt wird. Zwischen den verschiedenen, getesteten Laubbaumarten gibt es große Unterschiede hinsichtlich ihrer mechanischen und physikalischen Eigenschaften, sowie ihrer Brennbarkeit. Als am besten geeignetes Laubholz für den Einsatz in HFDS sind anhand der in dieser Arbeit durchgeführten Untersuchungen Buchenfasern zu beurteilen. Außerdem bietet sich ein großes Potential durch Fasermischungen von Laub- und Nadelholzfasern, bei denen die Nadelholzfasern teilweise durch Laubholzfasern substituiert werden. Die Beimischung von bis zu 80 % Laubholzfasern bei der HFDS-Produktion führt zu keinen Verschlechterungen gegenüber solchen aus reinen Nadelholzfasern. Dabei ist es nicht von Relevanz, welche Laubholzfasern in den Mischsortimenten genutzt werden.

Die vorliegende Dissertation liefert nicht nur wissenschaftliche Beiträge zur aktuellen Literatur, sondern auch neue Erkenntnisse für die HFDS-Industrie. Vor allem der Einsatz von Fasermischungen aus verschiedenen Laubbaumarten mit einem geringen Anteil Nadelholzfasern ist auch im industriellen Maßstab ein vielversprechender Ansatz, um die Rohstoffverfügbarkeit zu erhöhen und die Abhängigkeit vom knapper werdenden Nadelholz zu senken.

Ein zukünftiger Forschungsschwerpunkt sollte nun der Umstieg vom Batch-Verfahren in einen kontinuierlich arbeitenden Prozess sein. Diese Empfehlung wird durch die Ergebnisse der Computertomographie-Analyse in Kapitel 5 gestützt. Bisherige wissenschaftliche Arbeiten zu HFDS, wie auch die vorliegende, haben ausschließlich unter Laborbedingungen im Batch-System stattgefunden (Ostendorf 2022).

Des Weiteren sollten die Untersuchungen an den verschiedenen Laubbaumarten fortgeführt werden, um herauszufinden, aus welchem Grund sie sich unterschiedlich gut für die Verwendung in HFDS eignen. Eine mögliche Ursache sind die unterschiedlichen Extraktstoffe der verschiedenen Baumarten, die die Verklebbarkeit beeinflussen können (Roffael 2016). Die Untersuchungen sollten auch um Fasern weiterer Baumarten, beispielsweise von schnell wachsenden Plantagenhölzern, ergänzt werden. Zu

diesen zählen unter anderem Pappel und Kiri. Pappelfasern sind bereits in einer vorherigen Studie auf ihre Wärmeleitfähigkeit getestet worden (Heinrich und Hering 2004). Zum Einsatz von Kiri in HFDS wurde bereits eine Masterarbeit verfasst (Mayer 2018). Beide Baumarten lieferten in den Studien vielversprechende Ergebnisse, weshalb eine Intensivierung der Forschung in diesem Bereich angestrebt werden sollte.

Weitere Forschungsstudien zur Herstellung von HFDS aus Laubholzfasern mit Hilfe von naturnahen Bindemitteln erscheinen ebenfalls sinnvoll. So gab es für HFDS aus Nadelholzfasern bereits Untersuchungen mit Blutalbumin und Rapsmehl als Bindemittel (Ostendorf et al. 2020; Ostendorf et al. 2021).

Über die Untersuchungen in Kapitel 6 hinausgehend sollte nicht nur die Anfälligkeit von HFDS auf Laubholzbasis gegenüber Schimmelpilzen geprüft werden, sondern auch die Anfälligkeit gegenüber holzzerstörenden Pilzen wie Braun- und Weißfäule.

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Eidesstattliche Erklärung

Hiermit versichere Ich, Arne Imken, dass die vorliegende Arbeit selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt wurden. Wörtlich oder sinngemäß aus anderen Werken entnommene Stellen habe ich unter Angabe der Quellen kenntlich gemacht. Die Dissertation wurde in keinem anderen Prüfungsverfahren vorgelegt. Weiter erkläre ich, dass ich mich an keiner anderen Hochschule um einen Doktorgrad beworben habe.

Rotenburg (Wümme), 01.06.2022

Ort und Datum	Arne Imken

Curriculum Vitae

Persönliche Daten:

Name: Arne Imken
Geburtsdatum: 01.07.1991
Geburtsort: Bremen
Staatsangehörigkeit: Deutsch
Anschrift: Buhrfeindstr. 25B
27356 Rotenburg (Wümme)
Mobiltelefon: 0176/32954731
E-Mail: a.imken@gmx.de

Ausbildung:

02/2018 – heute **Georg-August-Universität Göttingen**, PhD Studiengang Wood Biology and Wood Technology
Dissertationsvorhaben: Verwendung von Laubholz zur Herstellung von Holzfaserdämmplatten

10/2014 – 09/2017 **Georg-August-Universität Göttingen**
Abschluss: Master of Science Forstwissenschaften und Waldökologie
Fachrichtung: Holzbiologie und Holztechnologie
Masterarbeit: Charakterisierung von Faserstoffen aus geringwertigen Laub- und Nadelhölzern zur Herstellung von Faserplatten

10/2010 – 09/2014 **Georg-August-Universität Göttingen**
Abschluss: Bachelor of Science: Forstwissenschaften und Waldökologie
Bachelorarbeit: Vergleich von nach Sturmwurf (Orkan Quimburga 1972) entstandenen Küstentannen- und Weißtannenbeständen

2003 – 2010 **Gymnasium Syke** (Abschluss Abitur)

Berufserfahrung:

02/2018 – heute	**Georg-August-Universität Göttingen** Wissenschaftlicher Mitarbeiter, Abteilung Holzbiologie und Holzprodukte
10/2017 – 02/2018	**Georg-August-Universität Göttingen** Wissenschaftliche Hilfskraft, Abteilung Molekulare Holzbiotechnologie und Technische Mykologie
04/2016 – 07/2016	**Georg-August-Universität Göttingen** Studentische Hilfskraft, Tutor für Holzkunde I (Einheimische Nutzhölzer),
04/2015 – 07/2015	**Georg-August-Universität Göttingen** Studentische Hilfskraft, Tutor für Holzkunde I (Einheimische Nutzhölzer)

Publikationen

- **Imken, A. A. P., Kraft, R. and Mai, C. (2021)** Production and characterisation of wood-fibre insulation boards (WFIB) from hardwood fibres and fibre blends. Wood Material Science & Engineering
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